NASA TECHNICAL NOTE

NASA TN D-5092

NASA TN D-5092

# DESIGN AND FABRICATION OF A COUNTERFLOW DOUBLE-CONTAINMENT TANTALUM – STAINLESS STEEL MERCURY BOILER

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • MAY 1969

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## ABSTRACT

A boiler was designed using 7 tantalum (Ta) tubes for containment of the mercury with each Ta tube placed inside a flattened stainless steel tube. These tubes were coiled, bundled, and inserted into a coiled, large diameter stainless steel tube which contains the primary NaK. The large difference in thermal expansion between the Ta and the stainless steel tubes was accommodated by the flattened stainless steel tube allowing the Ta tube to radially move with respect to the stainless steel tube. All tubes were equalized in length by uniformly twisting the tube bundle $360^{\circ}$.

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## SUMMARY

A boiler was designed using a double wall between mercury (Hg) and primary sodium potassium (NaK). Seven tantalum (Ta) tubes were used to contain the Hg with each Ta tube placed inside a flattened stainless steel (SS) tube. These tubes were coiled to a 4-foot (122-cm) diameter, bundled, and placed in a large SS tube for primary NaK containment. The space between the round Ta tube and the flattened SS tube was filled with static NaK while the primary NaK flowed outside the flattened SS tubes. This isolated the Ta from any inpurities in the primary NaK man-rated concept. The large difference in thermal expansion between the Ta and the SS tubes was accommodated by the flattened SS tube allowing the Ta tube to radially move with respect to the SS tube. The Ta tube was correctly positioned within the flattened SS tube during coiling by a unique method of freezing the tubes together. The tube assemblies were coiled individually and then assembled into a bundle. All tubes were equalized in length by uniformly twisting the tube bundle $360^{\circ}$. The bundle was inserted into the SS shell and the respective tube-to-header welds were performed. The final attachment of the Ta inlet and outlet tubes to the SS shell was accomplished through the use of a brazed tongue and groove bimetal joint and a SS bellows.

## INTRODUCTION

The Lewis Research Center is conducting the SNAP-8 program to develop a Rankine-cycle power system for space application. This system uses a nuclear reactor as the heat source; a primary loop to transfer the heat energy with NaK from the reactor to a boiler in the mercury loop; the mercury vapor drives a turboalternator assembly and then is condensed and subcooled by a secondary NaK loop; the secondary NaK loop transfers the waste heat to a radiator for rejection to space (fig. 1).

A major problem area in the development of the system has been in the design of the boiler for predictable heat-transfer rates and material compatibility with mercury, particularly in the high-temperature liquid and low-quality boiling region. Two types of boilers have been built and tested. The first was a tube-in shell boiler of L-605 material which consisted of four tubes for Hg flow coiled inside of a large cylindrical torus (ref. 1) through which the NaK flowed. This had a NaK flow pattern of counter or cross-counter flow. The second concept was a tube-in-tube counter flow boiler of AISI 505 material (ref. 2) which consisted of 7 small Hg containment tubes within a larger NaK containment tube. This assembly was then rolled into a helical coil.

The materials used for Hg containment in these boilers were either L-605 (Co-20Cr-10Ni-15W) or AISI 505 (Fe-9Cr-1Mo) both of which had exhibited good resistance to Hg corrosion in small-scale tests. These materials were difficult to fabricate because of their welding characteristics, ductility, and so forth. In addition, upon disassembly, it was observed that a great deal of erosion and/or corrosion had occurred in the boiling region.

This report presents the design of a double-containment counterflow boiler similar to the previous tube-in-tube boiler concept. The material selected for Hg containment was tantalum which in capsule tests and natural convection loops showed high resistance to Hg attack. It is readily wetted by Hg which is a very desirable characteristic due to the increased heat-transfer rate. A 300 series SS was selected for the NaK containment. An additional requirement added for this boiler was that it should be designed to meet requirements for man-rated compatibility in space. It was required that the primary NaK from the reactor could not mix with the mercury, which passes through unshielded areas of the system, if the boiler should fail. A double wall between the primary NaK and Hg met this criteria since there could be no mixing of active fluids if failure of any one fluid barrier in the boiler occurred. This report covers the design concepts, design details, and fabrication techniques, along with preliminary results of operational performance.

## DESIGN

The first-order design objectives were to develop a boiler which had the following characteristics:

(1) Good heat-transfer
(2) Predictable performance
(3) "Man-rated" system capability

(4) Compatible materials

(5) Sized for a given gallery

An illustration of the configuration selected is shown in figure 2. This is a counterflow boiler similar to the tube-in-tube boiler of reference 2 which had displayed adequate heat-transfer characteristics. The shell diameter and height were established by the SNAP-8 system integration layout which required two boilers. The space allocated was a torus shaped gallery, 30 inches (76.2 cm) high with a 42-inch (106.8-cm) outside diameter and a 36-inch (91.4-cm) inside diameter. A mean diameter of 48 inches (122.0 cm) for the boiler was selected with a double pitch spiral so that the two boilers could be nested together to fit within the height limit. The 4-foot (122.0-cm) diameter and 30-inch (76.2-cm) height permitted three complete turns with a length of approximately 37 feet (1130 cm); as can be seen in figure 2, the ends both had straight sections. The straight section on the Hg outlet was necessary in order to fit the headers (fig. 3); on the inlet end, the straight section was used for the plug insert so that it would not have to be coiled until the boiler had been tested and evaluated.

The requirement for a "man-rated" system was assurance that the NaK from the primary loop flowing through the reactor could not reach any other part of the system if any one wall failed. The result of this requirement was to maintain separation of the NaK from the Hg at all times by two walls so failure of any one wall would not mix the fluids. Because of the use of two walls, this concept is referred to as "double containment." The method adopted to accomplish this double containment was to place each Hg-carrying tube inside of another tube. Each set of tubes (i.e., Hg or NaK) was then welded into a different header. The primary NaK flowed around the second set of tubes while a separate chamber of static NaK filled the space between the two sets of tubes and their respective headers. This NaK was used to improve thermal conductance between tubes.

Experience has shown that Hg is very corrosive in the wet boiling region of a boiler. Capsule tests of many materials with Hg at elevated temperatures have been performed. An example of solubilities is shown in figure 4 which is taken from reference 3. This figure shows that tantalum had the lowest solubility of any of the Hg containment materials tested. Other unreported tests demonstrated that Ta was readily wetted by Hg. This characteristic is very essential for good boiler performance. On this basis, Ta was chosen as the Hg containment material.

The selection of Ta for Hg containment presented other problems. At elevated temperatures, Ta will oxidize very rapidly. Therefore, it was necessary to completely contain the Ta section of the boiler in another material. The 300 series SS have been used many times at SNAP-8 temperatures for NaK containment. For this application, 316 and 321 SS were selected for both primary and static NaK containment with the Ta material being completely surrounded with static NaK (fig. 3). This prevented either the primary NaK or environmental contamination of the Ta.

The use of the combination of Ta and SS over the temperature range of $70^{\circ}$ F ($15^{\circ}$ C) to $1400^{\circ}$ F ($760^{\circ}$ C) presented a problem caused by their large difference in coefficient of thermal expansion. This difference, varying between $6\times10^{-6}$ and $9\times10^{-6}$ inch/inch/$^{\circ}$F ($10.8\times10^{-6}$ and $16.2\times10^{-6}$ (cm/cm/$^{\circ}$C)), would cause a thermal growth differential of approximately 3.5 inches (8.9 cm) in 37 feet (1130 cm). To avoid this large change in length at the ends, the tubes were designed so that the difference was compensated for by a change in relative radius of the tube coils. An oval SS tube was used to contain the round Ta tube (fig. 2). At ambient conditions, the Ta tube should touch the outer side of the oval. When heated to operating temperature the SS tube coil radius would grow more and the Ta would move toward the inside of the SS oval with the ends of the two tubes fixed.

A 3/4-inch (1.9-cm) outside diameter by 0.040-inch (0.102-cm) wall Ta tube was used for the Hg side. Implementation of the concept of allowing the coil radius to vary to compensate for the difference in thermal expansion of the materials required a larger SS tube around the Ta. A 1-inch (2.54-cm) outside diameter by 0.035-inch (0.089-cm) wall SS tube was shaped into an oval with internal dimensions of 1.03-inch (2.62-cm) inside diameter on the major axis and 0.76-inch (1.93-cm) between flats (fig. 10). This permitted a maximum radial movement of the Ta relative to the SS of 0.28 inches (0.71 cm), while calculations showed 0.25 inch (0.64 cm) was required. Seven of these tubes were arranged symmetrically inside of a 5-inch (12.7-cm) outside diameter by 0.095-inch (0.241-cm) wall SS outer NaK containment tube.

A bundle of tubes when bent into a coil of a given diameter will have different lengths if their positions with respect to the centerline of the coil is always the same (i.e., outer tube always on the outside, inner tube always remains on the inner side). This length difference may be large depending on the difference in radii between inner and outer tubes. To correct for this effect and keep the tubes all of equal length, the tube bundle when assembled was given one $360^{\circ}$ rotation about the center tube, starting and finishing where the coil started and stopped. Spacers were placed to hold the tubes in position at each $30^{\circ}$ change in tube bundle rotation. Because of symmetry, this required only two different spacers (fig. 5).

Various devices were placed in the Hg tubes to aid boiling and maintain boiler stability. A restrictor (fig. 6) was placed at the inlet to each tube to help keep the flow balanced between tubes. This restrictor was a 0.071-inch (0.18-cm) diameter drilled hole 1.2 inches (3.2 cm) long with a chamfered inlet which at design flow conditions would cause a pressure loss of approximately 50 psi ($345\times10^{3}$ N/m$^{2}$). Immediately after the restrictor was a 4.5-foot (137-cm) fluted (multipassage) plug. This plug (fig. 7) increased velocity which aided boiling and helped prevent slugging. The helical grooves are spiraled on a 6-inch (15.3-cm) pitch which causes a centrifugal force in the fluid to force the drops against the hot wall. Following the plug and for the remainder of the tube length, a 0.062-inch (0.158-cm) diameter Ta-10 percent tungsten (W) wire spring with a 2-inch (4.9-cm) pitch was coiled against the inside diameter of the tube. This spring causes the flow to form a vapor vortex which forces the heavy drops to contact the wall by centrifugal action. This aids heat-transfer and helps prevent droplet carryover.

A critical area in any bimetal system is a reliable bond between the two dissimilar metals. In this case, since the point was between SS and Ta, the problem was more difficult because of the very large difference in coefficients of thermal expansion of the two metals. Calculations show that for the operating temperature of SNAP-8, when Ta and SS are bonded, one of the materials will yield during a full cycle. For this application, a tongue and groove joint was selected (fig. 3). This joint was brazed with an alloy (J-8400) consisting of 21Cs, -21Ni-8Si-3.5W-0.4C-0.8B-balance Co. Test results obtained with this type of joint are reported in reference 4.

In the coiled section of the boiler, the differential expansion was taken up by the change in radius but this method would not work in the straight sections at each end. Therefore, SS bellows were placed between the bimetal joints and the closure headers (fig. 8). These bellows were three plys of 0.012 inch (0.029 cm) 321 SS material. They were designed to allow for 1/2 inch (1.2 cm) of axial movement and small amounts of misalinement. A sleeve was inserted in the Hg passage at both ends which extended through both the bellows and the bimetal joint. The purpose of the sleeve was to make a smooth flow passage through the bellows and to reduce the thermal shock on the bimetal joint at startup when cold Hg would be injected into the hot boiler. Centering pins were placed between the outer boiler shell and the Hg tube at the point between the bellows and the bimetal joint. These pins were to help maintain bellows alinement as the boiler was brought up to temperature.

It was desirable to have all tube-to-header joints circular so a transition from oval to round was made in the 0.035-inch (0.085-cm) wall SS tube. A heavy 1/8 inch (0.32 cm) wall SS tube was butt-welded to this round section (fig. 3) so that a heavy weld could be made to the SS header. A sectioned sample is shown in figure 9. This heavy section reduces the stress levels at this point and permitted the thin lip on the head to be melted back and form a strong joint.

It is desirable to have headers maintained in an isothermal condition to reduce the thermal stress problems. As an aid to accomplish this, baffle plates were placed at both ends of the boiler around the SS tubes between the stainless headers and the primary NaK inlet and outlet (fig. 3). These baffles had clearance around the tubes and shell for filling and draining but reduced the NaK circulation. This reduced the NaK temperature at the SS header, particularly at the Hg inlet end since the heat would only be transferred by conduction.

The design specifications used are listed in table I and the model of the tube cross sections are shown in figure 10. An analysis was done by the Von Karman Center, Aerojet-General Corporation, Azusa, California (ref. 5) to determine expected heat transfer and pressure drop characteristics for SNAP-8 system operating conditions. Multipassage and single passage plug insert geometries were compared at design and off-design operating conditions to determine which would be more advantageous. The analysis was based on dropwise, dry wall boiling, and two-phase flow pressure drop conditions. The summary of calculated performance from reference 5 is listed in tables II and III. The results show that to meet heat-transfer requirements, the required boiler length is 30.7 feet (935 cm) and the plug insert length is 4.1 feet (125 cm). These are both less than the design lengths of 37 and 4.4 feet (1120 and 134 cm), respectively. The multipassage plug (fig. 11) was selected over the single passage geometry because of its relative insensitivity to varying NaK inlet temperatures.

In addition to the operating conditions listed in table I, the boiler was designed to withstand 200 complete temperature cycles. A cycle consists of heating the complete boiler slowly from room temperature to $1300^{\circ}$ F ($705^{\circ}$ C) with the primary NaK. At $1300^{\circ}$ F ($705^{\circ}$ C), Hg is injected dropping the temperature at the boiler inlet. These conditions were used in making the necessary stress calculations for sizing the materials. The two most critical areas and conditions were the thermal cycling at the boiler inlet and the long-term exposure to $1300^{\circ}$ F ($705^{\circ}$ C) temperatures. Details of the stress computations are contained in the appendix.

## FABRICATION

The fabrication can be divided into several stages: machining, forming and assembly, and welding. The machining aspect will not be discussed in detail since the procedures used were standard methods for the various materials. A chronological sequence will be followed in the discussion of the assembly. This assembly, when completed, was to be used in high-temperature liquid-metal systems which require a great deal of cleanliness. Since many places in the boiler would be difficult to clean after it was completed, all parts were cleaned before assembly and all Ta parts handled with white gloves in a controlled environment after cleaning.

The Ta tubing was only available in 8-foot (244-cm) sections. This, however, permitted the plugs and spring to be inserted in easily handled sections. The plug was inserted into a section of tubing (fig. 7) and the tube then was swaged over the plug. The swaging is required to minimize by-pass flow between tube and plug and to attain uniformity between assemblies. The wire spiral springs were made from 0.062-inch (0.158-cm) diameter Ta-10W wire on a 2-inch (5.1-cm) pitch. They were wound on a slightly undersized mandrel for easy insertion into the tubes (fig. 12). Both ends of the wire were clamped to the 9-foot mandrel when wound. After inspection, 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 then trimmed back to just inside the tube, and the ends were TIG welded to the tube. The 8-foot sections of the Ta tube were welded together in a vacuum chamber with a rotating head electron beam welder (fig. 13). Special port fittings were made to permit the long tubes to extend outside of the chamber.

The 1-inch SS tubes including the heavy wall stubs were TIG welded together to the design length. Each individual tube was packed with sand to prevent any curvature discontinuities when formed to an oval shape. The shaping was done by placing the tube in a die in order to restrict the maximum dimension and squeezed into shape with a large press (fig. 14).

So that the Ta would initially be in contact with the outer part of SS coil, the assembly and coiling of the Ta-SS tube required some innovations. The Ta tube was inserted into the stainless tube along with a plastic tube. The plastic tube was then pressurized which forced the Ta tube against one small radius wall of the oval SS tube. Clamps were used to squeeze on the oval tube, trapping the Ta tube to one side of the oval after which the plastic tube was withdrawn. The Ta tube was then frozen into position for coiling. This was done by inclining the tube, sealing the space between the two tubes at the lower end, and filling the space between the Ta and SS tubes with distilled water (fig. 15). At the elevated end, a clay dam was used to keep the tube completely full. Cold alcohol was then pumped through the inner Ta tube by a finger pump. The cooling of the alcohol was accomplished by passing the alcohol over frozen $CO_2$ in a container. The water froze from the low end and the excess from the expansion merely flowed out the open end. When the water was completely frozen, the tubes were coiled. The alcohol coolant was pumped throughout the coiling operation. The coiling did not give a pitch to the tubes, so this was done manually in a fixture and spacers inserted to maintain proper spacing and support.

A fixture was used for assembly of the tube bundle. The tube spacers were attached to the coil-holding fixture brackets. The tubes were threaded through the spacers one at a time with the center tube being the first. As the seceding tubes were screwed through the spacers they were also spiraled around the center tube so that one complete revolution ($360^o$) was made between the start and finish (fig. 16). The major axis of the oval tube was maintained perpendicular to the axis of the coil.

The large 5-inch (12.7-cm) outside diameter tube, which was coiled separately, was filled with high-pressure water as a filling agent to maintain roundness and then coiled. After coiling, the tube diameter varied ±1/32 inch (±0.079 cm). The tube was trimmed to length and then cut into four sections for ease of handling when threading it on to the tube bundle (fig. 17).

All welding of the assembly was by the TIG process. During welding at the SS tubes and headers, a positive flow of argon gas was maintained on the inside. When Ta welds were made on the assembly, a portable glove box (fig. 18) was used. The assembly and box was purged with argon until the oxygen concentration was less than 10 parts per million (ppm); this was determined by welding a sample piece of SS. If not blue shows on the sample weld, the $O_2$ content is less than 10 ppm. Weld samples using this technique are shown in figure 19. Just before welding the Ta, an arc was struck to a piece of Ti in the box which heats the electrode and also helps to getter part of the remaining $O_2$. On a large Ta weld, periodic checks of $O_2$ content in the box were made by welding SS samples. Every weld was He leak checked before proceeding to the next step.

The SS shell, spacers (fig. 20), and headers were assembled and welded. The SS tube stubs were positioned with 1/4-inch (0.635-cm) of stub extending from the header. This extension protected the Ta during welding and allowed a heavy filler pass to be made after the full penetration seal weld. The results can be seen in figure 21.

At this point, the Ta tubes were trimmed to length after being forced back into the SS oval coil to maintain maximum diameter. The Ta tubes were mechanically attached to the headers by expanding the tubes into the grooves in the headers with a special tool (fig. 21). The seal weld was a standard trepan type (fig. 9). A subassembly of the transition dome, bimetal joint, bellows and shell end (fig. 8) was welded to the Ta header. Zr foil which acts as an oxygen getter in the NaK was wrapped around the bimetal joint and covered with a short section of a 5-inch (12.7-cm) outside diameter tube which formed the final closure. A ratio of 1 square inch of foil for each cubic inch of NaK was used. The guide pins for the bellows were positioned and welded last. The completed boiler is shown in figure 22.

## OPERATIONAL PERFORMANCE

The boiler was instrumented with skin thermocouples and installed in an existing SNAP-8 development system at the Lewis Research Center (fig. 23). The boiler was operated for 1444 hours including three full cycles from room temperature to $1300^\circ$ F ($705^\circ$ C) with no malfunctions. The test was terminated due to system problems not connected with the boiler. Figure 24 presents typical boiler operating parameters. A complete description of the tests and results are presented in reference 6. This same boiler (designated -1) with minor external modifications, has since been operated at the General Electric Company, Evandale, Ohio, in excess of 7000 hours. Another boiler (designated -2) is being tested at Aerojet-General Von Karman Center, Azusa, California.

# CONCLUDING REMARKS

A design for a SNAP-8 boiler was completed and the boiler was fabricated and preliminary tests made. The design met the anticipated requirements for a man-rated system and would fit the allocated space in the system layout.

A new mercury containment material, tantalum, was used. The problems presented by the use of the Ta and SS combination were solved by the use of an oval SS tube permitting the differential thermal expansion to be taken radially. A brazed tongue and groove bimetal joint was used to join the Ta assembly to the SS shell. The Ta was completely surrounded by static NaK which aided the conductive heat-transfer and prevented the Ta from being contaminated by the primary NaK or environmental conditions. Tube-to-header joints for both the Ta and SS were designed with heavier sections which reduced the usually large weld stresses to acceptable levels.

Unique fabrication techniques were developed such as freezing the Ta-SS tube together so that the correct location of the Ta could be maintained during the coiling operating. Tube bundle assembly methods and the use of a portable glove box for Ta welding were developed.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 14, 1968,
701-04-00-02-22.

# APPENDIX - STRESS ANALYSIS

The operating conditions for the boiler which were assumed in order to make the necessary stress calculations are as follows:

| Media | Pressure | | Temperature | |
|---|---|---|---|---|
| | psia | $N/m^2$ | $^oF$ | $^oC$ |
| Mercury | | | | |
| Inlet | 350 | $241\times10^4$ | 550 | 288 |
| Outlet | 270 | 186 | 1275 | 692 |
| Primary NaK | | | | |
| Inlet | 55 | $380\times10^3$ | 1300 | 705 |
| Outlet | 50 | 345 | 1100 | 594 |
| Static NaK | 50 | 345 | 1100-1300 | 594-705 |

The boiler also was required to withstand 20 complete temperature cycles which would be from ambient to a $1300^o$ F ($705^o$ C) NaK hot soak to operating conditions with Hg.

The design philosophy of the boiler utilizing types 316 and 321 SS plus pure tantalum (99.9 percent) allowed the stress criteria to be based upon the stress-rupture strength at $1300^o$ F ($705^o$ C). Data on SS was used from reference 7. Typical data for tantalum are shown in figure 25 which was taken from reference 8 and table IV. The boiler was divided into seven areas for stress analysis which were outer shell, tube bundle, headers, transition dome, bellows, bimetal joint, and miscellaneous.

Type 316 SS welded tubing was selected for the outer shell. The minimum required wall thickness or stress level for the selected thickness was determined from the equation for loop stress in a thin wall pressure vessel:

$$\text{Stress} = \frac{(\text{Pressure}) \cdot (\text{Diameter})}{2 \cdot (\text{Wall thickness})}$$

The primary NaK segment of the outer shell had a wall thickness of 0.095 inch (0.241 cm). A calculation of hoop stress gives approximately 2000 psi ($13.8\times10^6$ $N/m^2$) which is considerably below the stress-rupture value of 12 000 psi ($84\times10^6$ $N/m^2$) for 10 000 hours at $1300^o$ F ($705^o$ C). The static NaK segment was 0.25 inch (0.635 cm) thick since it must contain Hg pressure if any part of the Hg system failed. This could cause a maximum stress of 3500 psi ($24.2\times10^6$ $N/m^2$).

The type 321 SS and tantalum tube bundle also utilized the loop stress equation for thin wall pressure vessels. The pressure differential on the oval SS tube can vary from -50 to +350 psi ($0.345\times10^3$ to $241\times10^4$ N/m$^2$) depending on the adjustment of static NaK pressure or failure of the Hg containment section. Normal working pressure of 0 to 50 psi (0 to $345\times10^3$ N/m$^2$) differential would cause a loop stress of up to 700 psi ($4.8\times10^6$ N/m$^2$) while a Hg leak into the NaK would cause a stress of 5000 psi ($346\times10^6$ N/m$^2$) for a short time. Both of these stresses are less than the 10 000-hour rupture value of 6000 psi ($415\times10^6$ N/m$^2$) at 1300$^\circ$ F (705$^\circ$ C) for 321 SS.

An extrapolated stress-rupture value for pure tantalum of 12 000 psi ($84\times10^6$ N/m$^2$) at 1300$^\circ$ F (705$^\circ$ C) was used. The full Hg pressure of 350 psia ($241\times10^4$ N/m$^2$) in the 0.75 inch (1.91 cm) outside diameter times 0.035 inch (0.089 cm) wall tantalum tube created a stress of approximately 3500 psi ($24.1\times10^6$ N/m$^2$). This stress is reduced in practice by pressurizing the static NaK volume to about 100 psia ($6.9\times10^4$ N/m$^2$), reducing the pressure differential and consequently, the loop stress to about 2500 psi ($17.3\times10^6$ N/m$^2$).

The headers were analyzed as perforated plates based upon the work of G. Horvay (ref. 9). The method was used to determine an equivalent, effective thickness after which conventional flat-plate theory was used to check the selected thickness for adequacy.

The tantalum transition dome (fig. 26) was analyzed on a 7094 digital computer using a program based on thin shell theory. At the inlet transition, the design operating Hg pressure and temperature at 350 psia ($2.41\times10^6$ N/m$^2$) and 550$^\circ$ F (288$^\circ$ C), respectively, were used for the stress calculations. Figure 27 is a sketch of the transition dome with a summary listing of the maximum surface stresses which were calculated.

The bellows were designed by the vendor using the criteria that for a three-ply bellows, any one ply could fail without causing complete bellows failure. Type 321 SS, 0.012 inch (0.030 cm) thick for each ply, was used to form the bellows which was a three-ply configuration with eight convolutions. The bellows was designed for a maximum axial compression of 0.50 inch (1.26 cm) with a 0.10 inch (0.25 cm) offset and a cycle life of 2000 cycles.

The Ta-to-SS transition joints were designed on the basis of thin wall pressure vessel theory (wall thickness determination), of the joint being in compression, and of the capability to undergo 20 temperature cycles under startup to mercury operating conditions. Bimetal joint philosophy and considerations are explained in reference 5, which comments on joint details, shear strength of the brazed area and axial strength of the joint.

Under miscellaneous items, the end flanges of the boiler static NaK containment were designed using flat-plate theory. The flanges were assumed to have uniform loading and fixed edges. Tube welds were designed on the basis of butt-weld tensile strength being within the yield stress value of the material at 1300$^\circ$ F (705$^\circ$ C). The Ta tube sheet welds, in part, utilized a mechanical fit or cuterlock to reduce the stress level in the weld.

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TABLE I. - DESIGN SPECIFICATIONS

| | |
|---|---|
| Operating parameters: | |
| Mercury flow rate, lb/hr; kg/hr | 11 500; 528 |
| Mercury inlet temperature, $^{\circ}$F; $^{\circ}$C | 500; 260 |
| Mercury exit pressure, psia, N/m$^2$ | 265; 18.3$\times 10^5$ |
| Mercury exit temperature, $^{\circ}$F; $^{\circ}$C: | |
| Low | 1250; 677 |
| Nominal | 1275; 692 |
| High | 1300; 705 |
| NaK inlet temperature, $^{\circ}$F; $^{\circ}$C: | |
| Low | 1280; 693 |
| Nominal | 1305; 708 |
| High | 1330; 721 |
| NaK inlet temperature drop, $^{\circ}$F; $^{\circ}$C | 170; 78 |
| External power loss, kW | 12 |
| NaK side film coefficient, Btu/(hr)(ft$^2$)($^{\circ}$F); J/(hr)(m$^2$)($^{\circ}$C) | 1500 to 3500; 30.6$\times 12^6$ to 71.5$\times 10^6$ |
| Containment tube data and physical constants: | |
| Mercury tube (Ta), inside diameter, in.; cm | 0.670; 1.7 |
| Mercury tube wall thickness, in.; cm | 0.040; 0.1 |
| NaK containment tube (SS), in.; cm | (see fig. 10) |
| NaK containment tube wall thickness, in.; cm | 0.035; 0.089 |
| Tantalum thermal conductivity, Btu/(hr)(ft)($^{\circ}$F); J/(hr)(m)($^{\circ}$C) | 39.6; 24.6$\times 10^4$ |
| Stagnant NaK thermal conductivity, Btu/(hr)(ft)($^{\circ}$F); J/(m)($^{\circ}$C) | 14.87; 9.3$\times 10^4$ |
| Stainless steel thermal conductivity, Btu/(hr)(ft)($^{\circ}$F); J/(m)($^{\circ}$C) | 12.4; 7.7$\times 10^4$ |
| Swirl wire pitch, in.; cm | 2.0; 5.1 |
| Swirl wire diameter, in.; cm | 0.063; 0.16 |
| Multipassage plug insert (NPP): | |
| Pitch, in.; cm | 6; 15 |
| Number of passages | 16 |
| Cross-sectional area, in.$^2$/passage; cm$^2$/passage | 0.005073; 0.03275 |
| Equivalent diameter, in.; cm | 0.075; 0.19 |
| Single passage plug insert (SPP): | |
| Preheat section pitch, in.; cm | 0.375; 0.954 |
| Preheat cross-sectional area, in.$^2$; cm$^2$ | 0.01921; 0.124 |
| Preheat equivalent diameter, in.; cm | 0.1044; 0.2655 |
| Vapor quality section pitch, in.; cm | 2; 5.1 |
| Vapor quality section cross-sectional area, in.$^2$; cm$^2$ | 0.08298; 0.535 |
| Vapor quality section equivalent diameter, in.; cm | 0.12025; 0.3058 |

TABLE II. - MULTIPASSAGE (MPP) AND SINGLE PASSAGE PLUG INSERT (SPP) BOILER PRESSURE DROP DISTRIBUTION AT HIGH AND LOW NaK TEMPERATURE SCHEDULE

(a) U.S. Customary units; boiler length, 37.0 feet; plug insert length, 4.4 feet

| Case | Inlet temperature, $^{\circ}F$ | Preheat section: Change in length, $\Delta L$, ft | Preheat section: Change in pressure, $\Delta P$, psi | Vapor quality, preheat section: Change in length, $\Delta L$, ft | Vapor quality, preheat section: Change in pressure, $\Delta P$, psi | Vapor quality, preheat section: Vapor exit quality, percent | Vapor quality, plug insert section: Change in length, $\Delta L$, ft | Vapor quality, plug insert section: Change in pressure, $\Delta P$, psi | Vapor quality, plug insert section: Vapor exit quality, percent |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1280 | 1.05 | 0.5 | ---- | ---- | --- | 3.35 | 18.4 | 13.1 |
| | 1330 | .79 | .4 | ---- | ---- | --- | 3.61 | 31.4 | 30.2 |
| 2 | 1280 | 1.14 | 0.6 | ---- | ---- | --- | 3.26 | 31.2 | 11.0 |
| | 1330 | .86 | .4 | ---- | ---- | --- | 3.54 | 54.8 | 26.7 |
| 3 | 1280 | 1.16 | 28.9 | 0.06 | ---- | --- | 3.24 | 18.8 | 10.5 |
| | 1330 | .93 | 24.5 | .17 | 9.4 | 0.6 | 3.30 | 35.3 | 24.0 |
| 4 | 1280 | 1.17 | 30.8 | 0.02 | 0.1 | 0.0 | 3.21 | 19.5 | 11.3 |
| | 1330 | .96 | 25.3 | .23 | 17.3 | .9 | 3.21 | 34.6 | 23.8 |
| 5 | 1280 | 1.19 | 31.4 | 0.09 | 1.9 | 0.2 | 3.12 | 19.0 | 10.9 |
| | 1330 | .98 | 25.7 | .30 | 24.9 | 1.0 | 3.12 | 34.2 | 23.9 |
| 6 | 1280 | 1.25 | 32.8 | 0.21 | 8.2 | 0.4 | 2.94 | 18.1 | 10.7 |
| | 1330 | 1.05 | 27.5 | .41 | 40.3 | 1.3 | 2.94 | 31.8 | 22.7 |

| Case | Vapor quality, unplugged tube section: Change in length, $\Delta L$, ft | Superheat section: Change in length, $\Delta L$, ft | Excess superheat section: Change in length, $\Delta L$, ft | Plug insert: Change in pressure, $\Delta P$, psi | Unplugged tube: Change in pressure, $\Delta P$, psi | Total: Change in pressure, $\Delta P$, psi | Preheat design length, ft | Pinch point temperature difference, $\Delta T_{pp}$, $F^{\circ}$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 21.82 | 5.23 | 5.55 | 18.9 | 35.7 | 54.6 | ---- | 33.6 | MPP, 4.4 ft; |
| | 15.66 | 5.75 | 11.19 | 31.8 | 35.8 | 67.6 | ---- | 72.8 | $\Delta P$, min. limit |
| 2 | 22.23 | 5.22 | 5.15 | 31.8 | 35.7 | 67.5 | ---- | 26.4 | MPP, 4.4 ft; |
| | 16.15 | 5.72 | 10.72 | 55.2 | 36.0 | 91.2 | ---- | 60.4 | $\Delta P$, max. limit |
| 3 | 21.92 | 5.39 | 5.29 | 47.7 | 36.0 | 83.7 | 1.10 | 32.4 | SPP, 4.4 ft |
| | 15.53 | 5.62 | 11.46 | 69.2 | 35.6 | 104.8 | 1.10 | 62.3 | |
| 4 | 22.25 | 5.22 | 5.13 | 50.4 | 36.4 | 86.8 | 1.19 | 31.7 | SPP, 4.4 ft |
| | 15.73 | 5.72 | 11.14 | 77.2 | 35.6 | 112.8 | 1.19 | 58.0 | |
| 5 | 21.45 | 5.10 | 6.05 | 52.3 | 35.7 | 88.0 | 1.28 | 30.1 | SPP, 4.4 ft |
| | 15.58 | 5.64 | 11.38 | 84.8 | 35.8 | 120.6 | 1.28 | 55.6 | |
| 6 | 21.46 | 5.04 | 6.11 | 59.1 | 35.7 | 94.8 | 1.46 | 26.3 | SPP, 4.4 ft |
| | 15.85 | 5.67 | 11.08 | 99.6 | 35.6 | 135.2 | 1.46 | 47.1 | |

TABLE II. - Concluded. MULTIPASSAGE (MPP) AND SINGLE PASSAGE PLUG INSERT (SPP) BOILER PRESSURE DROP DISTRIBUTION AT HIGH AND LOW NaK TEMPERATURE SCHEDULE

(b) SI Units; boiler length, 11.3 meters; plug insert length, 1.34 meters

| Case | Inlet temperature, $^oC$ | Preheat section | | Vapor quality, preheat section | | | Vapor quality, plug insert section | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Change in length, $\Delta L$, m | Change in pressure, $\Delta P$, $kN/m^2$ | Change in length, $\Delta L$, m | Change in pressure, $\Delta P$, $kN/m^2$ | Vapor exit quality, percent | Change in length, $\Delta L$, m | Change in pressure, $\Delta P$, $kN/m^2$ | Vapor exit quality, percent |
| 1 | 693 | 0.320 | 3.45 | ------- | ----- | ----- | 1.02 | 127 | 13.1 |
| | 721 | .241 | 2.76 | ------- | ----- | ----- | 1.10 | 217 | 30.2 |
| 2 | 693 | 0.348 | 4.14 | ------- | ----- | ----- | 0.99 | 215 | 11.0 |
| | 721 | .262 | 2.76 | ------- | ----- | ----- | 1.08 | 378 | 26.7 |
| 3 | 693 | 0.354 | 199.5 | 0.018 | ----- | ----- | 0.99 | 130 | 10.7 |
| | 721 | .284 | 169.0 | .518 | 64.9 | 0.6 | 1.01 | 244 | 24.0 |
| 4 | 693 | 0.357 | 212.5 | 0.061 | 0.69 | 0 | 0.98 | 135 | 11.3 |
| | 721 | .293 | 174.6 | .702 | 119.5 | .9 | .98 | 239 | 23.8 |
| 5 | 693 | 0.363 | 214.5 | 0.027 | 13.1 | 0.2 | 0.95 | 131 | 10.9 |
| | 721 | .299 | 177.4 | .915 | 172.0 | 1.0 | .95 | 236 | 23.9 |
| 6 | 693 | 0.381 | 226.2 | 0.640 | 56.6 | 0.4 | 0.90 | 125 | 10.7 |
| | 721 | .320 | 190.0 | .125 | 278.0 | 1.3 | .90 | 220 | 22.7 |

| Case | Vapor quality, unplugged tube section | Superheat section | Excess superheat section | Plug insert | Unplugged tube | Total | Preheat design length, m | Pinch point temperature difference, $\Delta T_{pp}$, $C^o$ | Remarks |
|---|---|---|---|---|---|---|---|---|---|
| | Change in length, $\Delta L$, m | | | Change in pressure, $\Delta P$ $kN/m^2$ | | | | | |
| 1 | 6.66 | 1.60 | 1.72 | 131 | 246 | 377 | ----- | 18.7 | MPP, 1.34 m; |
| | 4.78 | 1.75 | 3.41 | 220 | 247 | 467 | ----- | 40.4 | $\Delta P$, min. limit |
| 2 | 6.78 | 1.59 | 1.57 | 220 | 246 | 466 | ----- | 14.7 | MPP, 1.34 m; |
| | 4.92 | 1.75 | 3.27 | 381 | 248 | 629 | ----- | 33.5 | $\Delta P$, max. limit |
| 3 | 6.68 | 1.64 | 1.61 | 329 | 248 | 577 | 0.326 | 18.0 | SPP, 1.34 m |
| | 4.74 | 1.72 | 3.50 | 478 | 246 | 724 | .326 | 34.6 | |
| 4 | 6.79 | 1.59 | 1.56 | 348 | 251 | 599 | 0.363 | 17.6 | SPP, 1.34 m |
| | 4.80 | 1.75 | 3.40 | 533 | 246 | 779 | .363 | 32.2 | |
| 5 | 6.55 | 1.56 | 1.85 | 361 | 246 | 607 | 0.390 | 16.7 | SPP, 1.34 m |
| | 4.75 | 1.72 | 3.47 | 585 | 247 | 832 | .390 | 30.9 | |
| 6 | 6.55 | 1.54 | 1.86 | 408 | 246 | 654 | 0.445 | 14.6 | SPP, 1.34 m |
| | 4.75 | 1.73 | 3.38 | 688 | 246 | 934 | .445 | 26.2 | |

TABLE III. - SUMMARY OF RESULTS OF Ta-SS DOUBLE CONTAINMENT BOILER ANALYSES

(a) (a) U.S. Customary units; exit pressure, 265 psia; exit-end terminal temperature difference, 30 F°

| | Multipassage plug insert geometry | | | | | | | | Single passage plug insert geometry | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Off-design length | | | | Design length | | | | Off-design length | | | | | | | | | | Design length | |
| | Maximum limit | | Minimum limit | | Maximum limit | | Minimum limit | | Change in preheat length, $\Delta L_{PH}$, in. | | | | | | | | | | | |
| | | | | | | | | | 13.20 | | 14.28 | | 15.36 | | 17.52 | | 13.20 | | | |
| | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low |
| Overall length, ft | 37.0 | 37.0 | 37.0 | 37.0 | 32.3 | 32.3 | 31.6 | 31.6 | 37.0 | 37.0 | 37.0 | 37.0 | 37.0 | 37.0 | 37.0 | 37.0 | 37.0 | 37.0 | 30.7 | 30.7 |
| Plug insert: | | | | | | | | | | | | | | | | | | | | |
| Length, ft | 4.4 | 4.4 | 4.4 | 4.4 | 4.5 | 4.5 | 3.9 | 3.9 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.4 | 4.1 | 4.1 |
| Preheat length, ft | 0.86 | 1.14 | 0.79 | 1.05 | 0.86 | 1.10 | 0.77 | 1.00 | 0.93 | 1.16 | 0.96 | 1.17 | 0.98 | 1.19 | 1.05 | 1.25 | 0.87 | 1.07 | 0.85 | 1.12 |
| Preheat section pitch, in. | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 | 3/8 |
| Vapor quality section pitch, in. | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 6.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Preheat section mass velocity, lb/sec-ft$^2$ | 810 | 810 | 810 | 810 | 810 | 810 | 810 | 810 | 3421 | 3421 | 3421 | 3421 | 3421 | 3421 | 3421 | 3421 | 3421 | 3421 | 3421 | 3421 |
| Vapor quality section mass velocity, lb/sec-ft$^2$ | 810 | 810 | 810 | 810 | 810 | 810 | 810 | 810 | 792 | 792 | 792 | 792 | 792 | 792 | 792 | 792 | 792 | 792 | 792 | 792 |
| Unplugged tube mass velocity, lb/sec-ft$^2$ | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 | 186 |
| Pinch point temperature difference, °F | 60 | 26 | 73 | 34 | 61 | 26 | 78 | 37 | 62.3 | 32.4 | 58.0 | 31.7 | 55.6 | 30.1 | 47.1 | 26.3 | 54.0 | 28.3 | 57.2 | 36.3 |
| Plug insert: | | | | | | | | | | | | | | | | | | | | |
| Exit quality, percent | 27 | 11 | 30 | 13 | 28 | 12 | 27 | 12 | 24 | 10.5 | 23.8 | 11.3 | 23.9 | 10.9 | 22.7 | 10.7 | 29.0 | 12.5 | 28.0 | 11.0 |
| Preheat section pressure drop, psi | 0.4 | 0.6 | 0.4 | 0.5 | 0.4 | 0.6 | 0.4 | 0.5 | 24.5 | 28.9 | 25.3 | 30.8 | 25.7 | 31.4 | 27.5 | 32.8 | 22.8 | 28.0 | 22.2 | 29.0 |
| Vapor quality section pressure drop, psi | 54.8 | 31.2 | 31.4 | 18.4 | 58.3 | 33.8 | 25.8 | 15.3 | 44.7 | 18.8 | 51.9 | 19.6 | 59.1 | 20.9 | 72.1 | 26.3 | 61.5 | 24.7 | 62.7 | 17.6 |
| Total pressure drop, psi | 55.2 | 31.8 | 31.8 | 18.9 | 58.7 | 34.4 | 26.2 | 15.8 | 69.2 | 47.7 | 77.2 | 50.4 | 84.8 | 52.3 | 99.6 | 59.1 | 84.3 | 52.7 | 84.9 | 46.6 |
| Unplugged tube pressure drop, psi | 36.0 | 35.7 | 35.8 | 35.7 | 31.4 | 31.3 | 30.9 | 31.3 | 35.6 | 36.0 | 35.6 | 36.1 | 35.8 | 35.7 | 35.6 | 35.7 | 35.7 | 35.7 | 30.1 | 30.7 |
| Total boiler pressure drop, psi | 91.2 | 67.5 | 67.6 | 54.6 | 90.1 | 65.7 | 57.1 | 47.1 | 104.8 | 83.7 | 112.8 | 86.5 | 120.6 | 87.0 | 134.2 | 94.8 | 120.1 | 88.4 | 115.0 | 77.3 |
| NaK-side film coefficient, Btu/hr-ft$^2$-°F | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 2000 | 4000 | 4000 | 2000 | 2000 |

TABLE III. - Concluded. SUMMARY OF RESULTS OF Ta-SS DOUBLE CONTAINMENT BOILER ANALYSES

(b) SI units; exit pressure, 1830 $kN/m^2$; exit-end temperature difference, 17 $C^o$

| | Multipassage plug insert geometry | | | | | | | | Single passage plug insert geometry | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Off-design length | | | | Design length | | | | Off-design length | | | | | | | | | | Design length | |
| | | | | | | | | | Change in preheat length, $\Delta L_{PH}$, cm | | | | | | | | | | | |
| | Maximum limit | | Minimum limit | | Maximum limit | | Minimum limit | | 33.5 | | 36.2 | | 39.0 | | 44.5 | | 33.5 | | | |
| | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low | High | Low |
| Overall length, m | 11.3 | 11.3 | 11.3 | 11.3 | 9.86 | 9.86 | 9.65 | 9.65 | 11.3 | 11.3 | 11.3 | 11.3 | 11.3 | 11.3 | 11.3 | 11.3 | 11.3 | 11.3 | 9.36 | 9.36 |
| Plug insert: | | | | | | | | | | | | | | | | | | | | |
| Length, m | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.34 | 1.25 | 1.25 |
| Preheat length, m | 0.26 | 0.35 | 0.24 | 0.32 | 0.26 | 0.34 | 0.24 | 0.30 | 0.28 | 0.35 | 0.29 | 0.36 | 0.30 | 0.36 | 0.32 | 0.38 | 0.27 | 0.33 | 0.26 | 0.34 |
| Preheat section pitch, cm | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 | 0.96 |
| Vapor quality section pitch, cm | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 15.4 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 | 5.1 |
| Preheat section mass velocity, kg/sec-$m^2$ ($\times 10^3$) | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 | 16.6 |
| Vapor quality section mass velocity kg/sec-$m^2$ ($\times 10^3$) | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 3.92 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 | 3.84 |
| Unplugged tube mass velocity, kg/sec-$m^2$ ($\times 10^3$) | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| Pinch point temperature difference, $C^o$ | 33 | 14 | 41 | 19 | 34 | 14 | 43 | 21 | 35 | 18 | 32 | 18 | 31 | 17 | 26 | 15 | 30 | 16 | 32 | 20 |
| Plug insert: | | | | | | | | | | | | | | | | | | | | |
| Exit quality, percent | 27 | 11 | 30 | 13 | 28 | 12 | 27 | 12 | 24 | 10.5 | 23.8 | 11.3 | 23.9 | 10.9 | 22.7 | 10.7 | 29.0 | 12.5 | 28.0 | 11.0 |
| Preheat section pressure drop, $kN/m^2$ | 2.8 | 4.1 | 2.8 | 3.5 | 2.8 | 4.1 | 2.8 | 3.5 | 169 | 200 | 175 | 212 | 177 | 216 | 190 | 226 | 157 | 193 | 153 | 200 |
| Vapor quality section pressure drop, $kN/m^2$ | 378 | 215 | 216 | 127 | 403 | 233 | 177 | 106 | 309 | 130 | 358 | 135 | 407 | 144 | 497 | 182 | 425 | 170 | 433 | 122 |
| Total pressure drop, $kN/m^2$ | 381 | 220 | 220 | 130 | 405 | 237 | 181 | 109 | 477 | 330 | 533 | 347 | 585 | 361 | 687 | 408 | 582 | 364 | 585 | 322 |
| Unplugged tube pressure drop, $kN/m^2$ | 248 | 246 | 246 | 246 | 217 | 216 | 213 | 216 | 246 | 248 | 246 | 249 | 247 | 246 | 246 | 246 | 246 | 246 | 208 | 212 |
| Total boiler pressure drop, $kN/m^2$ | 630 | 465 | 465 | 377 | 622 | 453 | 394 | 325 | 724 | 578 | 779 | 597 | 833 | 600 | 927 | 655 | 830 | 610 | 795 | 533 |
| NaK-side film coefficient, J/hr $m^2$ - $C^o$ ($\times 10^6$) | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 40.8 | 81.6 | 81.6 | 40.8 | 40.8 |

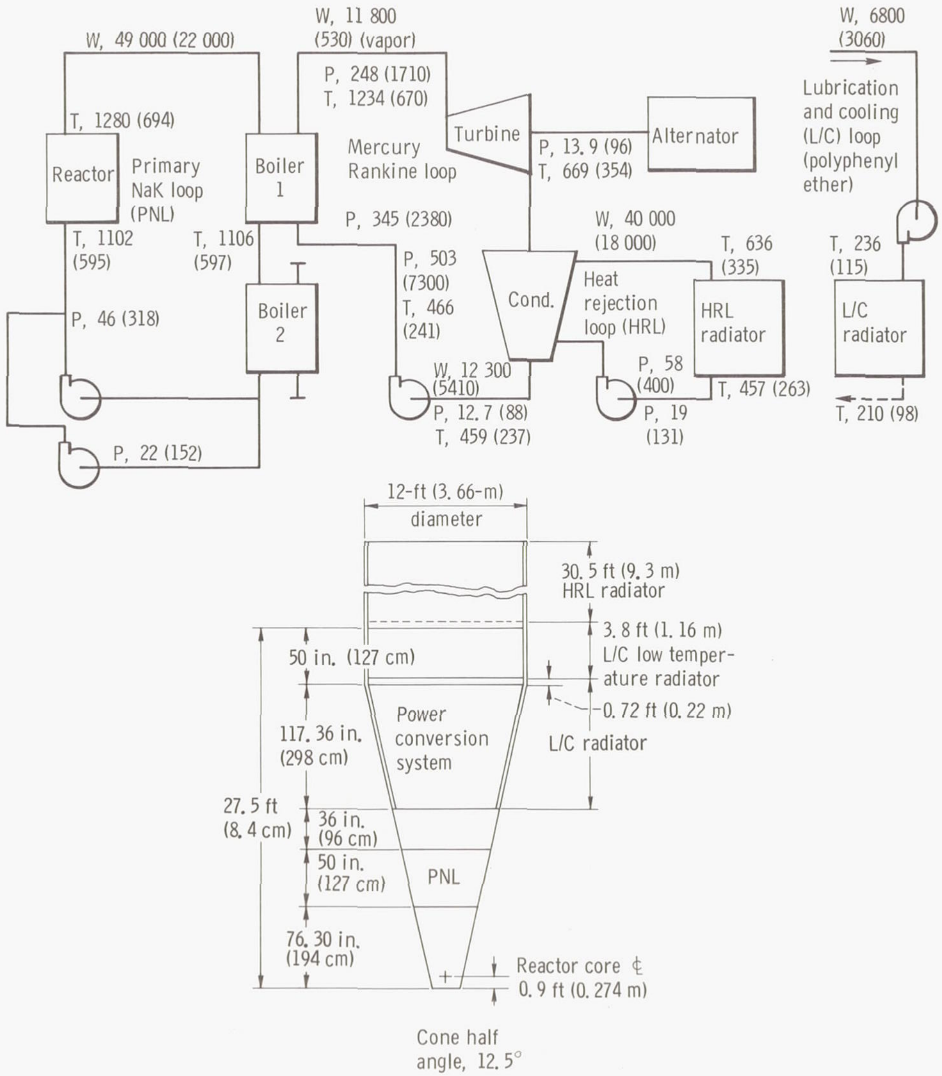
TABLE IV. - STRESS-RUPTURE STRENGTHS OF INTERSTITIAL ALLOY OF TANTALUM (FROM REF. 8)

[Ta, high purity, 6 ppm oxygen; Ta-C, 995 ppm carbon; Ta-N, 225 ppm nitrogen; Ta-O, 560 ppm oxygen.]

| Temperature | | Time, hr | TA | | Ta-C | | Ta-N | | Ta-O | | Ta-C | Ta-N | Ta-O |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Stress-rupture strength | | | | | | | | Strength increase, percent[a] | | |
| $^{\circ}F$ | $^{\circ}C$ | | psi | $kN/m^2$ | psi | $kN/m^2$ | psi | $kN/m^2$ | psi | $kN/m^2$ | | | |
| 1380 | 750 | 0.1 | $17.0\times10^3$ | 117 | [b]$29.0\times10^3$ | 200 | $25.0\times10^3$ | 173 | $22.5\times10^3$ | 155 | 71 | 47 | 32 |
| | | 1.0 | 16.0 | 110 | [b]28.0 | 193 | 22.5 | 155 | 17.5 | 121 | 75 | 41 | 9 |
| | | 10 | 15.4 | 106 | [b]27.0 | 186 | 19.5 | 135 | 15.0 | 103 | 80 | 30 | 0 |
| | | 100 | 14.0 | 97 | [b]26.0 | 179 | 17.0 | 117 | 14.0 | 97 | 86 | 21 | 0 |
| 2190 | 1200 | 0.1 | $8.4\times10^3$ | 58 | $17.5\times10^3$ | 121 | $10.0\times10^3$ | 69 | -------- | --- | 108 | 19 | -- |
| | | 1.0 | 6.1 | 42 | 14.5 | 100 | 7.2 | 50 | $8.6\times10^3$ | 59 | 138 | 18 | 24 |
| | | 10 | 4.5 | 31 | 11.8 | 81 | 5.2 | 36 | 4.3 | 30 | 153 | 16 | -4 |
| | | 100 | 3.2 | 22 | 9.6 | 66 | 3.6 | 25 | 3.2 | 22 | 200 | 13 | 0 |

[a]In comparison with the high-purity tantalum.

[b]Value is estimated.




| Power distribution | |
|---|---|
| Turbine shaft power, kW | 63.9 |
| Alternator efficiency, percent | 90.9 |
| Alternator gross output power, kW | 58.0 |
| Parasitic load total | 21.0 |
| Net output power, kW | 37.0 |

| Performance summary | |
|---|---|
| Net reactor input, kW thermal | 537 |
| Net electrical output, kW electric | 37 |
| Overall system efficiency, percent | 6.9 |
| HRL radiator: | |
| Area, $ft^2$ ($m^2$) | 1150 (107) |
| Heat rejected, kW thermal | 445 |
| L/C radiator: | |
| Area, $ft^2$ ($m^2$) | 335 (32) |
| Heat rejected, kW thermal | 19.08 |
| L/C low-temperature radiator area, $ft^2$ ($m^2$) | 144 (13) |
| Electrical generating system weight, less shield, lb (kg): | |
| Power conversion system frame | 1600 (720) |
| Components | 5340 (2400) |
| Radiators and supports | 2720 (1220) |
| Nuclear system | 790 (356) |
| Total | 10 450 (4696) |

W Flow rate, lb/hr (kg/hr)
T Temperature, °F (°C)
P Pressure, psia ($kN/m^2$)

CD-10224-22

Figure 1. - Schematic of SNAP-8 system. Turbine aerodynamic efficiency, 55.6 percent; NaK pumps: 5800 rpm induction motors (both NaK loops), cooled by L/C fluid; Hg pump with motor scavenger; tube-in-tube boiler (7 Hg tubes); parasitic load resistor (PLR) in heat rejection loop (HRL); radiator NaK ΔT, 179 F° (80 C°).

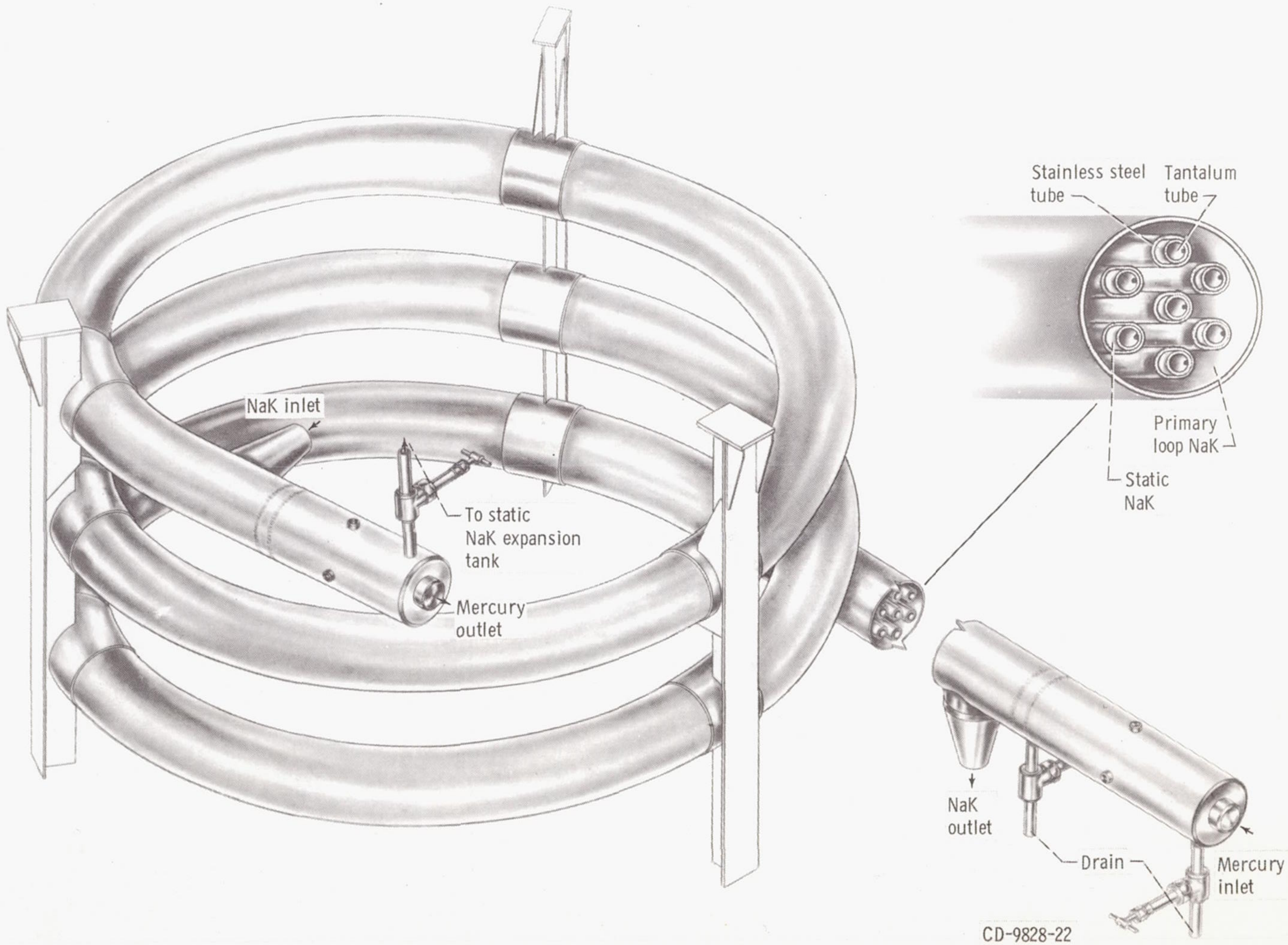



Figure 2. - SNAP-8 double containment tantalum - stainless steel boiler.

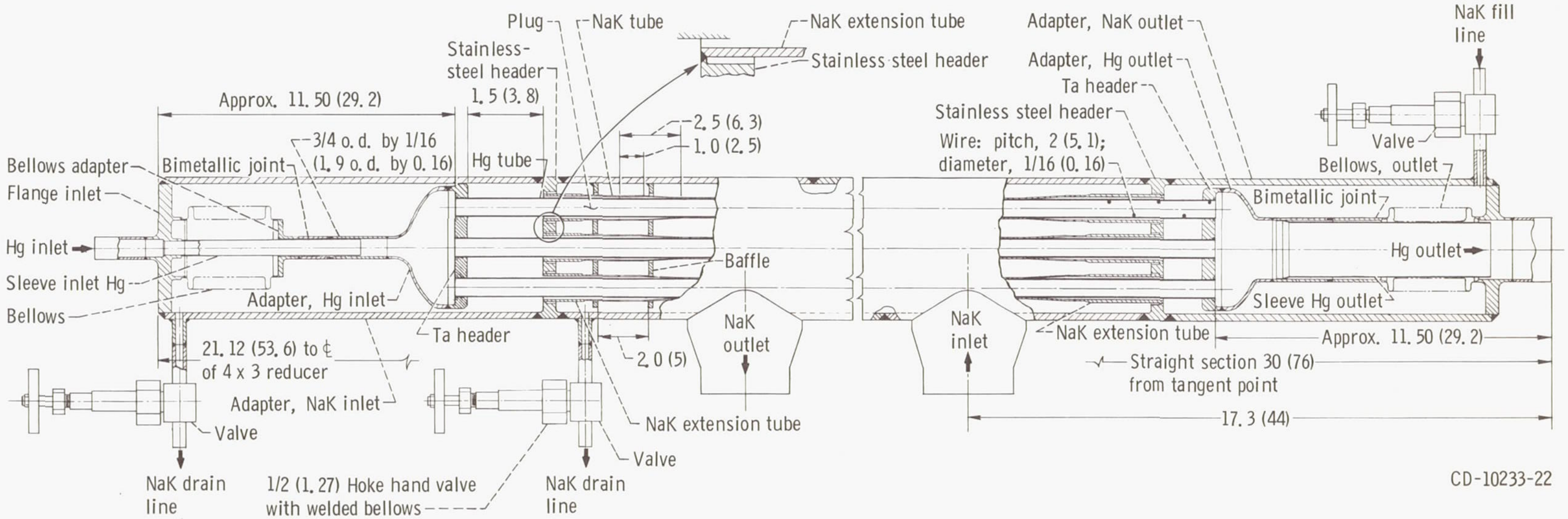



Figure 3. - Cross-sectional view of boiler ends.

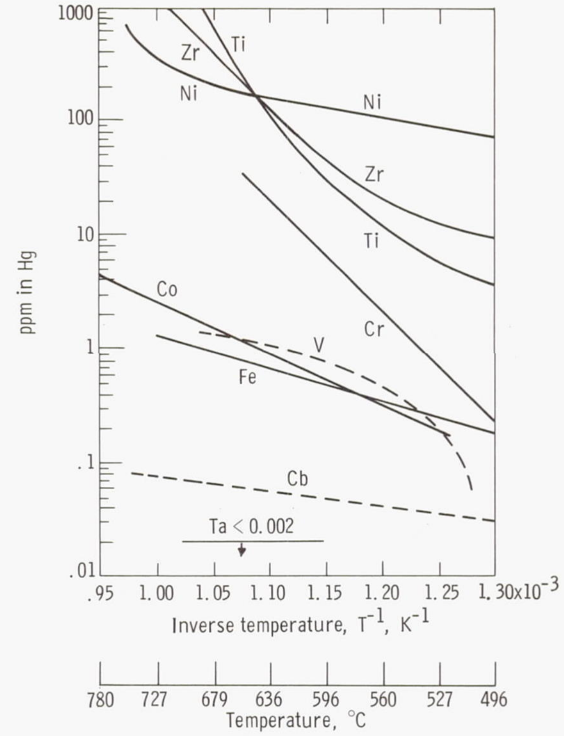



Figure 4. - Liquidus curves of metals in high-temperature mercury.

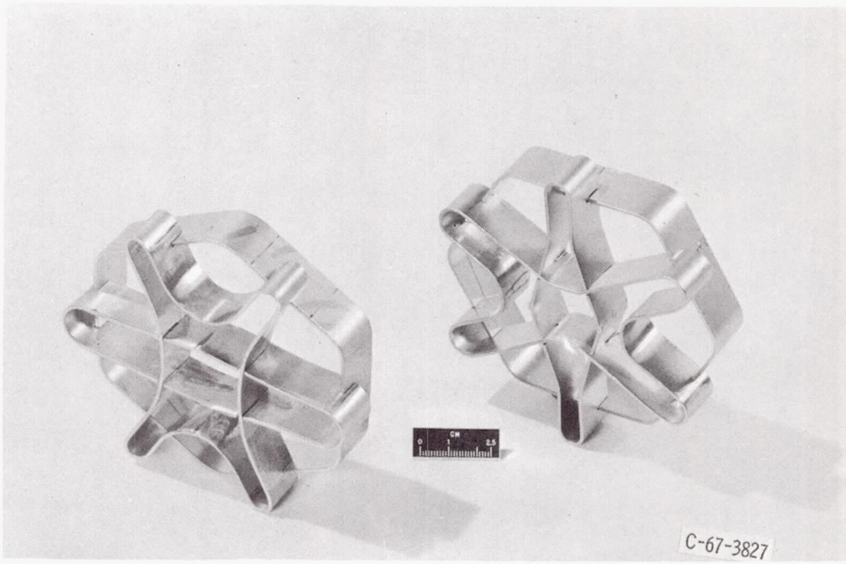



Figure 5. - Tube bundle spacers alternately placed every 30° of rotation.

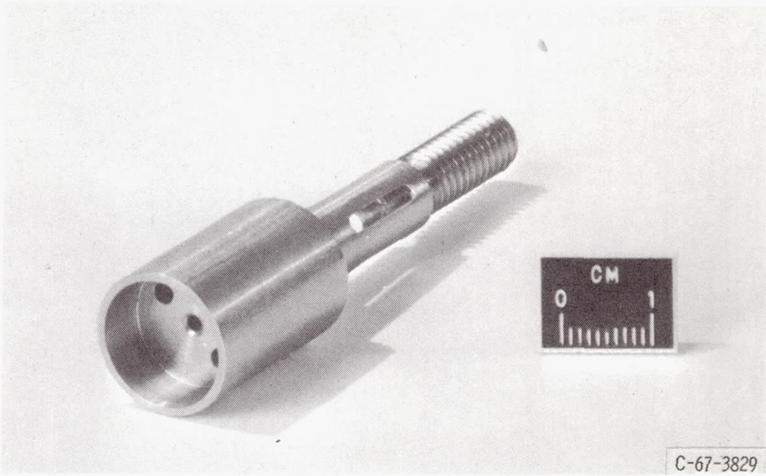



Figure 6. - Mercury flow resistor for balancing flow between tubes.

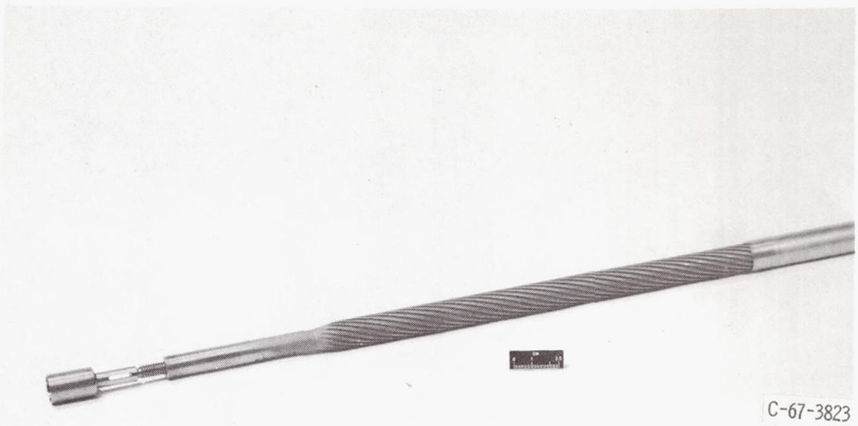



Figure 7. - Mercury flow resistor and convoluted plug being inserted into tantalum tube.

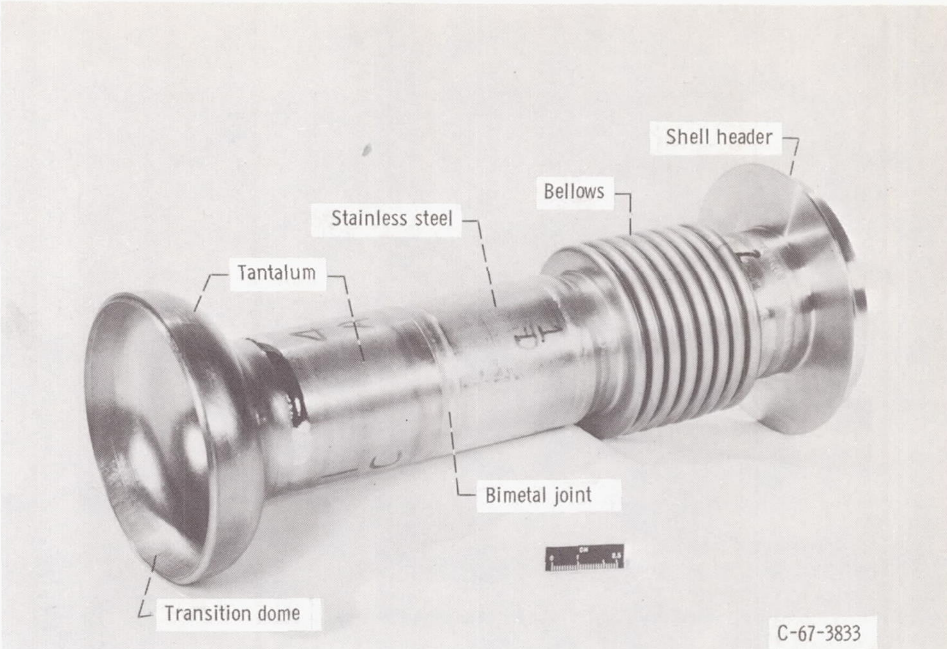
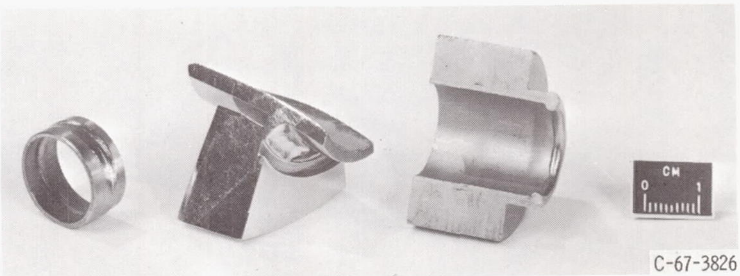



Figure 8. - Mercury inlet and outlet subassembly.




Tantalum 0.040-inch (0.10-cm) tubing, electron beam weld

Stainless steel tube-to-header gas tungsten-arc weld

Tantalum tube-to-header gas tungsten-arc weld

Figure 9. - Sample welds.

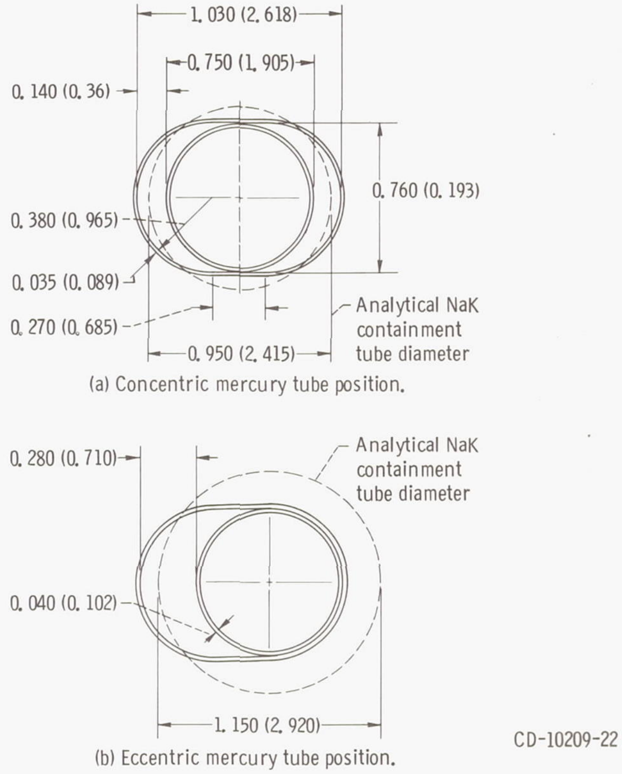
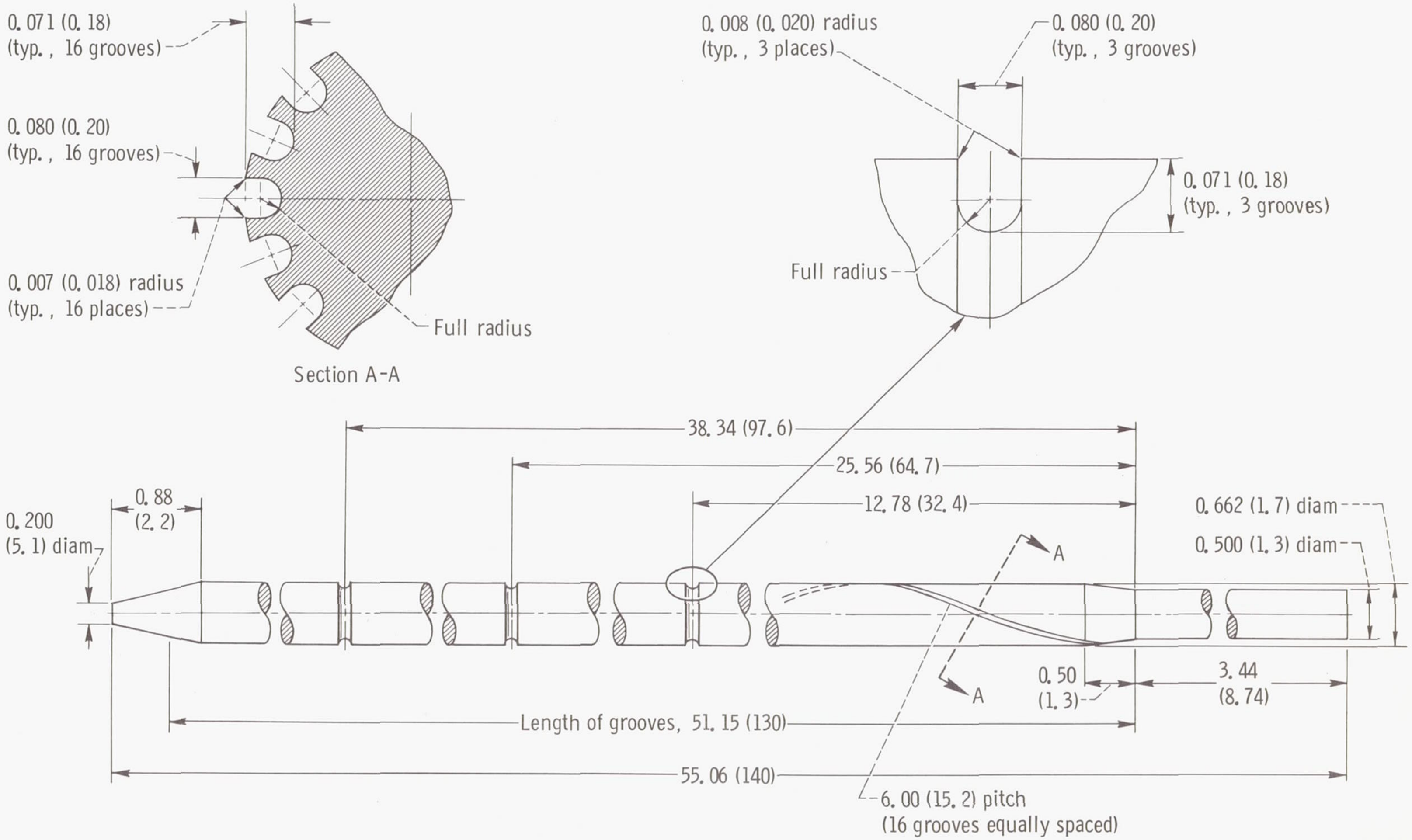



Figure 10. - Cross section of double-containment tube. (Dimensions are in inches (cm).)




CD-10065-22

Figure 11. - Multifluted tantalum boiler plug (seven required). (Dimensions are in inches (cm).)

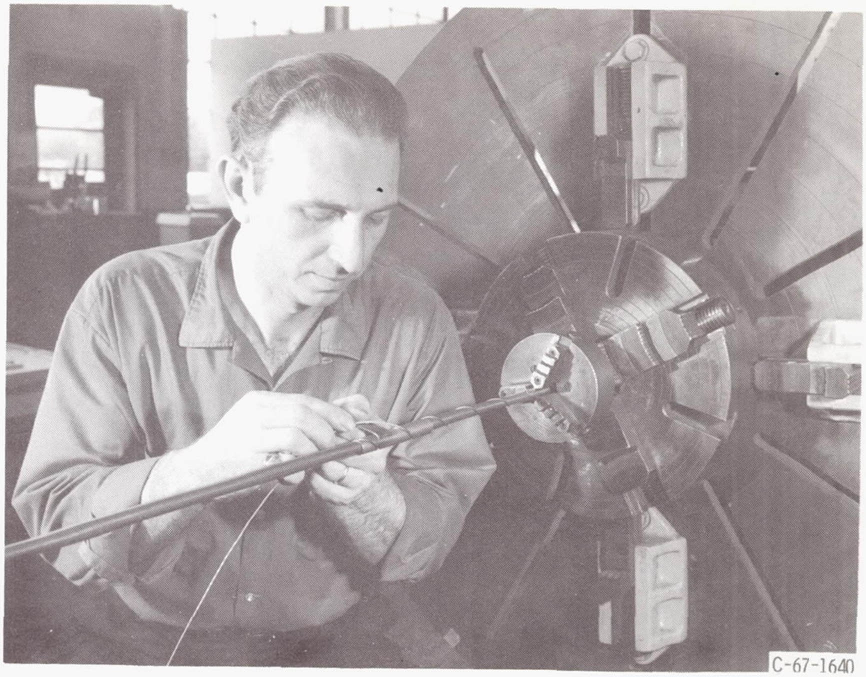



Figure 12. - Fabrication of tantalum-10W spiral wire insert.

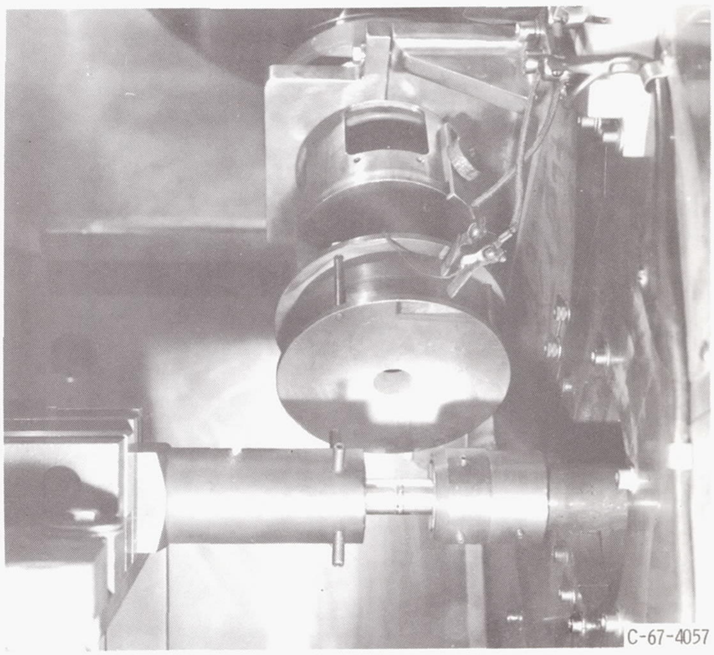



Figure 13. - Electron beam welder just after completion of tantalum tube butt-weld.

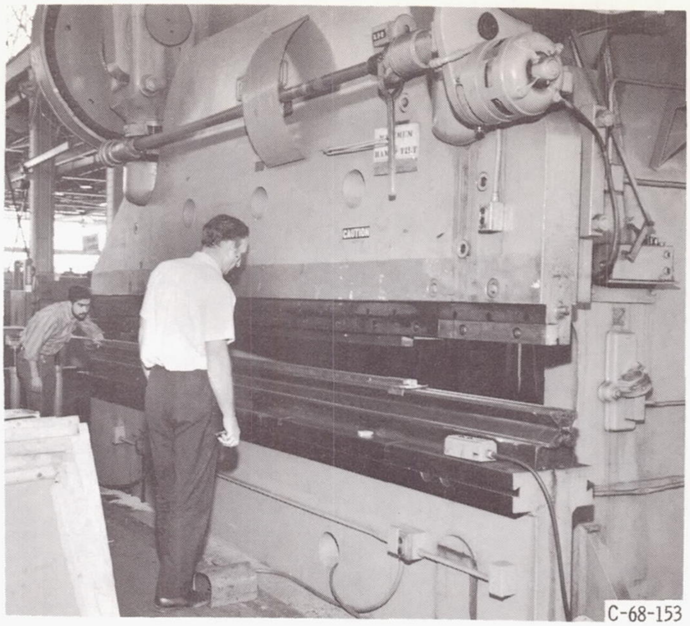
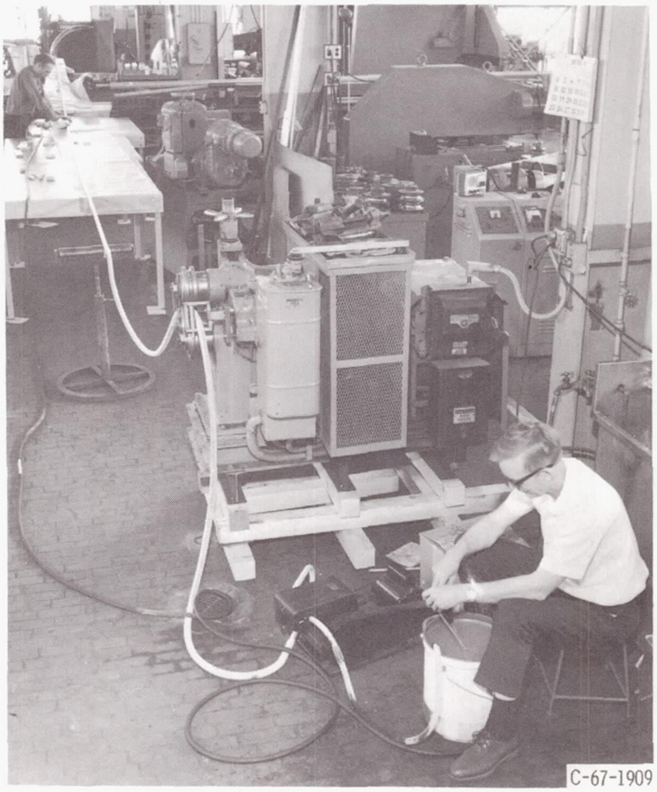


Figure 14. - Stainless steel tube being formed into oval shape.

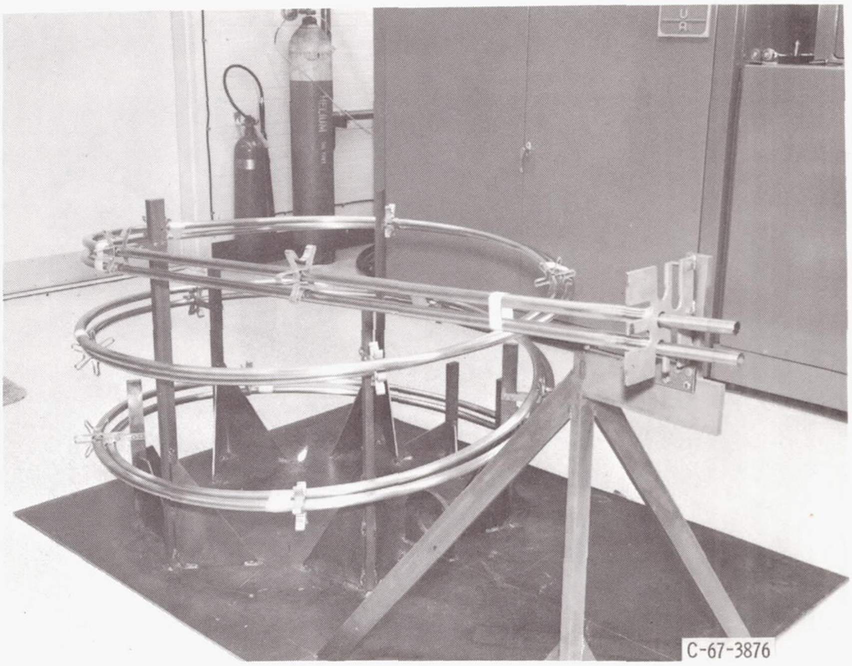


(a) Alcohol being circulated to freeze tubes together.

Figure 15. - Coiling tantalum - stainless steel tube combination.

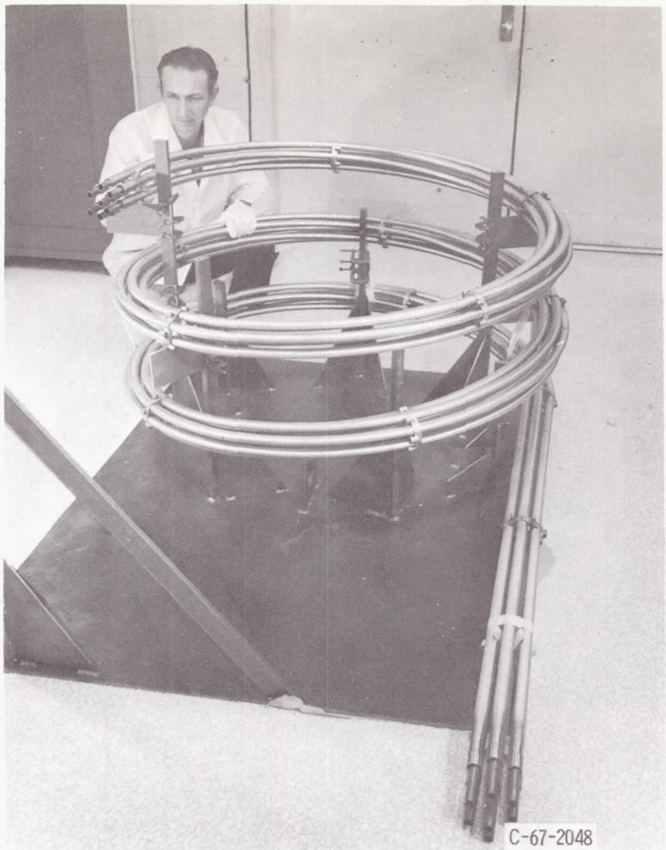

(b) Coiling tube with shaped rolls to fit stainless steel oval.

*Figure 15. - Concluded.*




(a) Center tube in place and second tube spiraled around center.

Figure 16. - Tube bundle on fixture.




(b) Complete bundle after repositioning for shell assembly.

Figure 16. - Concluded.

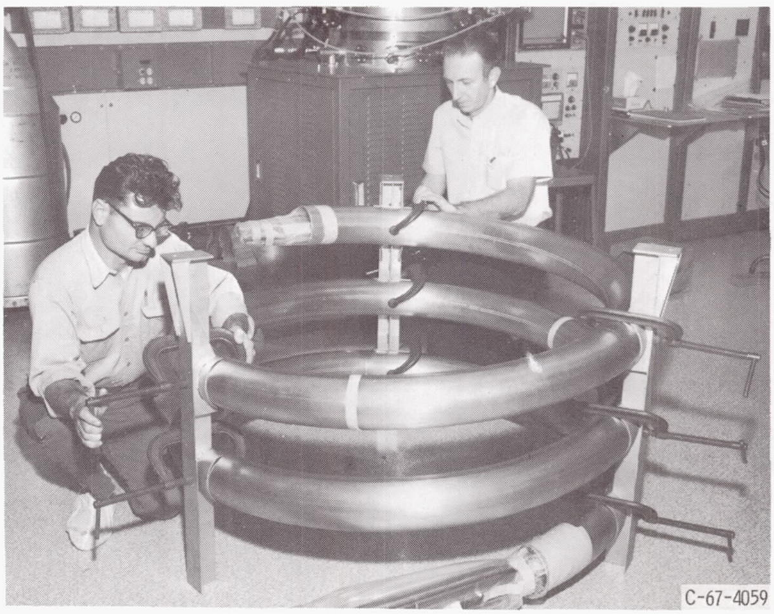



Figure 17. - Shell threaded on tube bundle.


Figure 18. - Portable glove box in position for tantalum tube-to-header weld.

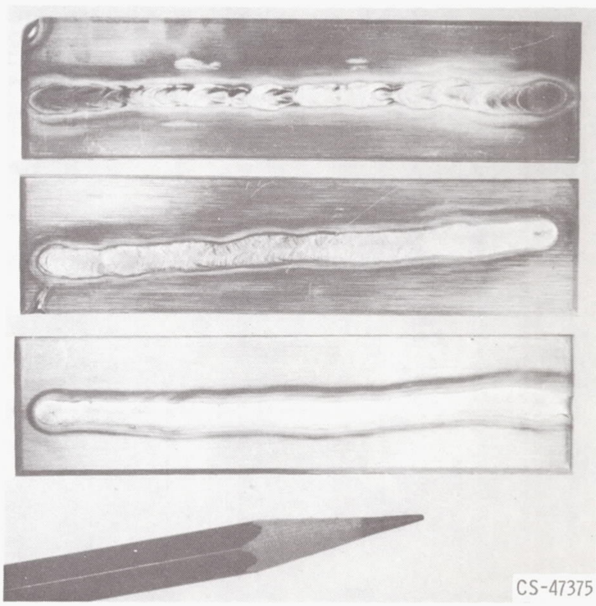



Figure 19. - Stainless steel weld samples indicating oxygen pressure.


Figure 20. - Spacers being welded into place.


Figure 21. - Tantalum being expanded into groove in tantalum header.

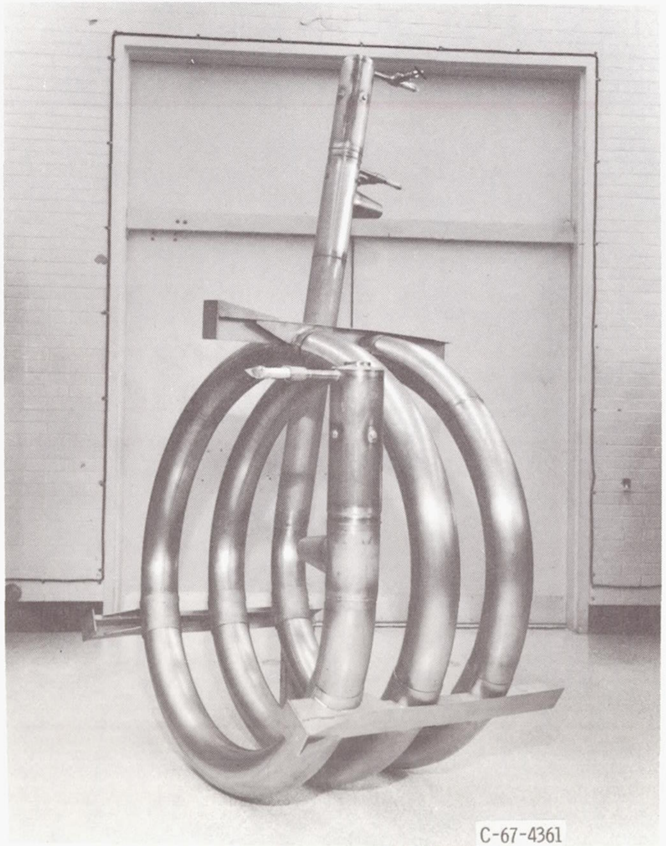


Figure 22. - Completed boiler.

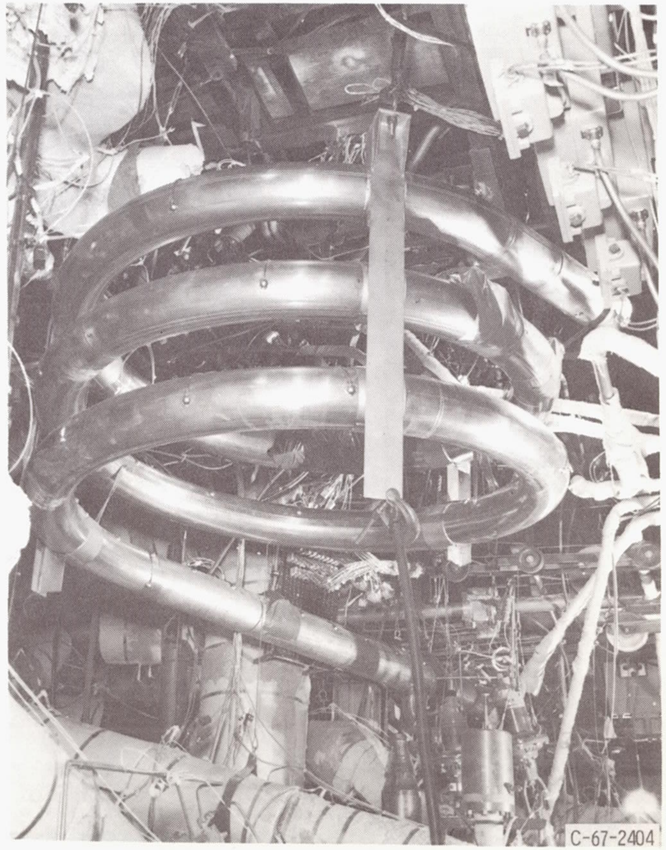


Figure 23. - Boiler installed in SNAP-8 test loop.

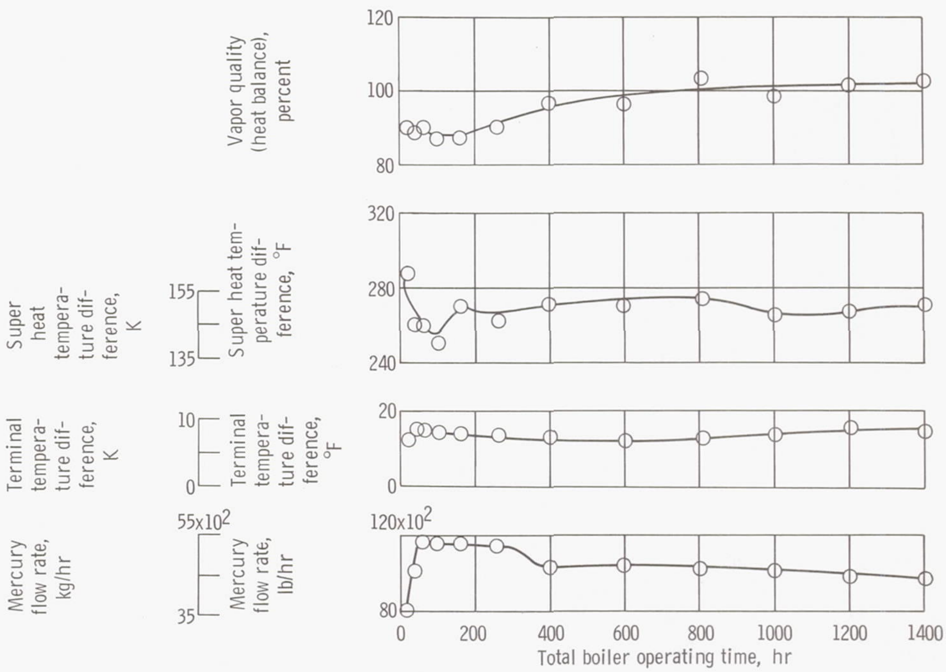
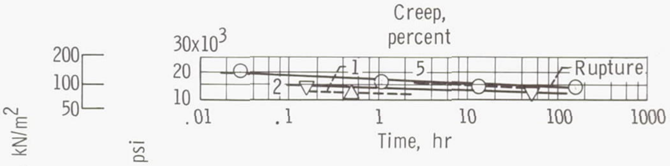
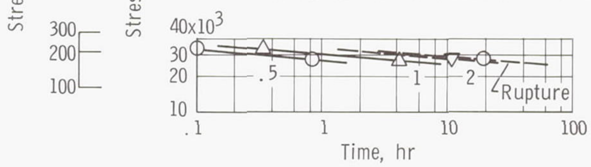



Figure 24. - Boiler operating history. Typical boiler conditions (data at 250 hr): NaK flow rate, 48 000 pounds per hour (21 773 kg/hr); NaK inlet temperature, 1307° F (981 K); NaK outlet temperature, 1154° F (896 K); mercury inlet temperature, 379° F (466 K); mercury outlet temperature, 1296° F (975 K); mercury inlet pressure, 375 psia (2586 kN/m$^2$); mercury outlet pressure, 215 psia (1482 kN/m$^2$). Total operating time, 1444.7 hours; number of startups, 4; total elapsed time, 1468.5 hours.




(a) Recrystallized sheet tested in vacuum.




(b) Cold-rolled 95 percent and stress-relieved 1/4 hour.

Figure 25. - Creep stress as function of time for constant values of total strain for electron beam-melted tantalum sheet at 1380° F (750° C) (from ref. 8).

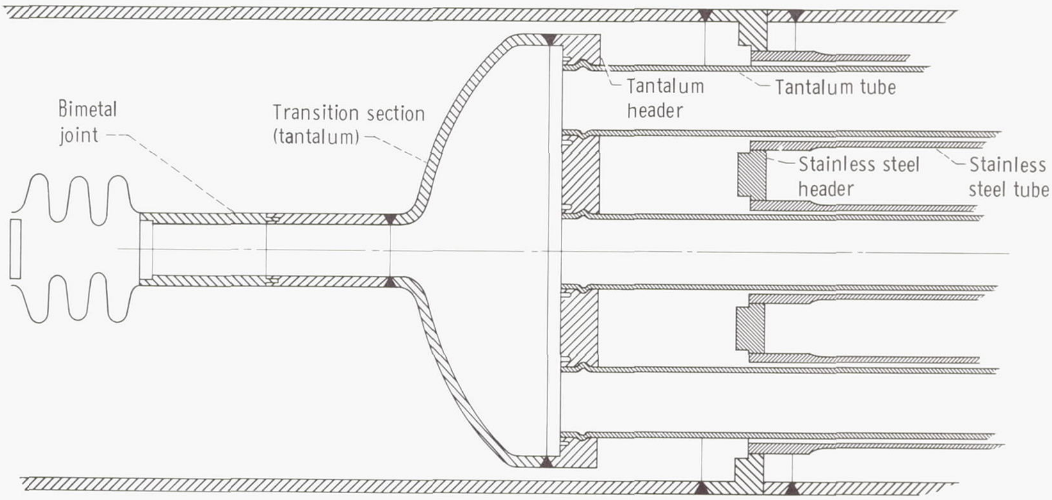



Figure 26. - Tantalum transition section.

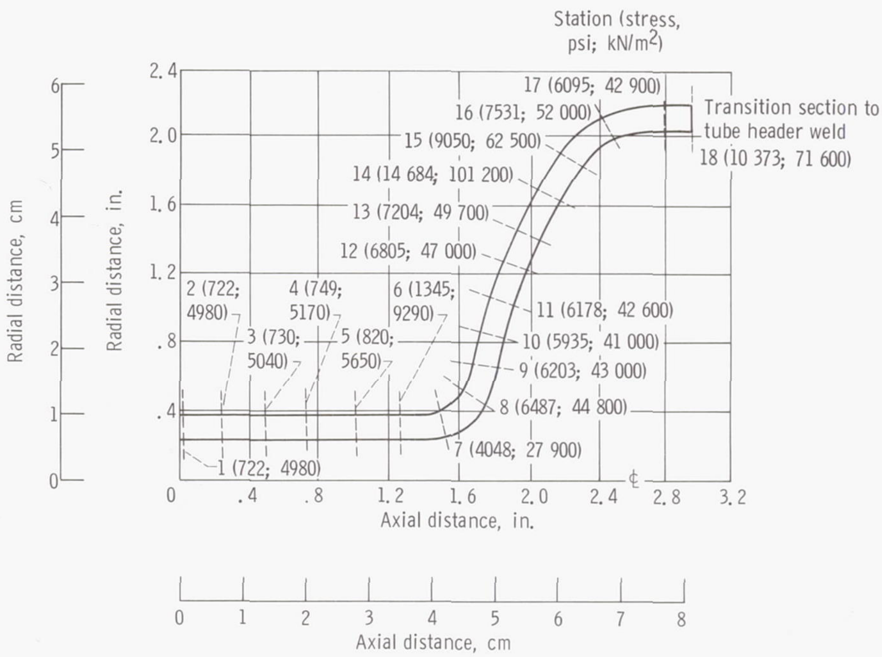



Figure 27. - SNAP-8 double containment boiler transition section analysis (geometry and maximum stresses).



NASA-Langley, 1969 —— 33 E-4702