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TECHNICAL MEMORANDUM

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TITLE: Design of the Bare Refractory Double-Containment (BRDC) Boiler Number 5 for PCS, SNAP-8

ABSTRACT

The design of the BRDC Boiler No. 5 is presented. The boiler meets all defined interfaces and requirements of the Power Conversion System (PCS). Tantalum is used as the mercury containment material and type 300 stainless steels are used as the NaK containment material. Zirconium is employed at the mercury inlet and outlet sections as a "gettering" material for the dissolved gases in the static NaK and to minimize carbon transport from the Type 300 stainless steel to the tantalum by "gettering" carbon. Coextruded tantalum-to-stainless steel transition joints (bimetal tubes) are used at the mercury inlet and outlet.

This design, P/N 1268600, contains the salient features of the BRDC Boiler P/N CF 751840 and BRDC Boiler P/N 1266911.

APPROVED:

DEPARTMENT HEAD

AEROJET-GENERAL CORPORATION

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FIGURES

I. INTRODUCTION

Historically, the first boiler fabricated for SNAP-8 was a single pass Tube-in-Shell design. Four 0.902 in. inside diameter, Haynes 25 material, 60-foot long mercury tubes were coiled in a toroidal NaK shell. Two of the four Hg tubes were coiled on a smaller helix than the other two, resulting in a significant difference in the lengths of each pair. The NaK flow was a combination cross-flow and counter-flow pattern relative to the Hg flow. Each Hg tube contained an inlet plug insert and swirl wire.

The design was inadequate from the diagnostic viewpoint. The heat transfer characteristics in terms of tube length could not be determined adequately because of the unavailability of accurate NaK temperature profile measurements. Poor heat transfer and relatively high liquid carry-over were attributed to the Haynes 25 flow passage contamination.

The second boiler fabricated for SNAP-8 was a single-pass, Tube-in-Tube design. Seven 0.652 in. inside diameter, 9M steel, 30-foot long Hg containment tubes were twisted and then coiled in a 4.25 in. O.D. helically coiled tube. Twisting the tube bundle prior to coiling resulted in equal length Hg tubes. Each Hg tube contained an inlet plug insert and swirl wire. The "dry-wall" concept of Hg heat transfer was used in designing the boiler and was based on SNAP-1 and SNAP-2 experience using Haynes 25 and 316 stainless steel material. Since 9M material was considered to be nonwettable, the "dry-wall" concept was applied.

The main problem with this design was metallurgical (NaK-side embrittlement, and Hg-side corrosion of the 9M material). The thermal performance was adequate with clean 9M flow passage surface conditions. The preservation of boiler Hg passage cleanliness in the integrated system's loop was not adequate however, and the boiler operated in a deconditioned state and relatively high liquid carry-over resulted.

The SB-1 test assembly was an experimental Ta-SS, double-containment, single-tube 1/7th scale boiler. Further investigations carried on with the SB-1 test assembly at AGN indicated that the two most important requirements for proper conditioning of the boiler were cleanliness of the mercury side of the boiler tubes and the assurance of a vacuum tight mercury system to preclude tantalum surface oxidation. Out of 2,558 hours of testing the SB-1, the last 165 hours were run with a conditioned boiler. The changes instituted prior to the last 165 hours were the thorough cleaning and the high vacuum integrity of the facility.

A bimetal boiler was designed at AGC using a stainless steel tube coextruded with a tantalum inner liner for the mercury containment tubes. The purposes of the tantalum was to improve mercury corrosion resistance and to enhance wetting by the mercury (which improves "conditioning" of the boiler). The boiler design was completed, and one was fabricated. However, this boiler has not been used to date.

During the design period of the bimetallic boilers, LeRC went ahead with the design and fabrication of an all-tantalum tube and header configuration for the Hg with a double-containment feature utilizing static NaK as the barrier fluid between the flowing NaK in the primary loop and the Hg. The AGC bimetal tube boiler was designed as a 30-foot long assembly while the LeRC bare refractory, double-containment (BRDC) Boiler was designed as a 37-foot long assembly.

The experimental 1/7th scale, single tube bimetal boiler (SF-1A) was designed and tested to investigate the bimetal tube and bimetal tube joint structural reliability and the single-fluted helix configuration for heat and momentum transfer performance characteristics. A 1200 hour test showed that the design had excellent and immediate performance throughout its operation. Obviously, clean Hg flow passage surfaces were provided and maintained in the leak tight Hg loop.

The SB-2 test assembly, simulating the design of the BRDC #4 boiler was tested at the Aerojet-General Corp., San Ramon facility.

The LeRC BRDC Boiler #1 has been tested at the W-1 facility at LeRC and at the General Electric Company while Boiler #2 has been tested at AGC. Problems associated with thermal differential bellows failures at the Hg inlet and outlet, shell failures at the NaK outlet, the incipient failure of the tantalum-to-stainless transition joint and the sagging of the tube bundle in the stainless shell prompted the redesign of the boiler which became BRDC #4, P/N 1266911.

The criteria used in designing the #4 boiler were:

1. It shall meet the requirements of the PCS-G prototype system using specifications AGC-10621 - "Boiler, NaK/Mercury, Prototype, SNAP-8" and AGC-10512 - "Power Conversion System, Model G, SNAP-8." The boiler envelope and interfaces shall be as described by the PCS-G.

2. The mercury lines at the inlet and outlet shall incorporate a coextruded tantalum-to-stainless steel transition joint in the form of a bimetal tube.

3. The boiler shall have double containment utilizing static NaK as the barrier fluid.

4. Collector rings at the flowing NaK inlet and outlet shall be used to more efficiently mix the fluid and to reduce thermal stresses.

This boiler was fabricated at the NASA-LeRC facility and tested at the Aerojet-General PCS-1 facility for 1620 hours and 28 cycles from March through June, 1970. Some deconditioning was noted during the initial runs due to system contaminants. However, as testing progressed the boiler became conditioned and performance was excellent. There was no instability over the extreme range of off-design testing and no failures or incipient failures were experienced. One area of concern was the high ($\sim$ 500°F) circumferential gradient in the shell between the mercury inlet and the NaK outlet collector ring. The thermal map was similar to that experienced with BRDC #2. It was deduced at the time of BRDC #4 design that the thermal gradient in BRDC #2 was due to forced convection of the flowing NaK past the loosely fitting baffles. BRDC #4 employed a very low leakage baffle as well as annular evacuated tubes surrounding the mercury containment tantalum tubes in this area to reduce heat transfer from the NaK to the colder mercury. Further analysis indicated that natural convection was the basic mechanism for non-symetrical circumferential thermal gradients, resulting in stratification of the NaK (The colder, more dense fluid settling to the bottom due to gravity).

The current coiled boiler, BRDC #4, became obsolete when the PCS system configuration changed from a conical shape to a parallelepiped and the performance criteria were changed. The design of the new bare refractory double-contained (BRDC) Boiler #5 is the subject of this report.

The criteria used in designing the Boiler were:

1. It shall meet the requirements of DE-0018, dated 13 July 1970 "Ground Rules, Design Approach and Program Plan for BRDC Boiler #5" which includes reference to Memo No. 7978:70:0002, dated 1 July 1970 "SNAP-8 12 Tube Boiler (BRDC #5) Design for Revised System State Point Conditions" by E.S.Chalpin/A.J.Sellers.

2. The criteria for stress shall be as noted in Memo No. 7978:70:0003 dated 6 July 1970 "BRDC Boiler #5 Operating Criteria for Stress Analyses" by E.S.Chalpin and Memo No. 7974:70:0047 (File SS 1020) dated 10 July 1970, "Boiler #5 Critical Areas" by W. Weleff.

3. It shall be an "S" shape with a horizontal mercury inlet and outlet, coextruded tantalum-to-stainless steel bimetal tube transition joints, double-containment, of a co-axial 12 tube array and have collector rings at the NaK inlet and outlet.

4. The "S" shape radii and straight sections shall meet the envelope requirements of the PCS and the length of the boiler from the NaK inlet to the NaK outlet shall be 21 feet. This is 6 inches shorter than that noted in Memo No. 7978:70:0002 above due to space limitations in the PCS. However, thermal performance analysis shows that the slight change will be acceptable.

II. BARE REFRACTORY DOUBLE-CONTAINMENT (BRDC #5) DESIGN

A. COMPARISON OF DESIGN TO PCS REQUIREMENTS

Assembly Drawing No. 1268600, Figure 1, shows the new boiler design that meets all the requirements of PCS as itemized in Specification AGC 10680 (Reference a) and the interface control drawing (Reference b).

The performance requirements were based on the "PCS-G State Point Conditions"- Revision Date 4/21/70," Memo EDF Serial N-SA-0014. These requirements were analyzed and Memo No. 7978:70:0002, dated 1 July 1970, "SNAP-8 12 Tube Boiler (BRDC #5) Design for Revised System State Point Conditions" by E.S.Chalpin/A.J.Sellers was published which identified the performance map for high and low NaK schedule as well as the basic configuration (see Appendix A). The design was approved by Systems Management in Memo No. 7992:70:0071, dated 6 July 1970 "Compatibility of Boiler Design Configurations for PCS-G" by R.G.Geimer.

The "S" configuration, double-containment, bare refractory (tantalum) mercury containment tubes with swirl wire inserts was approved by NASA in their letter No. 5211, dated 12 June 1970, "SNAP-8 PCS-G Boiler Design Contract NAS 3-13458" by M.J.Saari, Chief, SNAP-8 Project Office. In this letter he approved the 13-tube configuration. However, further analyses subsequent to the date of his letter indicated that the 12-tube concept resulted in a more compact co-axial design with acceptable performance.

B. OVERALL BOILER DESIGN

The boiler was designed for an effective boiler length of 21 feet from the flowing NaK inlet to the flowing NaK outlet, as shown in Drawing No. 1268600 (Figure 1). The two radii of the "S" shape boiler are identical at 25 inches. The NaK shell is 7.625 inches outside diameter with a 0.120 inch wall, made of 316SS. The shell will be made in two halves and welded along the centerline perpendicular to the plane of the "S". The flowing NaK manifolds (tees) will also be made in two halves, welded along their centerlines parallel to the plane of the 3 inch port.

The tube bundle will be spaced in an annular array, co-axial with a 3.5 inch central tube which will be evacuated and sealed.

Spacers for holding the 12 tubes and the central tube concentric with the outside shell will be placed throughout the boiler.

Turbulator wires around the central tube and along the inside diameter of the shell will be installed for 10 feet in the boiler, ending at the NaK outlet tee.

The boiler support configuration for PCS can be seen in Figure 5.

The overall design described above and the detail descriptions to follow have incorporated the best design features of previous boilers plus design considerations to minimize circumferential and axial thermal gradients at the mercury inlet end.

C. MERCURY INLET SECTION

The inlet header is shown in Figure 1 as a centrally located axial entry configuration. A coextruded, tantalum-to-type 316SS bimetal tube transition joint identical in size and length to that successfully used in BRDC Boiler #4 for 1600 hours and 28 starts is shown. The bimetal tube is 1.25 inches O.D. by .750 inches I.D. which includes a .150 inch wall of Type 316SS metallurgically bonded to a .100 inch wall of tantalum. The tube is Electron Beam (EB) welded to the stainless steel end cap. The total effective length of the transition joint bond is 8 inches.

The evacuated annular insulator between the tantalum dome and the shell reducer is designed for thermal management. The phenomenon of induced convective patterns, wherein the colder NaK surrounding the tantalum tubes sinks due to gravity effects, has been a persistent problem in all boilers tested to date. The design minimizes this effect by the use of the "honeycomb" structure in the area between the stainless steel header and the tantalum header.

The 12 tantalum tubes are spaced on a 5.625 inch bolt circle such that the oval static NaK tubes surrounding them downstream have a more distributed NaK flow around them. The tantalum tubes are welded into the tantalum header in the same manner as BRDC Boilers #1, 2, 3 and 4. The orifices shown at the entrance of the tantalum tubes are bored to .050 inches diameter and were calculated to produce a pressure drop of 128 psid at full flow conditions. The pressure drop versus flow for the orifice, added to the pressure drop versus flow for the remainder of the boiler is calculated to ensure a positive slop throughout all phases of the startup and steady-state operation of the boiler. This was a requirement of the SNAP-8 system to preclude problems in control and reactor operation.

The tantalum plugs placed in the tantalum tubes downstream of the orifices are 2.7 feet long. Sixteen equally spaced helical grooves are cut along the length of the plugs at a 6 inch pitch. Circumferential annuli are cut at ten inch intervals along their lengths to ensure a redistribution of mercury flow, should a helical groove become blocked or not perform properly.

The tantalum tube is swaged onto the tantalum plug. Seventeen plugs made as spares for BRDC #4 are to be cut from four feet to the required 2.7 feet for this boiler. The swaged plug assemblies and the orifices will be flowed with water to determine the actual pressure drop through each, as was done for BRDC #4.

Zirconium foil is shown in the tantalum dome area. Zirconium was found to be an excellent "hot getter" for dissolved gases and carbon in the static NaK as evidenced by the analysis of BRDC Boiler #1 and 2 following test.

The boiler shell is shown expanded radially in the area between the stainless steel header and the tantalum header. This is to allow for the vacuum chamber within the shell. The purpose and value of the vacuum insulator is discussed later in this report. Another vacuum chamber shown abutted to the stainless steel header is also discussed.

The joint between the tantalum dome and the bi-metal tube will be EB welded in the same manner as BRDC #4.

D. NAK INLET AND OUTLET MANIFOLDS

The NaK inlet and outlet manifolds or tees are designed as collector rings which surround twelve (12) 1.25 inch diameter holes spaced between mercury tubes and drilled into the 7.625 inch O.D. flowing NaK shell. The tees are forged in two parts and welded in the plane of the 3 inch port.

The two predominant reasons for the manifold design are the better distribution of heat in the critical zones where previous shell failures have occurred and the better mixing of the NaK entering and leaving the boiler. The acceptability of the design was borne out by plastic model tests with water as well as the results of Boiler #4 tests.

Mixing of the NaK leaving the boiler will also result in a better measurement of the NaK mixed-mean temperature which is essential to obtain good thermal performance data.

E. TANTALUM TUBE BUNDLE AND STATIC NaK TUBES

The twelve (12) tantalum tubes are of equal 21 foot lengths. They are not coiled along their lengths as in earlier boilers which were coiled to obtain equal length tubes. BRDC Boiler #4 was not coiled either and its performance was excellent. The tantalum tubes are .75 inch O.D. by .049 inch wall (the same as Boiler #4).

The tantalum tubes are placed in their respective Type 321SS oval static NaK tubes. The tantalum tube must then be held against the side of the oval tube such that it is at the greatest radius in both halves of the "S" shape. This means that the tantalum tube must cross over in the straight mid-section of the "S" (See Figure 1). Since the coefficient of thermal expansion for the stainless steel oval tube is more than twice that of the tantalum tube, the oval tube will grow outward or to a larger diameter relative to the tantalum tube. Consequently, no loading will be experienced between the two metals as the boiler heats up and cools down.

Seven (7) lattice-type spacer assemblies hold the tubes in their proper positions relative to the evacuated center tube and the NaK shell.

A .125 inch diameter wire with a pitch of 6 inches is wound on the center tube for 10 feet, starting at the mercury inlet, prior to installation of the 12 tantalum tubes and stainless steel static NaK tubes. Another wire of the same diameter, pitch and length is wound on the outside of the 12 tubes counter-rotational to the wire on the center tube. The purpose of these wires is to promote mixing of the flowing NaK in the area of the boiler where the greatest amount of heat transfer occurs. The adequacy of this configuration was vividly demonstrated by using a full scale plastic model of the boiler through which dye was injected in flowing water. The test also confirmed the calculations of the flowing NaK side pressure drop.

A coiled 90% tantalum-10% tungsten (90Ta-10W) .062 diameter wire with a 2 inch pitch was placed downstream of the plug for the remaining length of the tantalum tubes. The purpose of the wire is to maintain a centrifugal field for mercury droplets in the vapor such that the droplets would contact the hot tantalum tube walls, vaporize and thus "dry out" the mercury vapor before it leaves the boiler.

F. EVACUATED CENTER TUBE

The 3.5 inch O.D. by .120 inch wall center tube runs the full length of the boiler. It is bent into shape, evacuated to 10^{-4} Torr and sealed. This tube was placed in the center of the annular array of mercury tubes to decrease the free flow area of the flowing NaK which in turn increased the NaK velocity to 3.4 feet per second, thus assuring turbulent flow (Reynolds number of 110,000) and subsequent good heat transfer.

G. MERCURY OUTLET SECTION

The mercury outlet, like the inlet, is a centrally located axial discharge configuration. A coextruded tantalum-to-type 316SS bimetal tube transition joint, identical in size and length to that successfully used in BRDC Boiler #4 for 1600 hours and 28 starts is shown in Figure 1. The tube is 2.26 inches O.D. by 1.76 inches I.D. which includes a .150 inch wall of Type 316SS metallurgically bonded to a .100 inch wall of tantalum. The tube is Electron Beam (EB) welded to the stainless steel end cap. The total effective length of the transition joint bond is 8 inches, the same as the mercury inlet joint. Zirconium foil is located in the static NaK area surrounding the bimetal joint for "hot gettering" dissolved gases and carbon.

III. BOILER PERFORMANCE EVALUATION

Technical Memorandum 4921:68:550, "SNAP-8 Boiler Development Evaluation of SB-1 Boiler Test Results and Proposed Design Modifications" (Reference c), by A.J.Sellers, is an analysis of the 1/7th scale boiler and was applicable to the BRDC #4 boiler design. This technical memorandum was the basis used for determining many of the design aspects, especially as related to performance. The soundness of the analysis was borne out by the excellent performance of BRDC #4 during its tests in PCS-1 over a wide range of operating conditions (see Reference d).

As a matter of fact, BRDC #4 was the most stable boiler designed, fabricated and tested in the SNAP-8 program to date.

BRDC #5 boiler was designed using the same criteria as BRDC #4 except that the excess superheat length normally added to the boiler on previous designs was not added to BRDC #5. This was not done for two reasons - one being that its addition did not improve the performance of BRDC #4 appreciably and secondly, the envelope restrictions of the PCS precluded the addition of the extra length.

Appendix A shows the performance map and criteria computed for the high and low NaK schedule as well as the basic configuration of the BRDC #5 boiler.

IV. BOILER THERMAL ANALYSIS

Appendix B shows the results of the various design approaches to the mercury inlet section for the startup transient and steady-state conditions. The analyses were concerned with the following criteria:

- The inlet dome mercury volume should be as small as possible to minimize the time to fill during startup, yet not be so small that mercury boiling and flashing in the dome causes such a high back pressure on the mercury pump that startup becomes impossible. This can occur since the boiler is preheated to the NaK inlet temperature prior to mercury injection.

- No thermal gradients in any of the materials should be so high as to cause thermal stresses which exceed the allowable strength of the materials during the transient and steady-state operating conditions.

- Natural convection currents in the static NaK should be suppressed or destroyed such that circumferential thermal gradients are minimized. The analysis of the BRDC #4 design assumed the thermal gradients were caused by forced convection. As a result, a close fitting baffle, was placed in the flowing NaK area. However, the circumferential gradient remained essentially the same as BRDC #2. Figure 2 compares the various designs of boilers and lists the changes made to each in an effort to solve the problem.

However, it became evident as the design evolved, that the thermal gradients in the dome were too severe for a thick, flat dome which held the mercury volume to a minimum. A thinner, fairly flat dome was unacceptable from a pressure stress standpoint. It was determined that a hemispherical head was the least stressed but it also resulted in an unacceptably large mercury volume. An ellipsoidal dome proved to be the most acceptable as to stress, size and mercury volume. This configuration was analyzed for the transient and steady-state conditions. At the same time, the mercury inlet steady-state temperature was decreased from 420°F to 350°F, in keeping with the latest change dictated by the change from the 4-stage turbine to the dual multi-stage reaction turbine concept.

The vacuum chamber between the stainless steel header and the tantalum header was found to be a requirement to reduce the thermal gradient across the stainless steel header.

The vacuum chamber between the tantalum dome and the NaK shell was required to reduce the thermal gradient in the shell and in the area adjacent to the end of the NaK outlet manifold. The static NaK volume in this area was reduced to a minimum to decrease the available heat to the cold mercury during startup, thus reducing the thermal shock of the materials.

The compartmentalization ("honey-combing") of the area around each tantalum tube between the stainless steel header and the tantalum header is an approach designed to minimize the natural convection of the static NaK as the colder mercury flows through the tantalum tubes. The NaK outlet manifold was placed around this area to further reduce the natural convection by supplying heat over the whole circumference. These approaches were not employed in the BRDC #2 and #4 boilers.

An analysis of the natural convection phenomenon in liquid metals can be seen in Appendix B. It should be pointed out that there is very little information available on natural convection of liquid metals with the tubes-in-shell configuration described herein.

The thermal maps shown in Appendix B were then submitted to the Stress Group so that the maximum stresses could be computed throughout the startup and steady-state operation.

V. HYDRAULIC ANALYSES

A. MERCURY INLET ORIFICE PRESSURE DROP

The available boiler inlet pressure from the mercury pump must not be exceeded and the minimum pressure to the turbine must be met. With these defined, the total pressure drop allowable across the boiler can be determined. The pressure drop across the boiler (without inlet orifices) is positive with flows up to approximately 5,000 lbs. per hour and then goes negative from there to full flow. This can cause system perturbations that are undesirable, especially for the reactor.

The pressure drop through the short tube orifices upstream of the plugs rises as a square function as flow increases to normal operating conditions. Therefore, by choosing an orifice of the proper size (the sum of its pressure drop and the pressure drop of the remainder of the boiler) a positive slope of pressure drop versus flow can be attained throughout the boiler transient and at steady-state operation. The orifice size was calculated to be .050 inches diameter. The exact pressure drop versus flow curve desired was planned to be obtained by chamfering the orifice inlet, testing in water and then slightly rounding the inlet to achieve the proper curve.

Appendix C shows the calculations made by G.L.Lombard to determine the proper orifice shape and pressure drop. It is worthy to note that the determination of boiler pressure drop for past boiler designs was computed and then checked by building and testing single tube models in facilities such as the 1/7th scale loop. The correlation of design and test data for those earlier programs, plus testing of the BRDC #4 at very low flows (2500 lbs. per hr.) were used in designing BRDC #5 without the expensive and time-consuming methods employed previously. The new analytical method can be used on all future boiler designs as well.

B. TANTALUM PLUG SECTION PRESSURE DROP

The calculations to determine the tantalum plug pressure drop and its design length can be seen in Appendix A. Its relationship to the orifice pressure drop and the boiler overall pressure drop can be seen in Appendix C. The design length was calculated to be 2.7 feet. There are currently 17 plugs in stores that were made originally for two more boilers to the BRDC #4 design (4 feet long). However, a design change in the PCS from a conical shape to a parallelepiped shape and the changes in liquid metals temperatures, pressures and flows dictated that the coiled, 7 tube boiler design would have to be changed to the "S" shape 12 tube boiler design. Therefore, a minimum of 12 of the 17 machined plugs will be remachined to the 2.7 foot length. They will then be swaged into their respective tantalum tubes and tested with water to determine the pressure drop of each. The swaged plug assemblies of BRDC #4 were tested in this manner and found to vary from 49 to 63 psid. Knowing each swaged plug assembly and each orifice pressure drop, they can be matched for the best combination for a more balanced overall boiler assembly.

Figure 3 is a sketch of the typical water flow pattern leaving the plug section. It shows the helical, cone shaped swirl produced by the plug.

C. NaK SIDE OVERALL PRESSURE DROP.

An intermediate NaK loop side pressure drop analysis was performed for the boiler in the manner shown in Appendix D. The PCS-1 system requirement called for a maximum allowable pressure drop of 3.0 psid. The calculations showed that the total pressure drop would be 1.50 psid at the steady-state operating conditions.

Water testing of the boiler plastic model corroborated the calculations as a similar test did for BRDC #4. The testing of BRDC #4 in PCS-1 with NaK also agreed with the calculations and water test. It is concluded that BRDC #5 testing in PCS-1 will be in agreement also.

VI. WEIGHT ANALYSIS OF THE BOILER

The wet and dry boiler weight analysis can be seen in Appendix E. To summarize, the dry weight was calculated to be 833 pounds and the wet weight was calculated to be 1030 pounds.

The weight of static NaK was determined to be 39.3 pounds at ambient temperature. A typical design of a volume compensator reservoir to compensate for the expansion of the NaK through the thermal excursions of the boiler can be seen in Figure 4.

The conceptual design of the method of mounting the boiler based on the weights above as well as the thermal growth of the boiler can be seen in Figure 5.

VII. MATERIALS ANALYSES

A. RESULTS OF TANTALUM-TO-STAINLESS STEEL BIMETAL TUBE TRANSITION JOINT TEST AND INSPECTION PROGRAM

Typical bimetal tube transition joints used on BRDC #4 and planned for BRDC #5 were ultrasonically inspected at ANSC and at Westinghouse. Agreement was reached as to the best method of inspection. Some disagreement was found in the inspection results of one of the samples. Indications of debonding was noted at ANSC but no indications were noted at Westinghouse. This sample was sectioned at Westinghouse and no debonding was found. The reason for the evident discrepancy in the ANSC results is being investigated.

It was reported by the ANSC Materials Group that the thermal cycling tests of representative bimetal tubes indicated that debonding is not a problem. However, it was reported that a 7% decrease in inside diameter of these bimetal tubes occurred during test. It is assumed that the wide difference in expansion coefficients of the tantalum (4.1×10^{-6} in./in.) and the Type 316 stainless steel (10.7×10^{-6} in./in.), the difference in their yield strengths and relaxation of the residual fabrication stresses caused the change in diameter. The amount of change in diameter does not appear to be of a significance to affect boiler performance.

Appendix F describes the above test and inspection programs.

B. RESULTS OF TANTALUM PROPERTIES TEST PROGRAM

The tantalum properties test program was directed by the NASA-LeRC Materials Lab. Extensive work was done in connection with the design of BRDC #4. Welded and non-welded tantalum was investigated. Phase I tests for low cycle fatigue at 600°F and 1100°F, were completed, followed by Phase II testing at 1350°F. (not completed to date). Results indicated that tantalum is an excellent material for mercury containment in boilers.

C. MATERIALS ANALYSES RESULTS OF PREVIOUS BOILERS

Boilers #1, 2, 3, 4 and 5 all contain the same materials, namely:

1. Type 316SS for the NaK shell, headers, turbulator wire, spacers and center tube.

2. Type 321SS for the static NaK tubes

3. Zirconium for the "hot getter."

4. Tantalum for the mercury containment parts.

5. Tantalum - 10% tungsten (Ta-10W) swirl wire in the tantalum tubes.

Reference (e) is a report on the materials analyses of BRDC #1 performed by the General Electric Co. No materials problems were noted in this boiler after 15,250 hours of steady-state operation.

Reference (f) is a report on the materials analyses of BRDC #2 performed by ANSC. Other than cracking and failure of the Ta-10W wire (due to hydrogen embrittlement), some erosion of a tantalum tube caused by the flow of primary NaK through a crack in the static NaK tube (due to excessive thermal stress), and cracking of the shell at the NaK outlet port (again due to excessive thermal stress), the boiler materials were found to be acceptable for future boiler designs.

An excellent analysis of mass transfer deposition throughout the boiler trantalum tubing can also be seen in Reference (f). It was concluded that mass transfer deposition would not be a problem in the PCS.

VIII. OVERALL BOILER STRESS ANALYSES

A. BOILER OPERATING CRITERIA FOR STRESS ANALYSES

Appendix G itemizes the operating criteria of the boiler for stress analyses. The criteria define the transient, steady-state and maximum conditions for the flowing NaK side, the mercury side and the static NaK side. The expected interface loads were also defined.

B. E-11401 COMPUTER STRESS ANALYSIS INPUTS

Also included in Appendix G is a table of the inputs used in the E-11401 Computer Code for calculating the stresses in the boiler. Particular emphasis was placed on the mercury inlet configuration where the most severe pressure and thermal transients occur.

C. BOILER STRESS ANALYSIS RESULTS

The following areas were stress analyzed in detail using the criteria for pressure and temperature noted above:

1. NaK shell
2. Static NaK tubes
3. Center vacuum tube
4. Stainless steel inlet header
5. Stainless steel tees
6. Stainless steel vacuum insulators
7. Mercury inlet section
8. Overall boiler stresses with mountings recommended by PCS.
9. Mercury outlet section

Appendix G contains the work done in the above areas. All boiler stresses for the most severe conditions were calculated using the structural design criteria recommended in Reference (g). The approach and methods of analyses included the use of the finite element computer program E-11401 for the mercury inlet and outlet. These areas have axisymmetrical geometry and loading directly suited for application of this program.

The shell, tubes, stainless steel header tees and the vacuum insulators were hand calculated.

Thermal fatigue analyses employed the Manson equation and the computer output, where applicable. Thermal ratcheting was also considered.

The bimetal coextruded mercury inlet and outlet tubes were analyzed and compared to the values obtained when BRDC #4 was designed since the same size and length of tubes were used in BRDC #5.

The results of the boiler mounting analyses are shown in Appendix G. The piping flexibility analysis computer code MEC-21 was used. Figure 5 shows the recommended boiler mounting for PCS. It will be noted that the boiler is shown "cold sprung" such that the boiler stresses will be a minimum when steady state operation is reached.

IX. FAILURE MODES AND EFFECTS ANALYSIS

Appendix H itemizes the failure modes experienced on previous boilers or expected failure modes, the probable causes, effects on the boiler and the system, the probability of each occurrence and the criticality of each failure.

All of the failure modes occurred on all boilers to date with the exception of the BRDC #4 boiler which experienced only one. This boiler became deconditioned during the start of testing due to oil contamination from the mercury loop. However, the boiler conditioned fully after continued operation.

X. DESIGN REVIEW CHECK LIST

The Design Review Check List, Appendix I, is an integral part of the design review documentation package as required by Power Systems Division Procedure I-A6C. All items pertinent to the boiler were considered during the design phase.

XI. CLOSING REMARKS

Many problems have been in evidence with past boiler designs. Particular emphasis was placed on the resolutions of these problems during the design of BRDC Boiler No. 5 as noted below:

A. THERMAL STRATIFICATION OF THE INTERMEDIATE LOOP NaK FLOW

Manifolds or tees were incorporated with radial holes in the shell to provide more complete mixing of the NaK when entering and leaving the boiler. A turbulator wire was coiled around the center tube counter-rotational to the wire around the tube bundle for the 10 feet preceding the NaK exit. Water and dye tests on a plastic model of the boiler confirmed the efficacy of the design.

B. TANTALUM-to-STAINLESS STEEL JOINT RELIABILITY

Coextruded tubing of tantalum and stainless steel with an effective length of 8 inches for the mercury inlet and outlet was proven to be a reliable transition joint in BRDC #4. The same sizes and length of tubing were used on BRDC #5.

C. MERCURY-to-INTERMEDIATE NaK LOOP LEAKAGE CAUSING MAJOR CONTAMINATION OF THE NaK LOOP

Static NaK tubing surrounding the mercury tubes as a double containment feature was employed in the same manner as BRDC #1, 2, 3 and 4 boilers.

D. DIFFERENTIAL EXPANSION BETWEEN THE TANTALUM AND STAINLESS STEEL

The same concept of oval static NaK tubes surrounding the tantalum tubes for thermal growth allowances was used on BRDC #5 as was used on BRDC #1, 2, 3 and 4.

E. NEGATIVE SLOPE MERCURY PRESSURE DROP VERSUS FLOW

Design of the mercury inlet orifices to result in a positive slope of the mercury pressure drop versus flow was incorporated in this design. All previous boilers had a negative slope.

F. NATURAL CONVECTION OF STATIC NaK AT MERCURY INLET

Compartmentalization of areas around the tantalum tubes at the mercury inlet and the surrounding of this area with the NaK outlet tee will effectively diminish or destroy the natural convection currents which caused circumferential thermal gradients on all previous boilers.

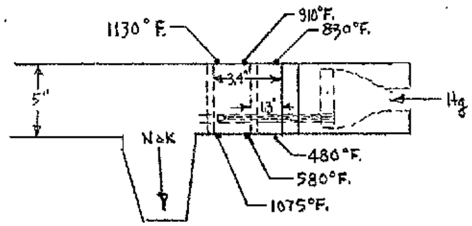
G. HIGH AXIAL THERMAL GRADIENTS IN THE SHELL AT THE MERCURY INLET

Vacuum insulators were placed between the stainless steel header and the tantalum header as well as the area surrounding the tantalum dome. The static NaK volume around the tantalum header was also reduced for the same reason.

BRDC MERCURY INLET DESIGN EVALUATIONS

ESC 6/29/70

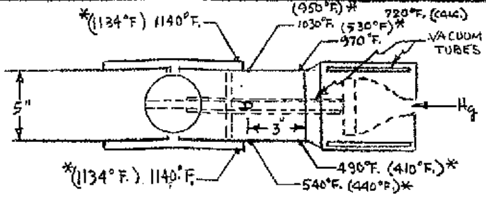
BRDC BOILER NO. 2
P/N CF751840



RUN D43-6-24, 9/4/68

$\dot{\omega}_H$ = 10,700 #/HR
ΔP_H = 172 PSID
T_{NBi} = 1300 °F.
T_{NBo} = 1135 °F.
T_{HBi} = 436 °F.
$\dot{\omega}_N$ = 50,000 #/HR.
NO. TUBES = 7

BRDC BOILER NO. 4
P/N 1266911



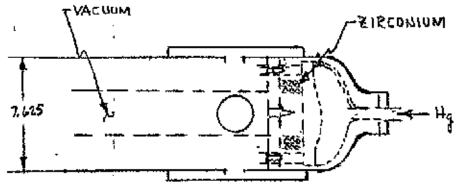
RUN D43-6-51, 3/25/70

$\dot{\omega}_H$ = 12,700 #/HR
ΔP_H = 126 PSID
T_{NBi} = 1314 °F.
T_{NBo} = 1140 °F.
T_{HBi} = 426 °F.
$\dot{\omega}_N$ = 51,000 #/HR

RUN D43-6-54, 4/15/70 ( )*

$\dot{\omega}_H$ = 12,300 #/HR.
ΔP_H = 138.5 PSID
T_{NBi} = 1303 °F.
T_{NBo} = 1134 °F.
T_{HBi} = 384 °F.
$\dot{\omega}_N$ = 48,500 #/HR.
NO. TUBES = 7

BRDC BOILER NO. 5



DESIGN

$\dot{\omega}_H$ = 13,600 #/HR.
ΔP_H = 46.4 + 140 = 186.4 PSID
T_{NBi} = 1211 °F.
T_{NBo} = 1044 °F.
T_{HBi} = 420 °F.
$\dot{\omega}_N$ = 57,148 #/HR.
NO. TUBES = 12

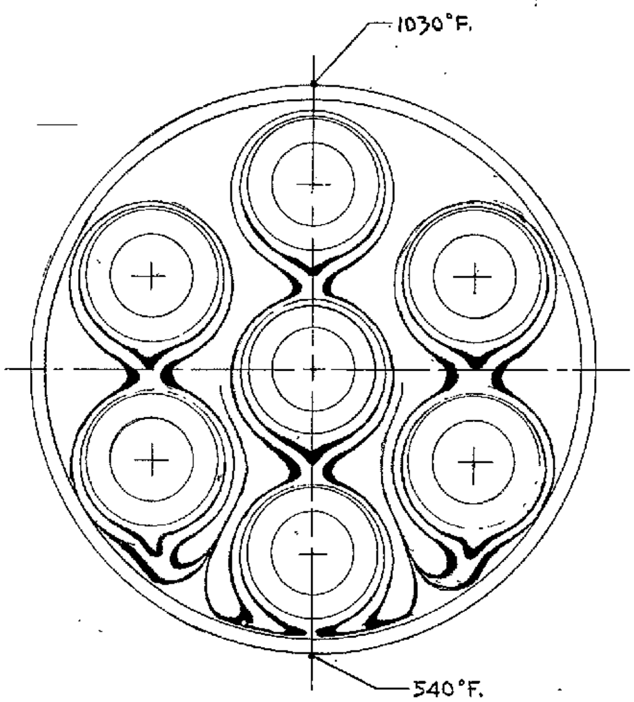
BRDC MERCURY INLET DESIGN EVALUATIONS

BRDC BOILER NO. 2 P/N CF 751840		BRDC BOILER NO. 4 P/N 1266911		BRDC BOILER NO. 5
POSTULATIONS FOR THERMAL GRADIENTS	SOLUTIONS	POSTULATIONS FOR THERMAL GRADIENTS	SOLUTIONS	
1. STRATIFICATION (FLOW & TEMP) OF PNL NaK CROSS-FLOW NEXT TO BAFFLE DUE TO SINGLE RADIAL EXIT.	1. ADD COLLECTOR RING WITH RADIAL HOLES IN SHELL. ADD TURBULATOR WIRE UPSTREAM OF NaK EXIT.	1. TIGHT BAFFLE IS TOO EFFECTIVE TO ALLOW FOR THERMAL MIXING.	1. REMOVE BAFFLE.	
2. TOP Hg TUBES DE-CONDITIONED DUE TO CONTAMINATION (OIL).	2. ADD VACUUM TUBES TO REDUCE HEAT TRANSFER. MODIFY PCS TO DECREASE INFLUX OF CONTAMINANTS.	2. TOP Hg TUBES DE-CONDITIONED DUE TO CONTAMINATION (OIL) FLOTATION.	2. FURTHER REDUCE INFLUX OF CONTAMINANTS, VERTICAL Hg INLET.	
3. GRAVITY DIFFERENTIAL BETWEEN TOP & BOTTOM Hg TUBES.	3. VERTICAL Hg INLET	3. GRAVITY DIFFERENTIAL BETWEEN TOP & BOTTOM Hg TUBES.	3. VERTICAL Hg INLET.	
4. CONVECTION IN SEMI-BAFFLED NaK AREAS INDUCED BY FLOWING NaK THRU ANNULUS BETWEEN BAFFLE PLATE & STATIC NaK TUBE,	4. DELETE ONE BAFFLE, INCREASE BAFFLING WITH TIGHTER FIT, ADD VACUUM TUBES, OVERLAP BAFFLE WITH TEE,	4. CONVECTION IN TIGHT-BAFFLED NaK AREAS CAUSED BY INEFFECTIVE VACUUM TUBES &/OR HOT WALL TO COLD WALL HEAT TRANSFER.	4. REMOVE VACUUM TUBES, DECREASE Hg VOLUME IN TUBES & INLET DOME, REMOVE BAFFLE, ENVELOP. SS HEADER & Ta HEADER WITH TEE, DECREASE STATIC NaK VOLUME, ADD TURBULATOR FOR FULL BOILER LENGTH ALONG INNER TUBE OD & SHELL ID FOR MORE COMPLETE PNL MIXING, INCREASE NO. OF RADIAL SHELL HOLES FROM 6 TO 12.	

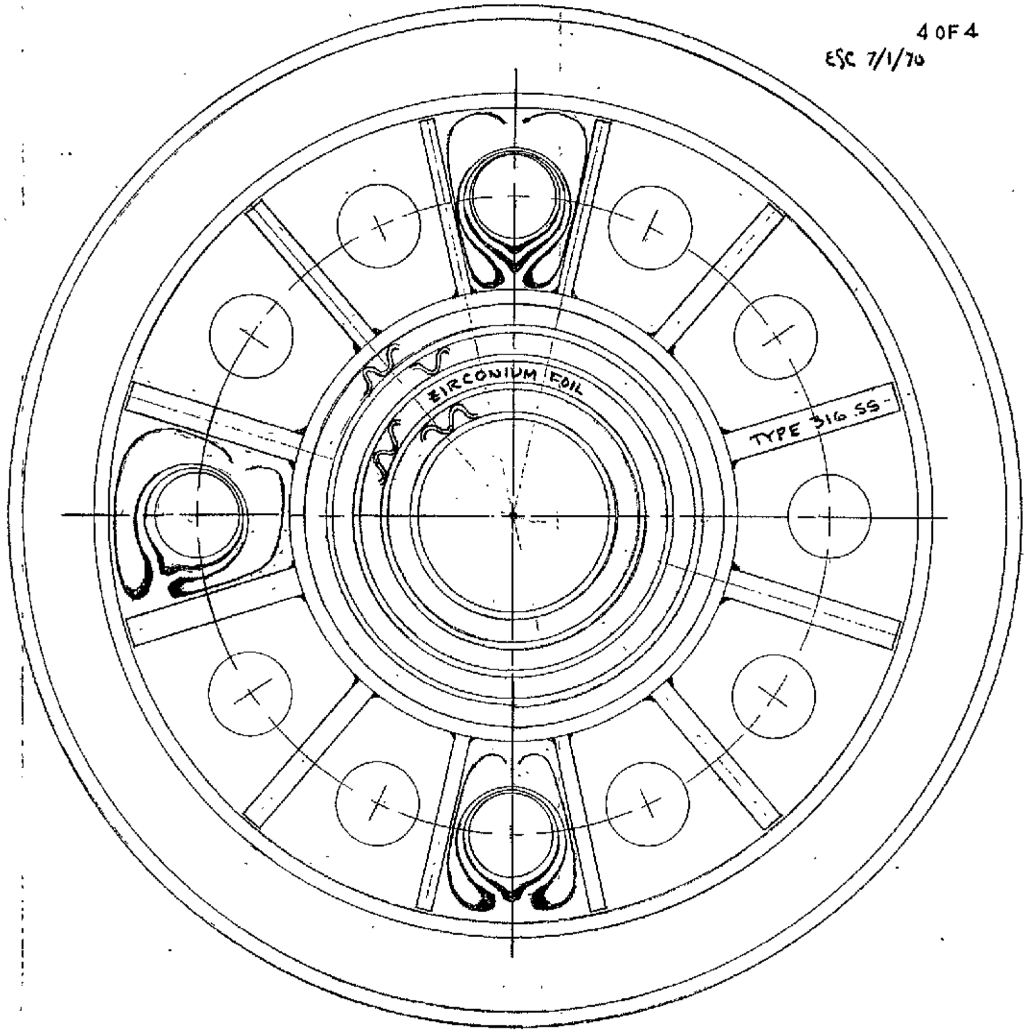
BRDC MERCURY INLET DESIGN EVALUATIONS

BRDC BOILER NO. 2 P/N CF 751840		BRDC BOILER NO. 4 P/N 1266911		BRDC BOILER NO. 5
POSTULATIONS FOR THERMAL GRADIENTS	SOLUTIONS	POSTULATIONS FOR THERMAL GRADIENTS	SOLUTIONS	
		5. FREE CONVECTION EFFECT BETWEEN BAFFLE PLATE, SS HEADER & TANTALUM HEADER WHEN Hg. VOLUME IN Ta DOME IS CONSIDERED AS AN EFFECTIVE HEAT SINK.	5. ADD ZIRCONIUM FOIL IN AREA BETWEEN SS HEADER & Ta HEADER TO MINIMIZE CONVECTIVE CURRENTS & APPROACH PURE CONDUCTIVE HEAT TRANSFER THRU NaK.	

4 OF 4
ESC 7/1/70



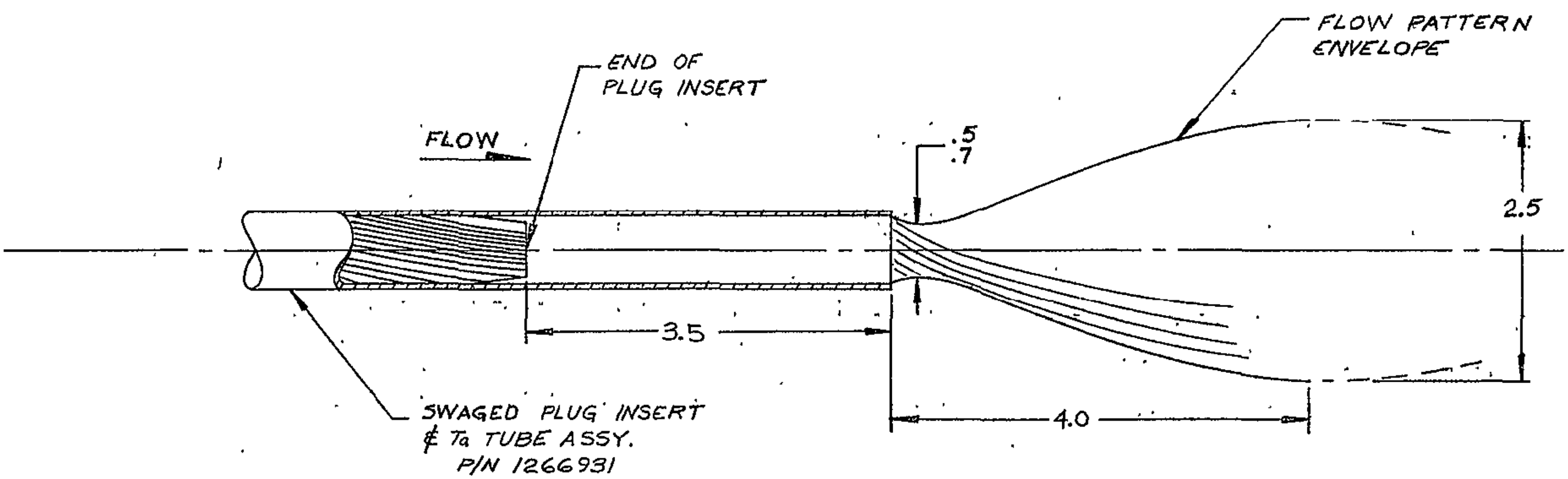
BRDC #4
CROSS-SECTION
FREE CONVECTION



BRDC #5
CROSS-SECTION
FREE CONVECTION

FIGURE 3

EFFLUENT WATER FLOW PATTERN OBSERVED DURING FLOW TESTS OF BRDC BOILER NO. 4 SWAGED PLUG INSERT / TUBE ASSEMBLIES P/N 1266931



FLOW: $\dot{W}_{H_2O} = .474$ LB/SEC

FIGURE 3

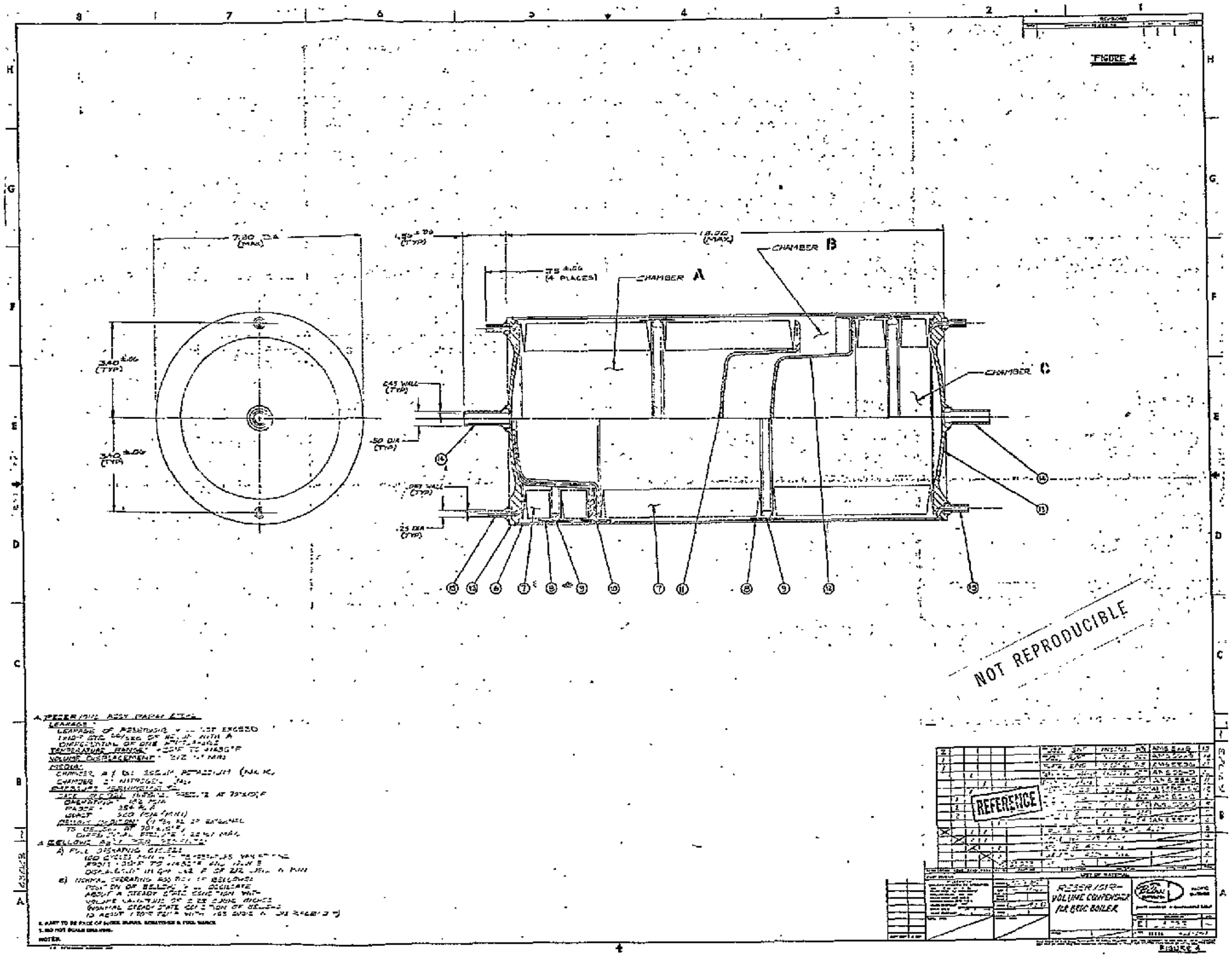


FIGURE 4
7.00 DIA (MAX)
18.00 (MAX)
CHAMBER A
CHAMBER B
CHAMBER C
(4 PLACES)
NOT REPRODUCIBLE
REFERENCE

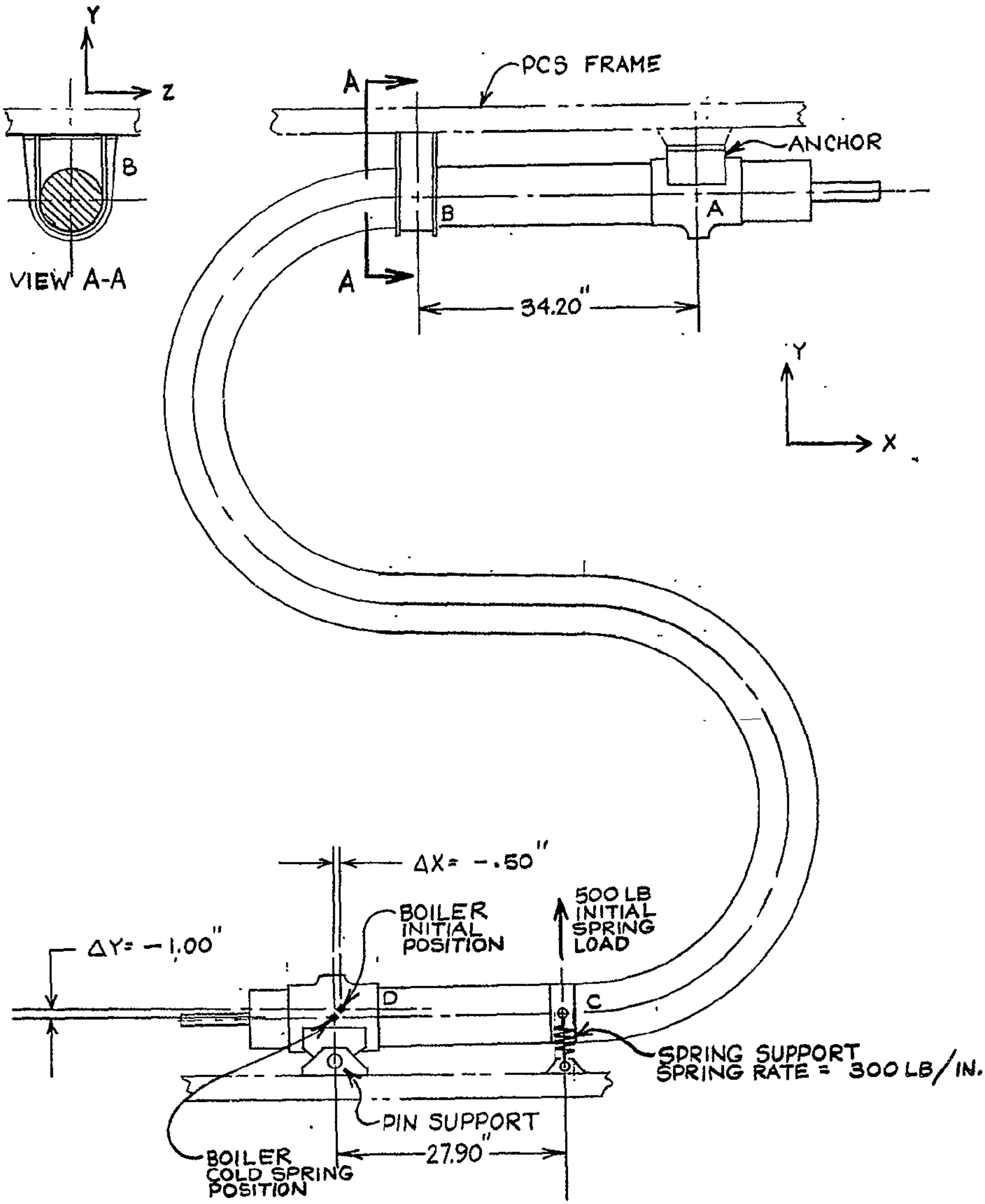


FIGURE 5
BOILER SUPPORT CONFIGURATION

REFERENCES:

a. Specification AGC-10680 - Power Conversion System, Model G, SNAP-8.

b. Drawing No. 1268489 - Interface Control Drawing, Boiler for PCS-G.

c. Technical Memorandum 4921:68:550, SNAP-8 Boiler Development Evaluation of SB-1 Boiler Test Results and Proposed Design Modifications, by A.J.Sellers.

d. Technical Memorandum 7992:70:633, PCS-1 Testing of March - May 1970, by J.N.Hodgson.

e. Memorandum 7978:70:0001, Post-test Materials Analyses of BRDC Boilers Numbers 1 and 2, by E.S Chalpin.

f. Technical Memorandum 7972:70:640, Evaluation of SNAP-8 Bare Refractory Double Contain ent Boiler No. 2 After 8700 Hours of Operation, by H.E.Bleil.

g. Specification AGC-10650 - Structural Design Criteria, SNAP-8.

APPENDIX A

GROUND RULES, DESIGN APPROACH AND CRITERIA

FOR BRDC BOILER #5

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS
ENGINEERING DESIGN FILE

ENGINEERING FILE NO.
EDF SERIAL NO. DE 0018
DATE July 13, 1970
W. O. NO. 1475-44-0114, 0117

PROJECT SNAP-8

SUBJECT

GROUND RULES, DESIGN APPROACH AND PROGRAM PLAN FOR BRDC BOILER #5.

ABSTRACT

The subject is set forth in the following manner:

1. Scope
2. Boiler Design Approach
   - A. Thermal
   - B. Mechanical
   - C. Stress
   - D. Materials
3. Program Plan

DISTRIBUTION H.Bleil, B. Breindel, H. Derow, R.G.Geimer, C.Hawk, J.Hodgson, A.H.Kreeger, G.L.Lombard, L.Lopez, R.W.Marshall, Jr., U.A.Pineda, A.J.Sellers, W. Weleff,

COVER SHEET ONLY

KEY WORDS BRDC Boiler #5, Ground Rules, Design Approach, Program Plan

AUTHOR	DEPT	REVIEWED	DATE	REVIEWED	DATE
E.S.Chalpin E S Chalpin	7978			R Muir	8/5/70

GROUND RULES, DESIGN APPROACH AND PROGRAM PLAN
FOR
BRDC BOILER #5

1. SCOPE.- The design of the BRDC Boiler #5 shall be based on the salient features of BRDC Boilers #2 and #4, and the analytical results of stress, thermodynamics and materials. It shall incorporate double-containment, tantalum as the mercury containment materials, swirl wire downstream of the tantalum plug, tantalum/stainless steel bimetal transition joints, twelve (12) mercury tubes and of an "S" configuration. This design scope is based on the recommendations of M. J. Saari, Chief, NASA SNAP-8 Project Office in his letter to Dr. W. F. Banks, subject "SNAP-8 PCS-G Boiler Design Contract NAS 3-13458," dated 12 June 1970.

2. BOILER DESIGN APPROACH.-

A. Thermal - As itemized in Memo 7978:70:0002, E.S.Chalpin/A.J.Sellers, Subject "SNAP-8 12 Tube Boiler (BRDC #5) Design for Revised System State Point Conditions," dated 1 July 1970. This was corroborated by R.G.Geimer, Systems Management, in Memo 7992:70:0071, subject "Compatibility of Boiler Design Configurations for PCS-G," dated 6 July 1970.

B. Mechanical - See Memo 7978:70:0002 above.

C. Stress - As itemized in Memo 7978:70:0003, E.S.Chalpin to Dr. W.Weleff/H.Derow, Subject "BRDC Boiler #5 Operating Criteria for Stress Analyses," dated 6 July 1970. The method of approach will be as itemized in Memo 7974:70:0047 (File: SS1020), W.Weleff to H.Derow, subject "Boiler #5 Critical Areas," dated 10 July 1970.

D. Materials - This shall include a review of the post-test inspection of BRDC #1 and #2 noted in Memo 7978:70:0001, E.S.Chalpin to U.A.Pineda, Subject "Post-Test Materials Analyses of BRDC Boilers Numbers 1 and 2," dated 22 June 1970, dimensional inspection and metallurgical evaluation of the low cycle fatigue exposure tests of bimetal sleeves and Memo 7972:70:0075 (File: 2104), H.Bleil to H.Derow, subject "Metallographic Examination of E.B.Welded Tantalum," dated 2 July 1970.

3. PROGRAM PLAN.-

As itemized in PMR book, Ident. Code: 6-1.1.4 Detail (July 1970). A plastic model of the boiler design will be fabricated and tested as noted in Memo 7990-70-0049, from A.H.Kreeger to M.J.Saari, subject "Additional Authorized Work," dated 6 July 1970.

A final design review is planned for 23 October 1970 and will include all of the foregoing analyses as well as a complete set of reproducible drawings to be delivered to NASA-LeRC for fabrication of the boiler.

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS

DATE: 1 July 1970
7978:70:0002:mrs
Bldg.160/X5522

M E M O R A N D U M

TO: Distribution

FROM: E. S. Chalpin/A.J.Sellers

SUBJECT: SNAP-8 12 Tube Boiler (BRDC #5) Design for Revised System State Point Conditions

COPIES TO: W.F.Banks, R.Chesworth, H.Derow, C.Hawk, J.Hodgson, A.Kreeger, G.Lombard, L.Lopez, U.A.Pineda, R.W.Marshall, Jr., L.Breindel

REFERENCES:
(1) "BODEPE - IBM 360 Computer Code for SNAP-8 Boiler Heat and Momentum Transfer Analysis," TM 4921:68-551, Oct. 1968.
(2) "PCS-G State Point Conditions - Revision Date 4/21/70," EDF Serial N.SA0014

ENCLOSURES:
Table I - SNAP-8 PCS-G BRDC #5, Boiler Design Specifications and Operating Parameters
Fig. 1 - SNAP-8 PCS-G BRDC #5, BODEPE Temperature and Pressure Profiles

This memo presents the summary of the bare refractory double contained 12 tube boiler design analysis. Per NASA-LeRC direction (5-19-70), the mercury flow containment in the oval/round SS-Ta tube assembly with a multipassage plug insert (MPP) and swirl wire (SW) internal geometry was assumed to be identical to that of BRDC #4. To meet the revised PCS-G state point conditions (Reference 2) the tube count was increased from 7 to 12. Lower boiler operating pressure level and pressure drop, and increased mercury flow rate were reasons for the increase in the tube count.

Relatively good agreement between the BODEPE code design predictions and the test results of the SB-2, SF-1A and BRDC #4 boilers is the basis for the new boiler design approach. The heat and momentum transfer correlations used in this analysis are those established from the wetting and non-wetting two-phase flow models in a helical flow passage (Reference 1).

The summary of the thermal design analysis is presented in Table I. It specifies the assumed boiler cross section geometry and the calculated boiler MPP and total length requirements for low NaK inlet temperature schedule as well as the boiler operating thermal and dynamic parameters for the prescribed PCS-G systems state point conditions. Figure 1 shows the graphical interpretation of the predicted boiler performance characteristics at low and high NaK inlet temperatures.

E. S. Chalpin, Supervisor
Mechanical Design Group
Design Engineering Section
Engineering Department

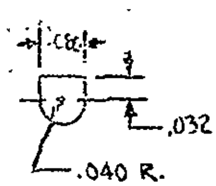
A. J. Sellers
Analytical Design Group
Design Engineering Section
Engineering Department

TABLE I

SNAP-8 PCS-G BRDC No. 5

BOILER DESIGN SPECIFICATIONS AND OPERATING PARAMETERS

MECHANICAL

Design Concept:	"Once Through" mercury preheat, boiling and superheat
Boiler Type:	Parallel counterflow NaK-Ta-Hg heat exchanger
Design Configuration:	Parallel tube Bundle-In-Tube
Number of HG Tubes	12
Hg Containment:	In round Ta tube contained in oval 321SS tube with stagnant NaK in annular space.
TA Tube	.750" OD x .049 wall
Oval 321SS Tube:	.830" x 1.45" x .049 wall
Effective MPP Length:	2.7 Ft., Tantalum
Number of Helical MPP Flow Passages:	16
MPP Flow Pass. Pitch:	6"
MPP Flow Passage Crossection	
Swirl Wire:	.062" Dia. x 2" Pitch. 90% Ta-10%W
NaK Shell Tube:	7.625" OD x .120" Wall, 316SS
Length-Centerline to Centerline of NaK Inlet and Outlet	21.5 Ft.

Boiler Crossection: See Table I
Effective Boiler Length: 21.5 Ft.

THERMAL

Item	Parameter	Symbol	Dimension	NaK Inlet Temp. Schedule Low	High
1.	NaK Flow Rate	W_N	LB/HR	57148	57148
2.	NaK Inlet Temp.	T_{Nbi}	°F	1185	1211
3.	NaK Temp. Drop	ΔT_N	°F	170	167
4.	NaK Pressure Drop	P_N	PSI	~3	~3
5.	HG Flow Rate	W_{HG}	LB/HR	13775	13600
6.	HG Exit Pressure	P_{Hbo}	PSIA	148	147
7.	HG Exit Temp.	T_{Hbo}	°F	1165	1190
8.	HG Inlet Temp.	T_{Hbi}	°F	420	420
9.	HG Vapor Region Pres. Drop	ΔP_{HG}	PSI	32	46
10.	HG Flow Restr.Pres. Drop	ΔP_R	PSI	143	140
11.	HG Inlet Pressure	P_{Hbi}	PSIA	323	333
12.	Pinch Point Temp. Diff.	ΔT_{pp}	°F	38	54
13.	Terminal NaK-To-HG T	ΔT_t	°F	20	22
14.	Vapor Superheat	ΔT_{SH}	°F	197	224
15.	Mean Preheat Flux	q''_{PH}	B/HR-FT^2	188465	215553
16.	Mean MPP Boiling Flux	q''_{MPP}	"	49237	71292
17.	Mean SW Boiling Flux	q''_{SW}	"	57921	63338
18.	Mean Superheat Flux	q''_{SH}	"	5176	5707
19.	Boiling Termination Point	L_{100}	FT	15.4	13.4
20.	MPP Vapor Exit Quality	X_{PL}	%	12	18
21.	Thermal Power Req'd.	q_t	KW	600	598
22.	External Power Loss (Assumed)	q_{HL}	"	5	5

SNAP-8 PCS-G BRDC #5 - BODEPE TEMPERATURE AND PRESSURE PROFILES

AT $\dot{W}_N$ = 57148 LB/HR, T_{Nbi} = 1185 to 1210°F, ΔT_N = 170°F, $\dot{W}_{HG}$ = 13775 to 13600 LB/HR, P_{Hbo} = 148 to 147 PSIA.

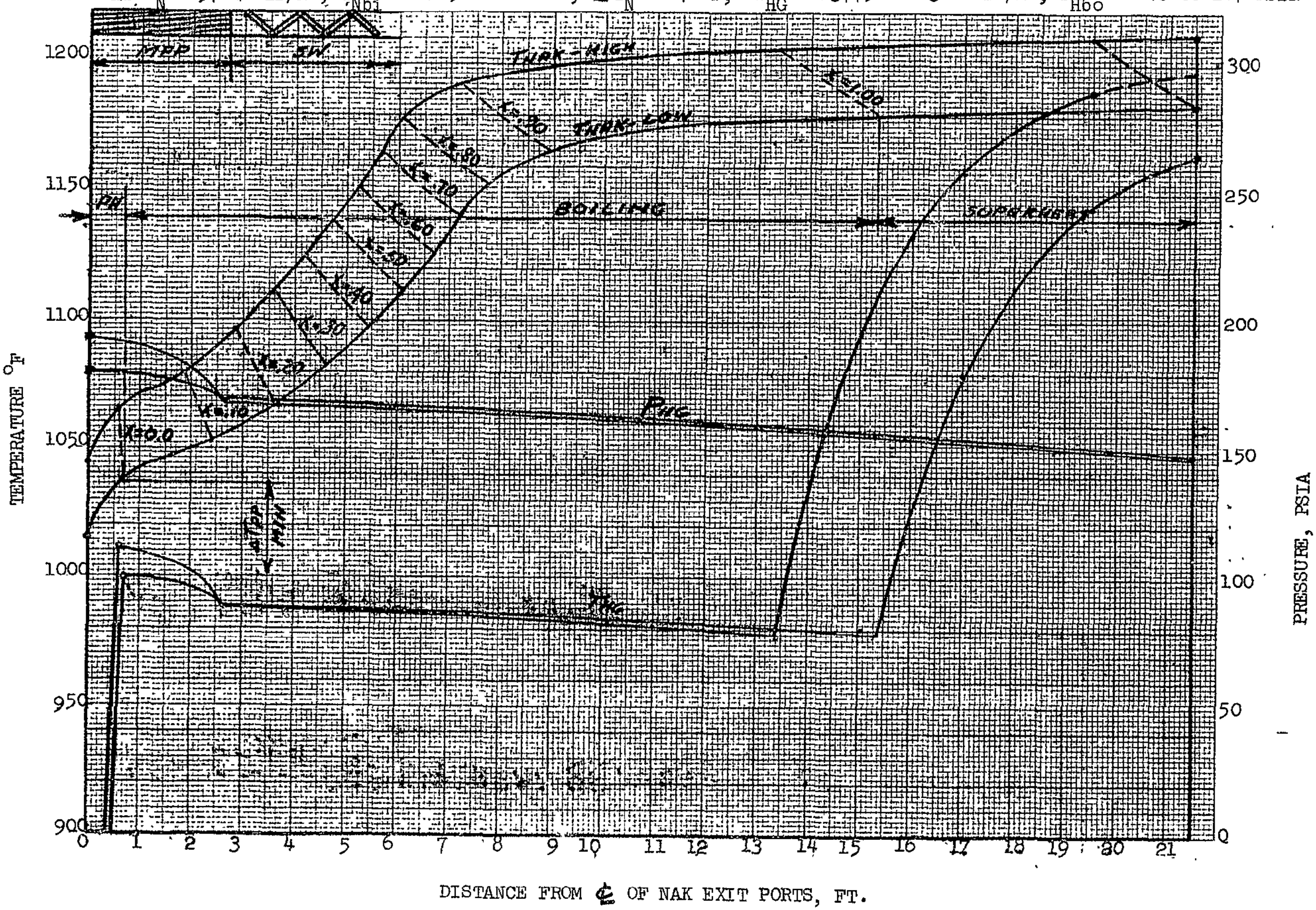


FIGURE 1

7978:70:0002:mrs

26

INTEROFFICE MEMO

AEROJET-GENERAL CORPORATION
AEROJET NUCLEAR SYSTEMS COMPANY
Power Systems Operations

TO: E. S. Chalpin

DATE 6 July 1970
RGG:mhm:7992:70:0071

FROM: R. G. Geimer

SUBJECT: Compatibility of Boiler Design Configurations for PCS-G

COPIES TO:
ANSC-Azusa: WF Banks, B Breindel, CE Hawk, JN Hodgson, AH Kreeger, GL Lombard, LP Lopez, RG Geimer, RW Marshall, JH Noble, AJ Sellers, File
ANSC-Cleveland: WL Snapp
NASA-LeRC: ER Furman, HG Hurrell, AW Nice, MJ Saari, A Stromquist, GM Thur
NASA-Plum Brook: DM Entrikin
NASA-Hq: PR Miller
NAVPLANTREP: DE Blasco

Reference:
(a) Memo 7992:70:0068 from RG Geimer to Distribution, dtd 1 July 1970, Subj: PCS-G State-Point Conditions - Revision Date 26 June 1970
(b) Memo 7973:70:0007 from ES Chalpin/AJ Sellers to Distribution, dtd 27 May 1970, Subj: SNAP-8 13 Tube Boiler (BRDC No. 5) Designs for Revised State-Point Conditions
(c) Memo 7961:70:0567 from CE Hawk to Distribution, dtd 22 June 1970, Subj: 18 June 1970 Preliminary Conceptual Design Review BRDC No. 5 Boiler

The PCS-G state-point conditions presented in Reference (a) are based on the boiler design calculations for the 13 tube configuration, as contained in Table I of Reference (b). The results of the boiler design review, per Reference (c), indicated that a 12 tube configuration should also be evaluated before a final configuration is selected for PCS-G. An action item from Reference (c) requested that the Systems Group evaluate the acceptability of the 12 tube configuration. A performance evaluation of the 12 tube configuration was conducted, based on the following preliminary design point information from Mr. A. J. Sellers:

$$T_{NaK\ in} = 1185^{\circ}F$$

$$\Delta P_{vapor} = 32\ psi$$

$$\Delta T_{pinch\ point} = 38^{\circ}F$$

$$\Delta T_{terminal\ temp.} = 20^{\circ}F$$

The results of the evaluation by the Systems Group are presented below, along with the design conditions for the 13 tube configuration.

		12 tube config.	13 tube config.
W_{NaK}	(lb/hr)	57050	57050
$T_{NaK\ in}$	(^{o}F)	1185	1185
ΔP_{vapor}	(psi)	32	26
$\Delta T_{pinch\ point}$	(^{o}F)	38	44
$\Delta T_{terminal\ temp.}$	(^{o}F)	20	20
$W_{Hg\ vapor}$	(lb/hr)	13775	13775
$P_{boiler\ out}$	(psia)	146	145

A comparison of the above results shows that, although some variations exist in the boiler operating characteristics, the interface conditions remain essentially unchanged. Therefore, if the 12 tube configuration is adopted in the future, there will be no significant changes in system state-point conditions, but boiler operating characteristics would be reflected in a state-point revision.

R. G. Geimer

R. G. Geimer
Systems Management
SNAP-8 Systems and Test
SNAP-8 Program

APPENDIX B

BOILER THERMAL ANALYSES

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS
ENGINEERING DESIGN FILE

PROJECT SNAP-8

ENGINEERING FILE NO.
EDF SERIAL NO. DE-0048
DATE 10 September 1970
W. O. NO.

SUBJECT SNAP-8 12 TUBE BOILER (BRDC #5) MERCURY INLET END THERMAL MAPPING

ABSTRACT

A thermal analysis was made on the BRDC #5 boiler mercury inlet design configuration under PCS-G start-up transient and steady-state operating conditions using TAP computer code. The results of the analysis are provided for several design configurations in the form of thermal maps depicting the temperature conditions of the various structural elements. The design L and the associated thermal mapping is recommended for the purpose of checking the boiler mercury inlet end structural reliability from the combined thermal and pressure stress viewpoint.

DISTRIBUTION C. Hawk, U.A.Pineda, R.W.Marshall, Jr., G. Lombard, L. Lopez, A. Kreeger, H. Derow, W.M.Waters, File

COVER SHEET ONLY

KEY WORDS Thermal analysis, structural elements, temperature gradients, vacuum insulation

AUTHOR	DEPT	REVIEWED	DATE	REVIEWED	DATE
A. J. Sellers	7977	W. M. Waters	9/15/70	R.W.Marshall	9/15/70

INTRODUCTION

The purpose of this memorandum is to present the boiler mercury inlet end thermal design analysis. Because of relatively very high temperature difference between the primary NaK flow exit temperature (T_{Nbo} = 1210 to 1045°F and the mercury inlet temperature (T_{Hbi} = 80 to 420°F) during the startup, the boiler mercury inlet end structural elements are exposed to severe thermal transient gradients. One can also visualize that under the steady-state operating conditions there is a significant temperature difference ($T_{Nbo} - T_{Hbi}$ = 1045 - 420 = 625°F) between the NaK exit and mercury inlet ports. To assure the boiler mercury inlet end structural reliability, the above temperature conditions have been investigated in a series of different inlet end design configurations. The readily available TAP-IBM 360 computer program was utilized to determine the thermal gradients in the various structural elements of the boiler during start-up transient and for the steady-state operating conditions of the boiler. The following sections describe the analytical approach, the results of the analysis and the selection of the optimum mercury inlet end design configuration.

I. THERMAL TRANSIENT AND STEADY-STATE CONDITIONS IN THE BOILER MERCURY INLET SECTION

The basic mercury inlet end design configuration is shown in Figure 1. Prior to mercury injection the boiler is exposed to NaK flow at T=1210°F. The forced convection NaK flow region extends up to the stainless steel header where it exits from the NaK shell tube by means of 12 radial ports and an annular manifold around the NaK shell. Under these conditions the structural elements as well as the stagnant NaK contained between these structural elements assumes the flowing NaK temperature when there is no heat loss from the outer surface of stagnant NaK containment shell. During mercury injection, the mercury flow and inlet temperature as well as the NaK temperature are acting as forcing functions in accordance to Reference (b) conditions until the steady-state boiler operating conditions are established. The early part of the mercury injection is visualized as immediate mercury vaporization (flashing) on the hot tantalum surfaces until the buildup of the pressure in the boiler surpresses the mercury vaporization. Thereafter, the relatively high available capacitance around the tantalum bell can be the reason for transitional subcooled mercury boiling until the thermal capacitance is consumed and the Ta wall-to-bulk Hg temperature difference is reduced to a level compatible with the forced convection liquid mercury preheating flow regime. Following the capacitance consumption and the final Hg flow establishment, the boiler assumes the performance characteristics as provided in Reference (a). The determination of the temperature distribution in the boiler Hg inlet end is provided by the following analytical approach.

II. ANALYTICAL APPROACH

The basic inputs for the boiler Hg inlet end thermal mapping are the structural geometry and the time functions of T_{Nbo}, w_{Hg} and T_{Hbi} respectively. In view of the radial symmetry of the boiler cross-section only 1/24 or a 15^{o} sector was selected to generate the three dimensional R-C network for the thermal analysis. Readily available TAP-7 IBM 360 computer code was utilized for the analysis. Typical radial and axial R-C network arrangements are shown in Figure 2 and 3 respectively. Strictly conductive heat transfer passages were assumed through the stagnant NaK volume and structural elements of the geometry. The heat source $T_{Nbo} = f_1(\theta)$ in the forced convection region next to the SS header was coupled axially to R-C network by h_N = 3000 Btu/hr-ft^2-^{o}F, which is the calculated NaK side film coefficient in the boiler proper. Similarly, $T_{Nbo} = f_1(\theta)$ was coupled radially to R-C network axial layers surrounded by the annular NaK exit manifold using a conservative h_N = 1000 Btu/hr-ft^2-^{o}F. The heat sink represented by Hg flow passage volume capacitances was coupled to the Ta wall by mercury side film coefficients of h_{Hg} = 5000, 1000 and 500 Btu/hr-ft^2-^{o}F in the plug insert region, open tube region and the Hg inlet region up to the Ta header respectively. In view of possible flashing and subcooled film boiling of mercury, as will be shown in the following section, these film coefficients may not be realistic during the early part of the mercury injection period (θ = 0 to 30 sec.). Based on Reference (c) Figure VII-2 plot, the mercury vaporization at elevated surface-to-saturation temperature differences ($\Delta T = (T_{surface} - T_{sat}) \gg 20^{o}F$) takes place in the transition and film boiling regime. This boiling regime is characterized by relatively low film heat transfer coefficients ($h \ll 500$ Btu/hr-ft^2-^{o}F) and high temperature gradients across the vapor film. The latter condition implies that relatively uniform Ta chilling will take place in the Ta bell area during the early part of the mercury injection period. The employment of relatively high mercury side film coefficients as indicated earlier during the transition period will, therefore, result in conservative (high) thermal gradients in the structural elements containing the stagnant NaK. The assumption of strictly conductive heat transfer passages through the stagnant NaK volume is based on the condition that this volume will be subdivided in relatively small cells in the actual design thus approaching a solid configuration. The purpose of these cells is to prevent the natural convection effects in the stagnant NaK volume. In view of the relatively high thermal diffusivity (1.47 ft^2/hr) of the NaK the compartmentized NaK volume can be treated as a solid conductor. Under these conditions a uniform and symmetric R-C network can be visualized around the individual Hg tubes between the SS and Ta headers and the Hg inlet passage up to the Ta header. The physical properties of the structural materials and working fluids were taken from the SNAP-8 H-100 Manual.

Several mercury inlet end design configurations were investigated to determine the most plausible thermal map for the boiler startup transient and steady-state operating conditions. The purpose of this mapping is to identify the locations of the maximum temperatures gradients in the structural materials and to evaluate the most prospective design configuration in the light of allowable stresses and overall structural reliability. To minimize the thermal gradients in critical areas, the application of vacuum insulation was considered in the form of annular and/or radial stainless steel vacuum cans. Radiant heat transfer across the vacuum space was specified assuming the emmissivity of the shell SS surface (ϵ = .55) for the temperature range 0 to 1210^{o}F.

III. DISCUSSION OF THE RESULTS

The initial results of the analysis are provided in Figure 4. It represents the basic boiler mercury inlet end design configuration with different annular NaK exit manifold locations denoted by DES A, B, C, D, E and F respectively. The comparison of the corresponding NaK shell-tube temperature profiles (⊙———⊙) under steady-state operating conditions (Θ_{11} = 1200 sec.) reveals that relatively severe NaK shell-tube axial temperature gradient occurs at the termination point of the annular NaK exit manifold. The plot (x----x) referring to DES E and F represents the SS header radial temperature profiles for KND-1 and 2 respectively. Both (x----x) profiles also indicate severe radial thermal gradients between points 1, 2, 3 and 4 and 9, 10, 11 and 12 in the radial plane of KND=1 and 2 respectively. To minimize the NaK shell-tube axial thermal gradient at the NaK exit manifold termination point, the vacuum insulation can was placed inside the NaK shell-tube, and the NaK exit manifold termination point was located between the KND = 4 and 5 as shown by the DES. G in Figure 5. The NaK exit manifold termination point location as provided in the DES G is a compromise consideration. Firstly, it ensures a symmetric primary NaK temperature environment around the stagnant NaK volume between the SS and Ta headers, thus preventing the stagnant NaK temperature stratification under adverse heat input conditions into the mercury. Secondly, in conjunction with the vacuum insulation, it reduces the heat input from the primary NaK into Ta bell mercury volume thus minimizing the mercury vapor generation during the early part of the mercury injection period. A complete thermal map of DES G is depicted in Figures 5 and 6 for the SS and Ta structural elements of the boiler. As denoted by (x --- x) plot in Figure 5, the maximum axial temperature gradient occurs in the stagnant NaK containment tube (SS) during the transient state (Θ_8 = 300 sec., ΔT = 1031°F/in). A relatively large temperature gradient also results in the same tube (ΔT = 708°F/in) and the SS header (308°F/in) at the steady-state operating point (Θ_{11} = 1200 sec.). To minimize the thermal gradients in the stagnant NaK containment tube and the SS header as well, the DES G was modified by placing the vacuum can insulation around the Ta tubes in the SS header area as shown in Figure 7 for the DES H. The resulting temperature profiles of this design are depicted in Figures 7 and 8 for the SS and Ta structural elements of the boiler mercury inlet end. The examination of these profiles shows them to be the most plausible thermal gradients in all the structural elements of this design configuration. When considered in the light of the mercury tube circumferential pitch spacing as specified in the boiler layout (D_{pitch} = 5.65 in) the vacuum can placement around the tantalum tubes is not possible because of spacing limitations unless the Ta tube pitch diameter in the SS and Ta header area is increased. An alternate modification of DES G and the associated temperature profiles are shown in Figures 9 and 10 which becomes DES J. This design incorporates the radial vacuum insulation can placed on the SS header face on the stagnant NaK volume side. The purpose of this vacuum can is to minimize the axial and the radial temperature gradients in the stagnant NaK containment SS tube and the SS header. As compared to DES G the temperature gradient reduction in DES (J) at Θ_8 and Θ_{11} are from 1034 to 1028°F/in. and from 757 to 748°F/in. respectively. The comparative axial ΔT reduction across the SS header is from 492 to 412°F/in and from 406 to 154°F/in respectively. The latter is a significant improvement over DES G. The combined effect of vacuum can placement on the Ta tubes in the SS header area and next to the SS header on the stagnant NaK side is shown in Figure 11 and 12 for the DES K. As compared to DES G, the effect of the DES K vacuum can placement is the SS header axial temperature gradient reduction from 492 to 55°F/in. and from 406 to 34°F/in. at transient and steady-state operating conditions respectively.

The stress analyses of the mercury inlet dome indicated that the initially proposed configuration would not meet the stress requirements. During the same period, a decision was made to replace the 4 stage turbine with a multi-stage reaction turbine. This change resulted in a decrease of the steady-state mercury inlet temperature from 420°F to 350°F. These two inputs prompted a redesign of the mercury inlet configuration. This design change is shown in Figures 13 and 14 as DES L.

The use of the vacuum cans, the location of the flowing NaK manifold (tee), etc. remained the same as that noted in DES K. However, the distance between the tantalum header and the mercury inlet bimetal tube was increased to accommodate the larger tantalum dome. The volume of the mercury in the dome was increased over DES.K which in turn increased the time to fill.

Table I shows a tabulation of the maximum axial temperature gradients of various mercury inlet and design configurations considered herein.

CONCLUSIONS AND RECOMMENDATIONS

The results of the boiler mercury inlet end thermal analysis under the prescribed start-up transient and steady-state operating conditions lead to the following conclusions and recommendations:

1. Because of relatively high temperature differences between the NaK heat source and the mercury heat sink the SS NaK shell tube, the SS header and the SS stagnant NaK containment tube are exposed to relatively high thermal gradients in the basic inlet end design configuration.

2. Under steady-state operating conditions the maximum thermal gradients are located in the structural elements next to the convective heat source,

3. Under start-up transient conditions the maximum thermal gradients are located in the structural elements next to the capacitative heat source,

4. Plausible thermal gradient reduction in the critical structural elements can be secured by selective utilization of vacuum can insulation,

5. To minimize the axial thermal gradient in the NaK shell the placement of vacuum can insulation on the ID of the NaK shell is recommended between the annular NaK exit manifold termination point and the mercury inlet SS plate,

6. The annular NaK exit manifold termination point is to be located in the radial plane next to the tantalum header in the downstream mercury flow direction. This annular manifold location will secure a symmetric thermal environment around the stagnant NaK volume between the two headers, and substantially reduce the temperature st ratifications in it,

7. To prevent possible free convection effects in the stagnant NaK volume the compartmentization of this volume is to be provided,

8. To secure the minimum axial and radial thermal gradients in the SS stagnant NaK containment tube and the SS header, the vacuum can placement on the Ta tubes in the SS header area is visualized as a most desirable design feature. Unless the Ta tube pitch diameter is modified to a larger value in the SS and Ta header area the vacuum can utilization on the Ta tubes can't be realized.

9. Because of relatively high thermal conductivity, the thermal gradients in the tantalum structural elements are expected to be within acceptable limits.

10. The recommended mercury inlet end design configuration and the associated thermal transient and steady-state conditions of the structural elements are depicted in Figures 1, 13 and 14 respectively.

11. The thermal mapping shown in Figures 13 and 14 is provided for the purpose of checking the boiler mercury inlet end structural reliability from the combined thermal and pressure stress viewpoint.

REFERENCES:

(a) "SNAP-8 12 Tube Boiler (BRDC #5) Design for Revised System State Point Conditions," 7978:70:0002, July 1, 1970.

(b) "PCS Startup Transients Affecting Boiler Inlet Section," EDS Serial No. SA-0051, June 2, 1970.

(c) H.F.Poppendiek, J.F.Brown, et al., "Investigation of SNAP-8 Boiler Conditioning and Heat Transfer Characteristics in a Mercury-Tantalum System," NASA-LeRC Contract NAS3-11836, Geoscience Final Report GLR-78

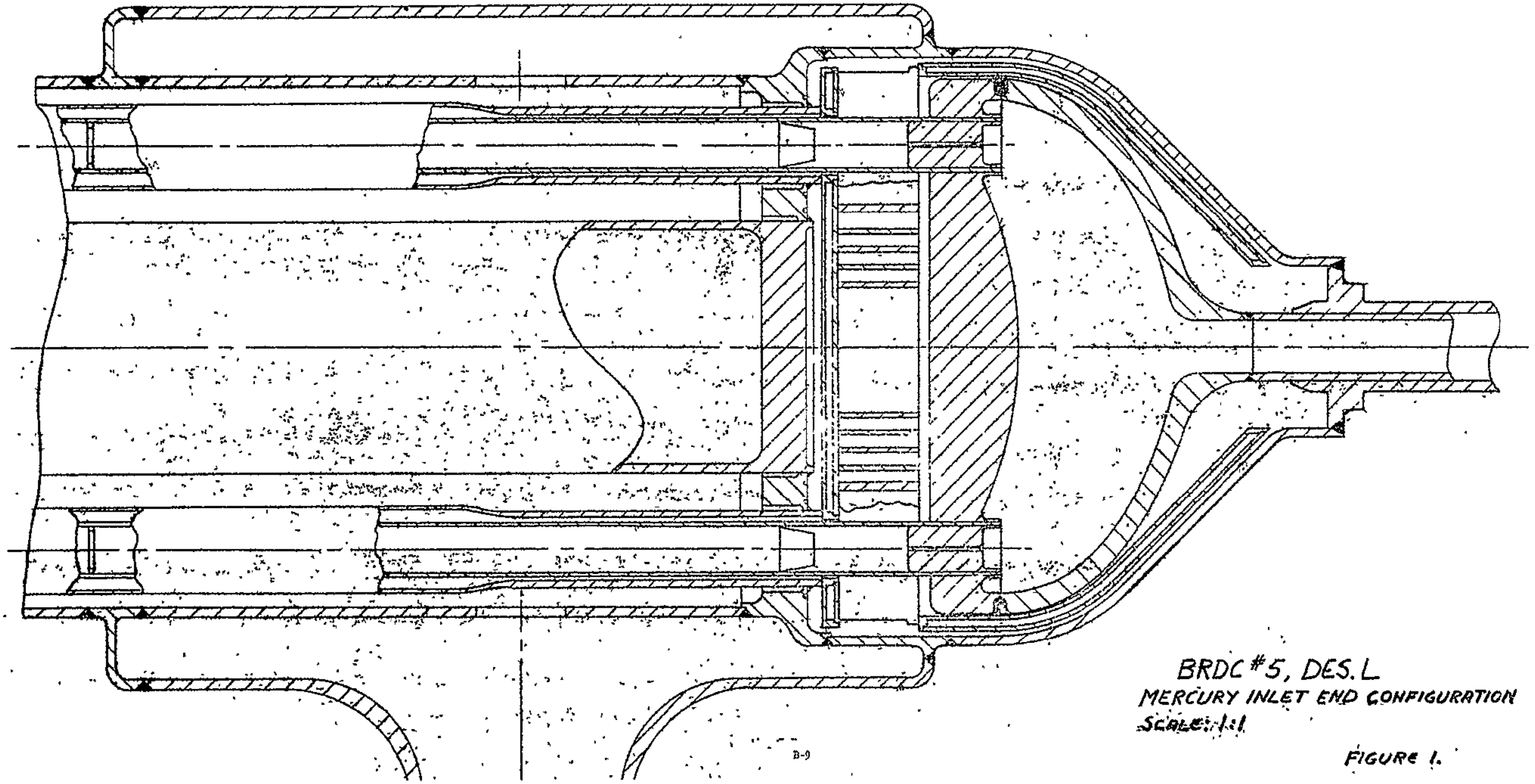
ENCLOSURES:

(1) Figure 1, Mercury Inlet End, Design Configuration, DES.L
(2) " 2, Typical Radial R-C Network, DES.L, KND = 1, 4 and 7.
(3) " 3, Typical Axial R-C Network, DES.L, KND= -3 through 21.
(4) " 4, BRDC #5 DES A, B, C, D, E, and F Thermal Map
(5) " 5, BRDC #5 DES G, SS Thermal Map
(6) " 6, BRDC #5 DES G, Ta " "
(7) " 7, BRDC #5 DES H, SS " "
(8) " 8, " " " " Ta " "
(9) " 9, " " DES J, SS " "
(10) " 10, " " " " Ta " "
(11) " 11, " " DES K, SS " "
(12) " 12, " " " " Ta " "
(13) " 13, " " DES L, SS " "
(14) " 14, " " " " Ta " "
(15) Table I, BRDC #5 - Temperature Gradients of Various Hg Inlet End Design Configurations

TABLE 1

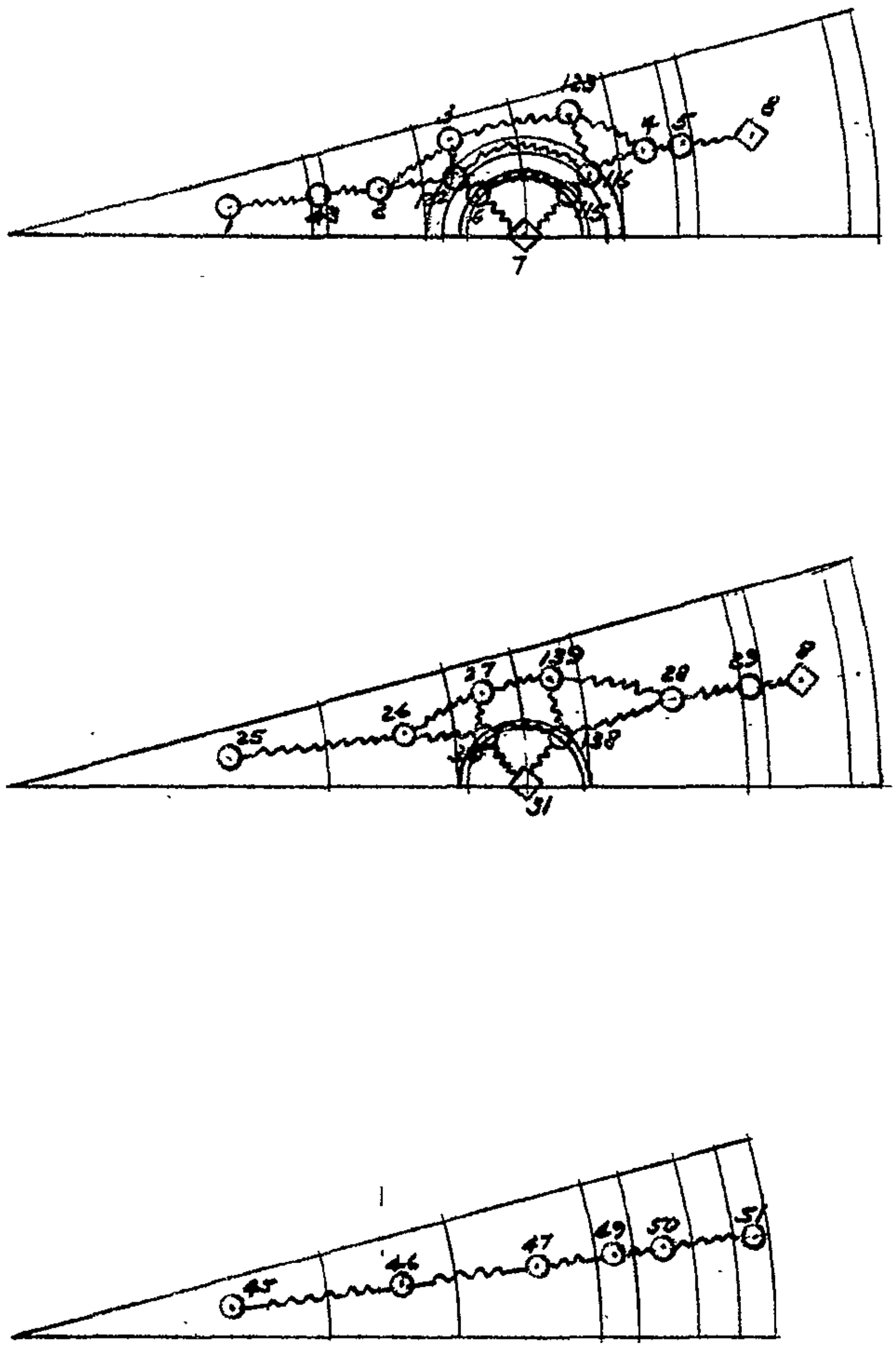
BRDC #5 - TEMPERATURE GRADIENTS OF VARIOUS HG INLET END DESIGN CONFIGURATIONS

DES.	REF. FIGURE	MAX. AXIAL TEMPERATURE GRADIENT, °F/IN										TIME REFERENCE		REMARKS
		NaK SHELL		STAG.NaK TUBE		TA TUBE		SS HEADER		TA HEADER		TRANSIENT	STEADY	
		T	S	T	S	T	S	T	S	T	S	T	S	
A	4		587						363				X	
B	4		649						372				X	
C	4		416						354				X	
D	4		364						348				X	
E	4		418						409				X	
F	4		508						455				X	
G	5,6	539	217	1034	757	502	317	588	409	*188	130	X	X	*Ta Bell
H	7,8	539	217	194	129	855	489	440	301	*188	133	X	X	*Ta Bell
J	9,10	539	217	1028	748	569	314	480	335	*188	125	X	X	*Ta Bell
K	11,12	539	217	394	308	917	498	55	34	*188	122	X	X	*Ta Bell
L	13,14	342	186	717	509	509	320	554	410	334	137			



BRDC #5, DES. L
MERCURY INLET END CONFIGURATION
SCALE: 1:1

FIGURE 1.



KND = 1

TH = .3125

KND = 4

TH = .4250

KND = 7

TH = .3750

BRDC #5

TYPICAL RADIAL R-C NETWORK DES. "L"

FIGURE 2

FOLDOUT FRAME 1

FOLDOUT FRAME 2

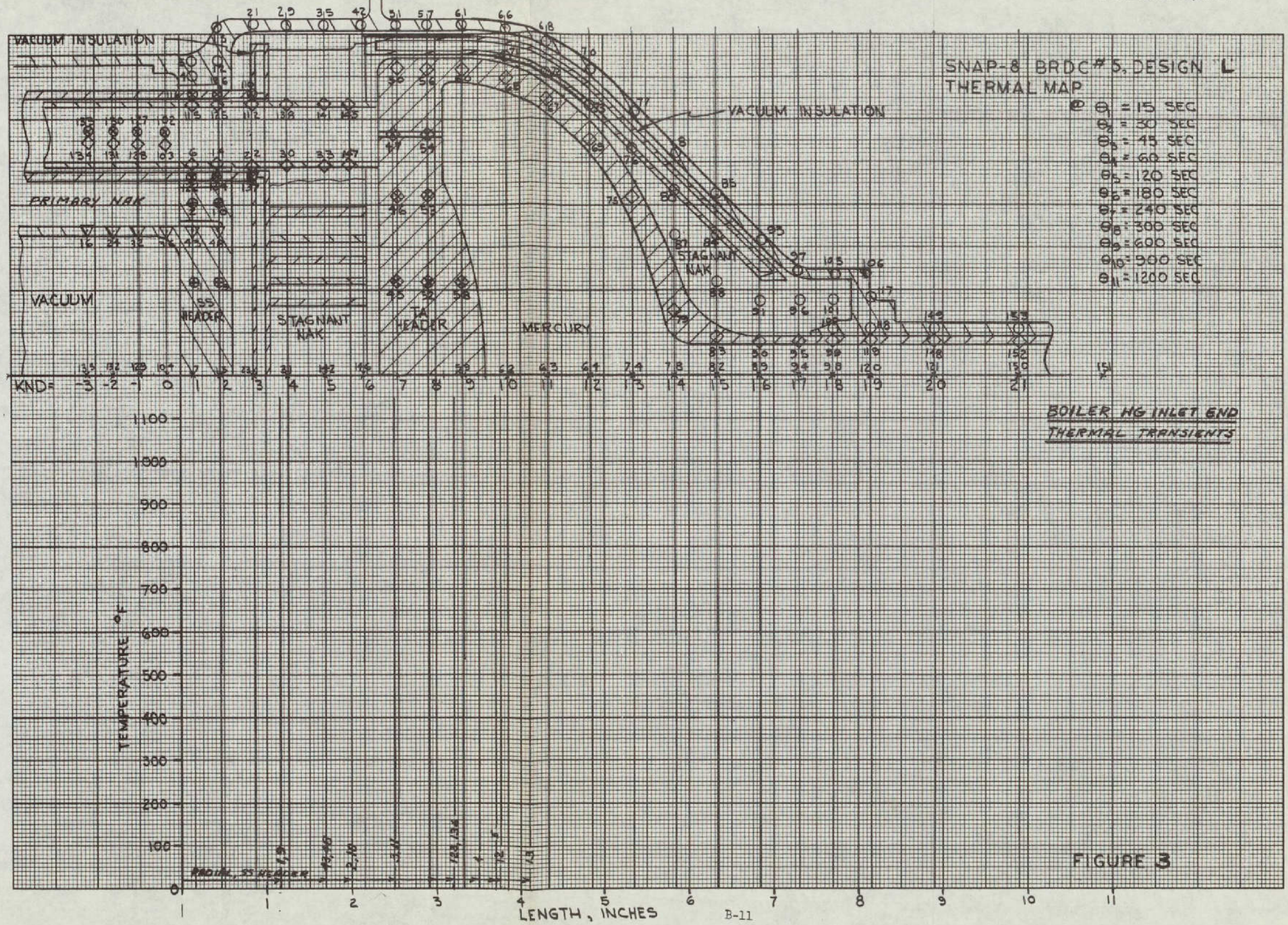


FIGURE 3

FOLDOUT FRAME 1

FOLDOUT FRAME 2

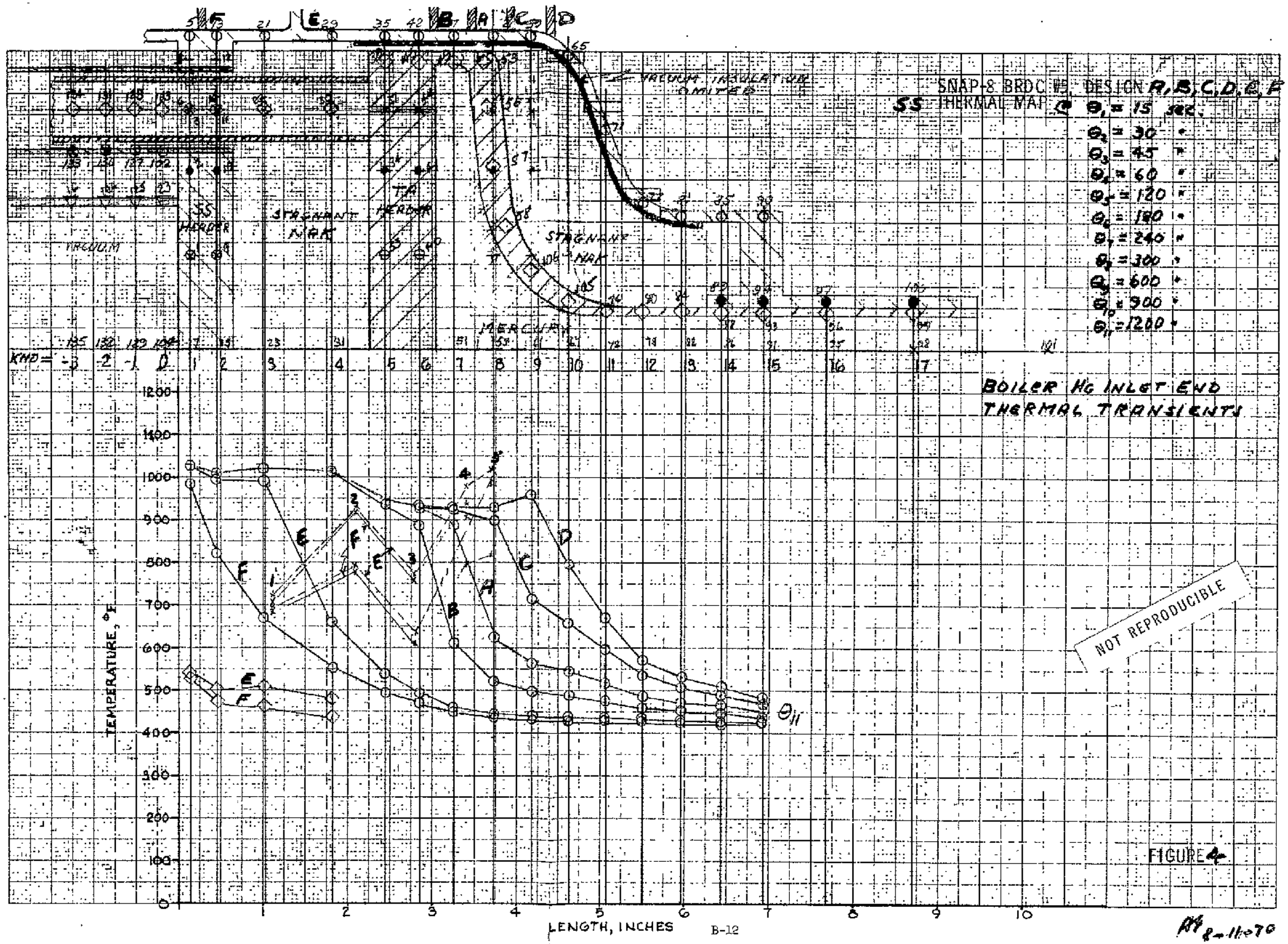


FIGURE 4

B-12

AA 8-11-70

FOLDOUT FRAME 1

FOLDOUT FRAME 2

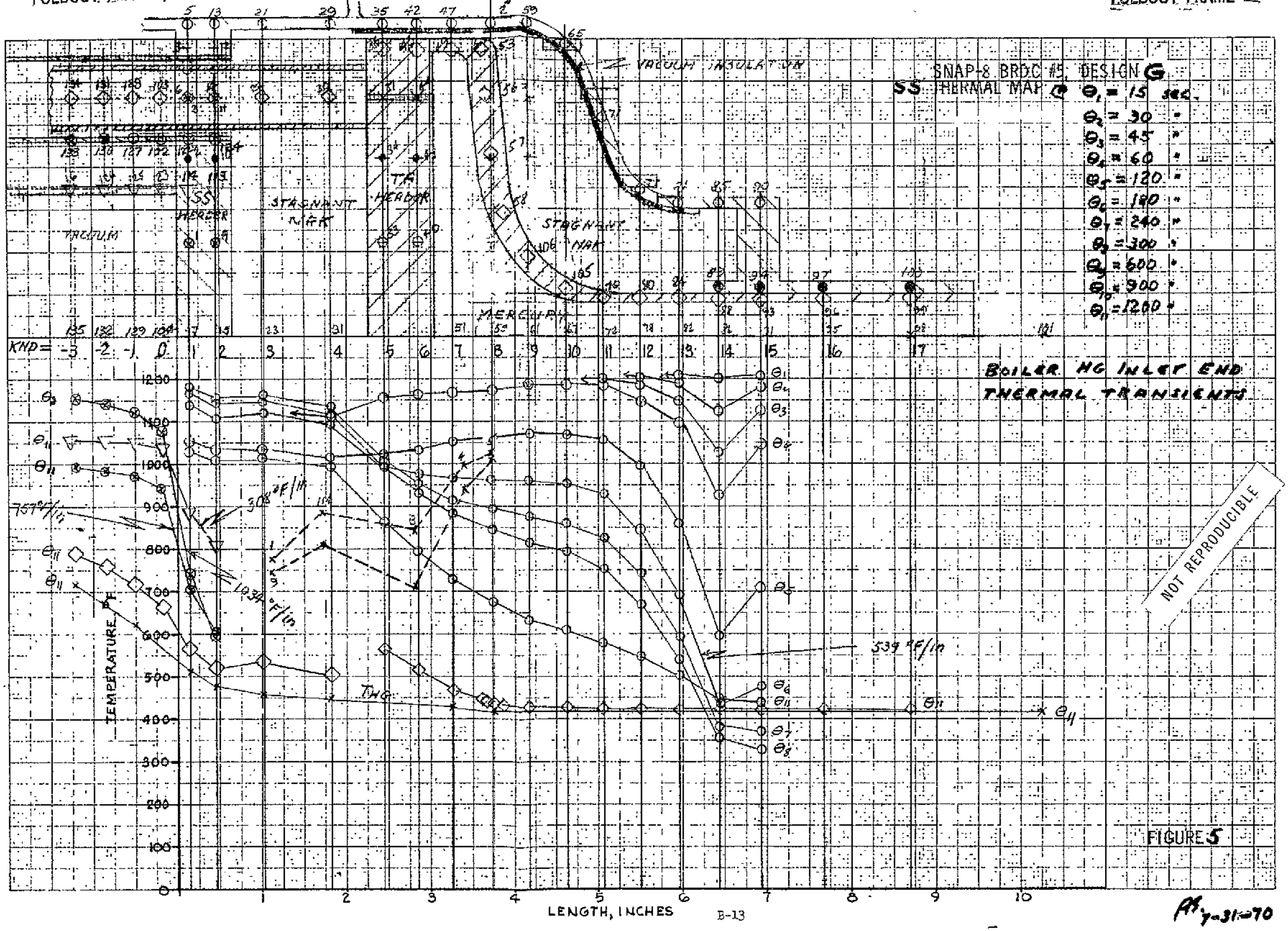


FIGURE 5

AT 7-31-70

FOLDOUT FRAME 1

FOLDOUT FRAME 2

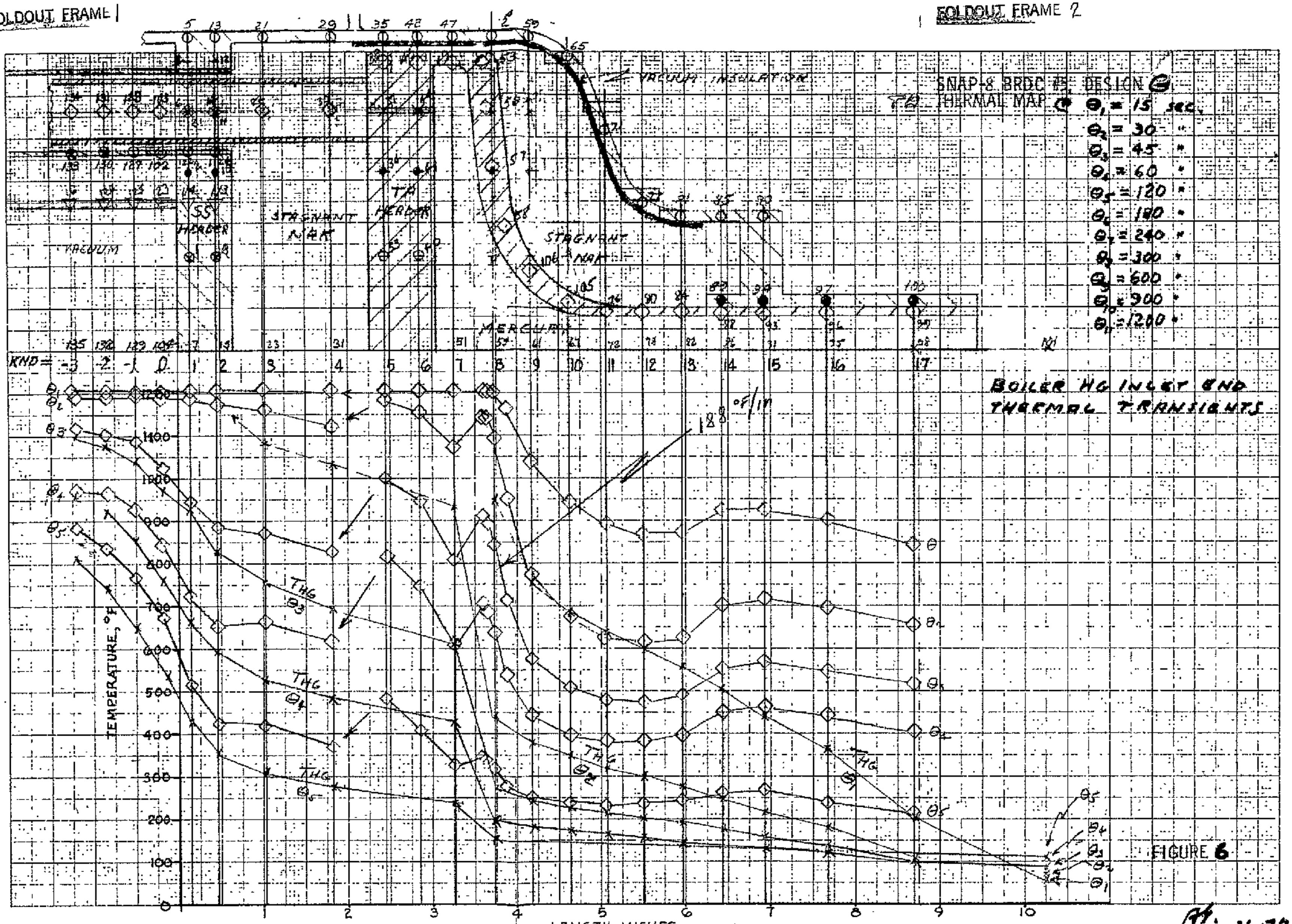


FIGURE 6

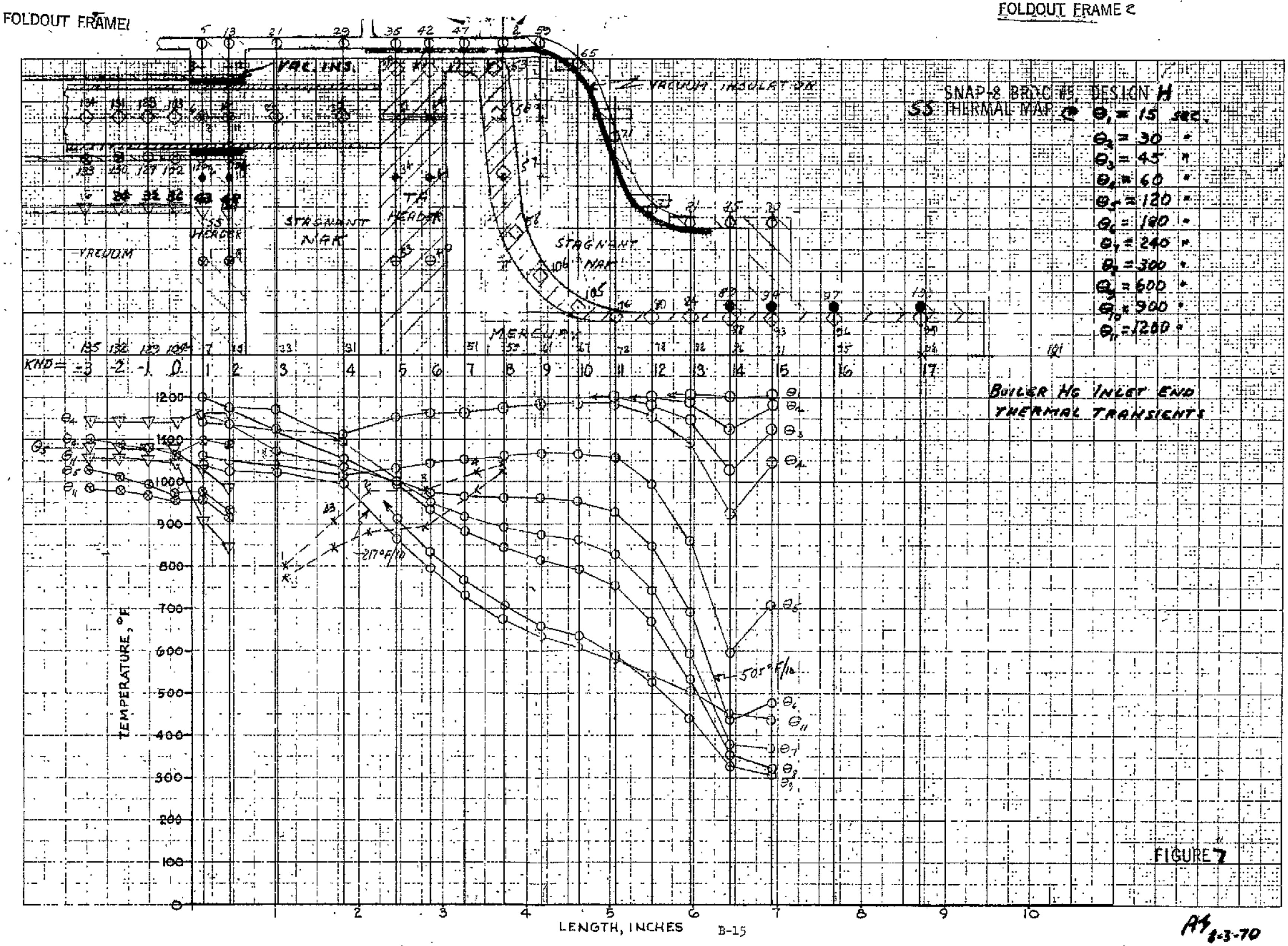
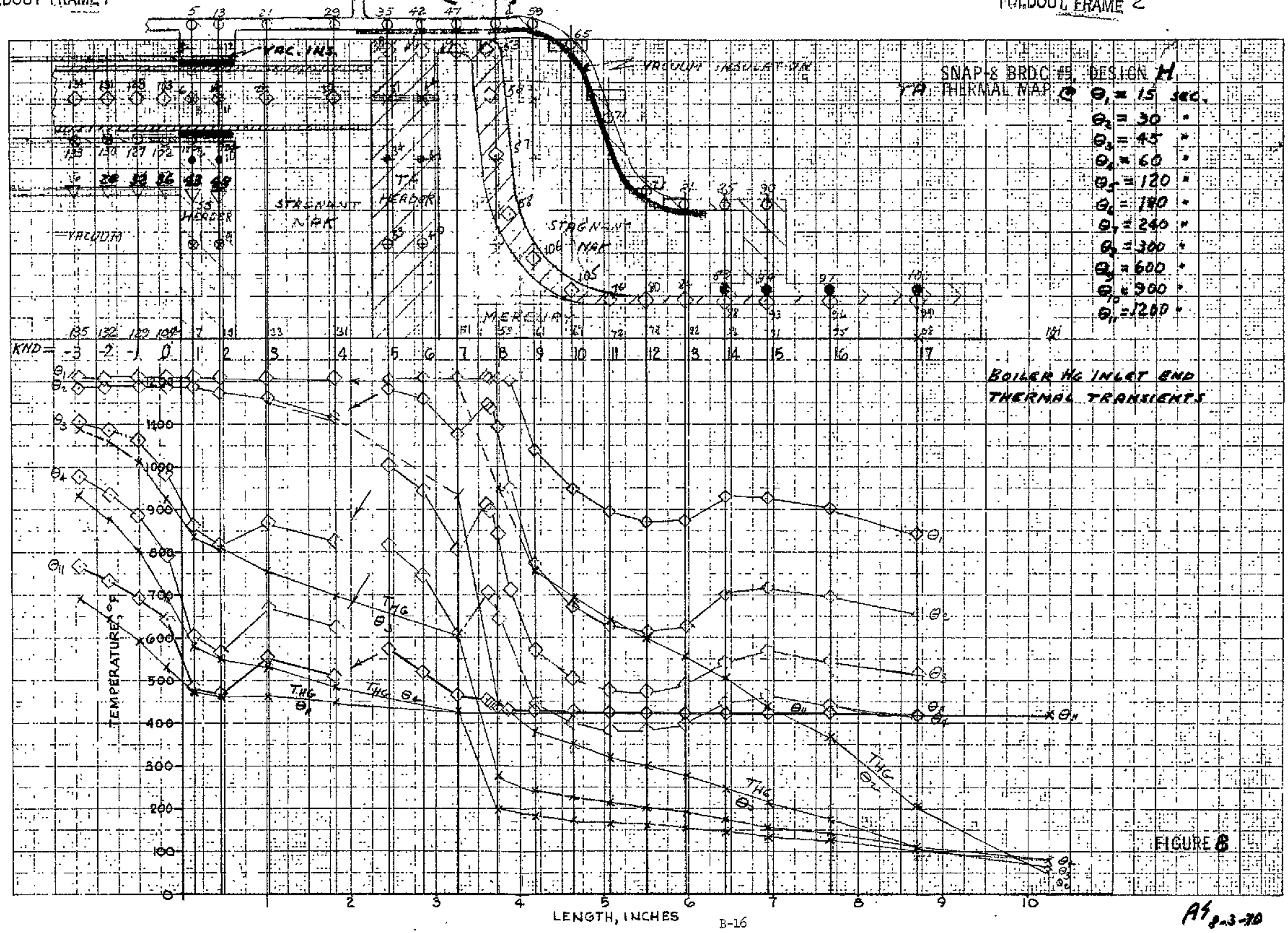


FIGURE 7

RS 8-3-70

FOLDOUT FRAME 1

FOLDOUT FRAME 2



AS 8-3-70

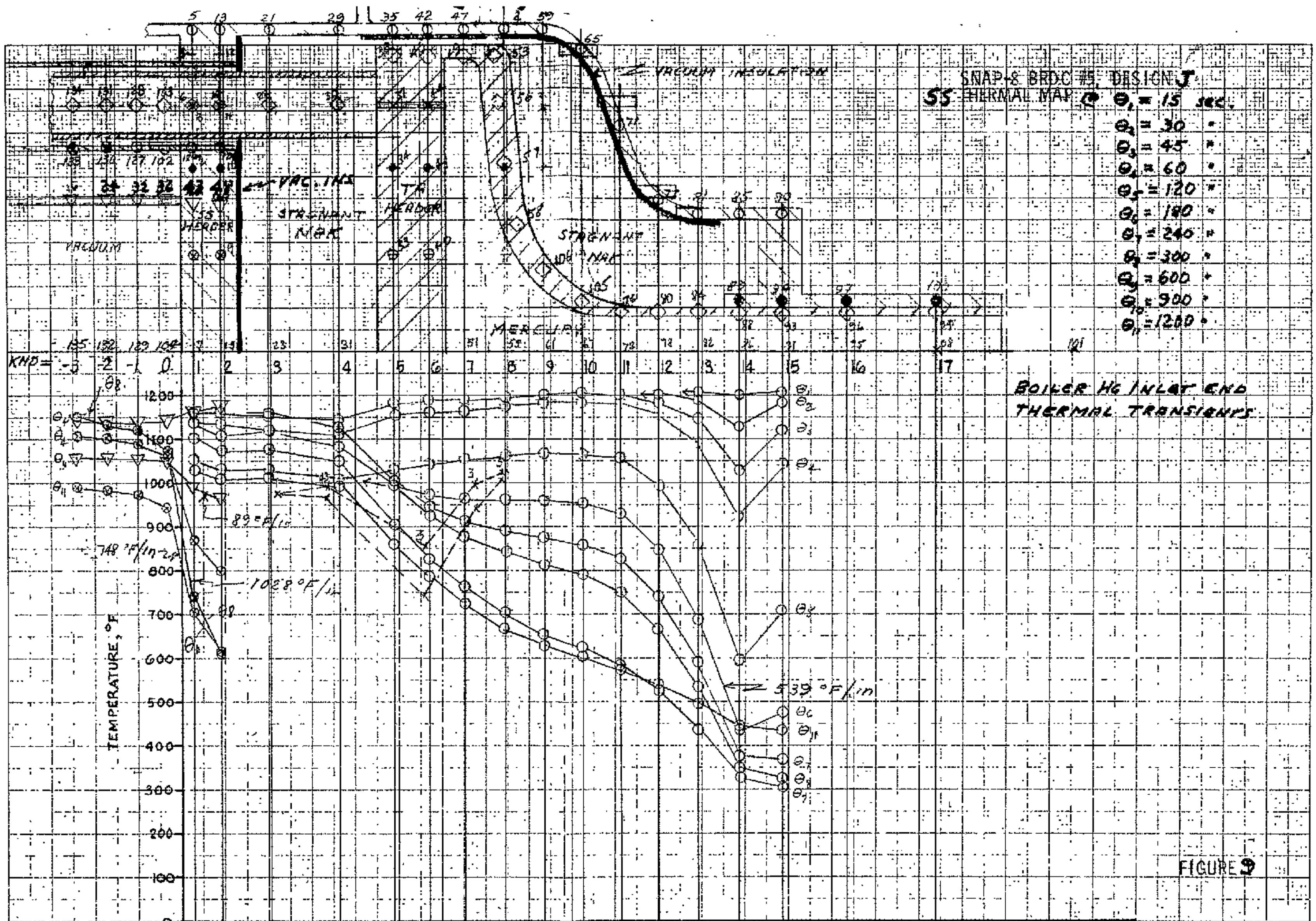

SNAP-8 BRDC #5, DESIGN J
55 THERMAL MAP @ θ1 = 15 sec.
θ2 = 30
θ3 = 45
θ4 = 60
θ5 = 120
θ6 = 180
θ7 = 240
θ8 = 300
θ9 = 600
θ10 = 900
θ11 = 1200
VACUUM INSULATION
VAC. INS
STAGNANT NaK
STAGNANT NaK
TR HEADER
HEADER
VACUUM
MERCURY
KNO =
BOILER Hg INLET END
THERMAL TRANSIENTS
89 °F/in
748 °F/in
1028 °F/in
539 °F/in
TEMPERATURE, °F
LENGTH, INCHES

FIGURE 9

FOLDOUT FRAME 1

FOLDOUT FRAME 2

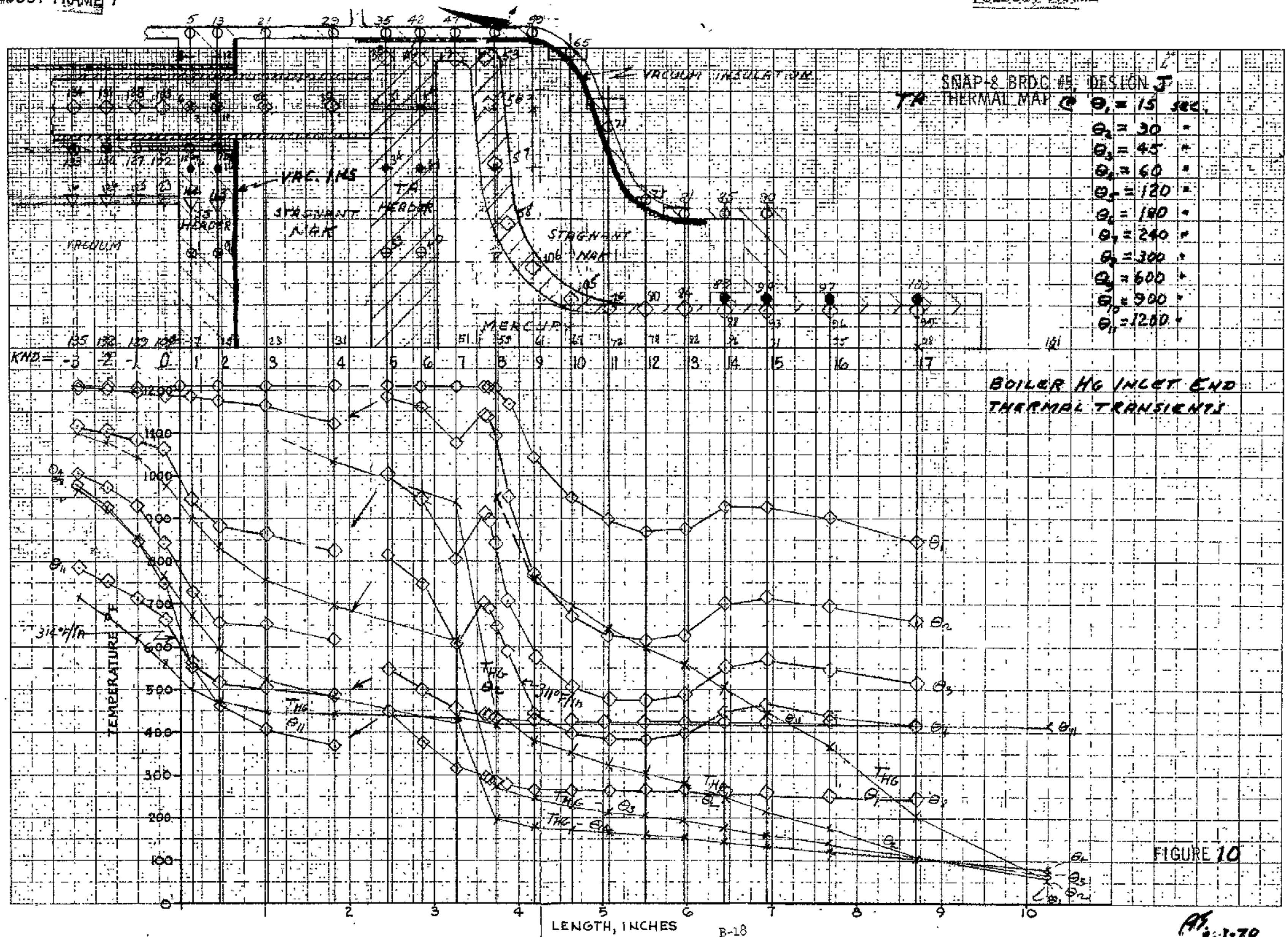


FIGURE 10

8-3-70

FOLDOUT FRAME 1

FOLDOUT FRAME 2

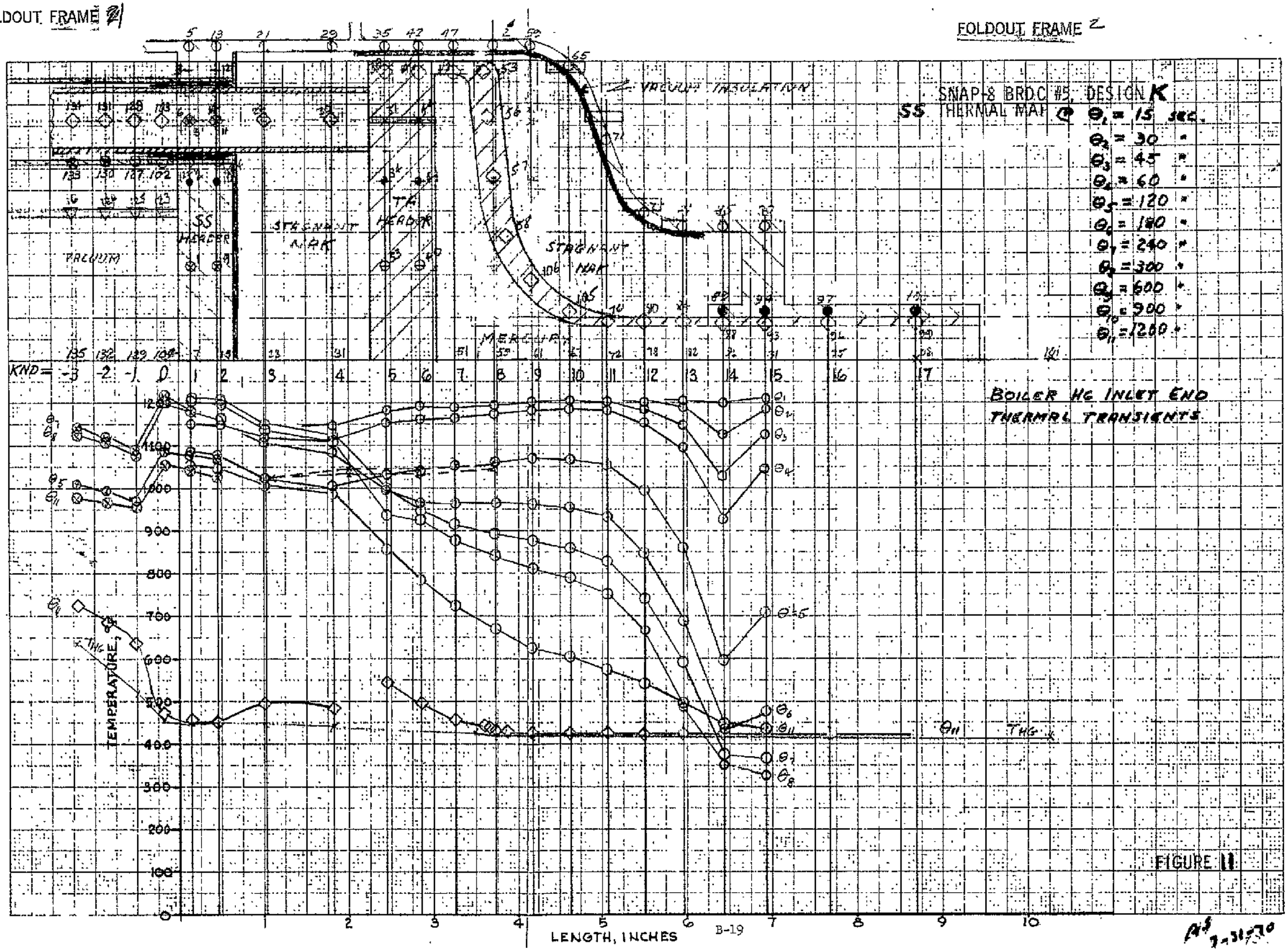


FIGURE 11

7-31-70

FOLDOUT FRAME 1

FOLDOUT FRAME 2

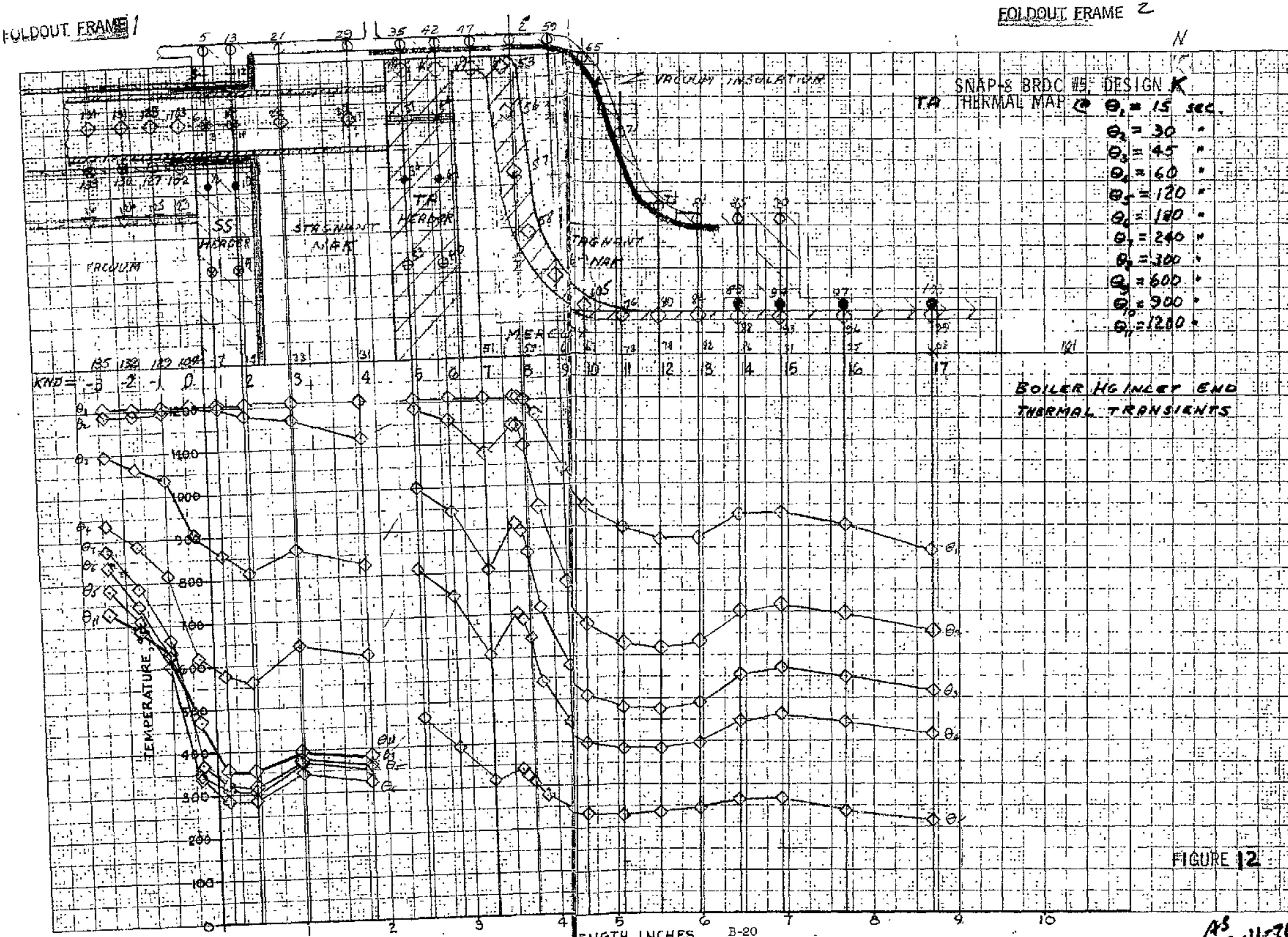


FIGURE 12

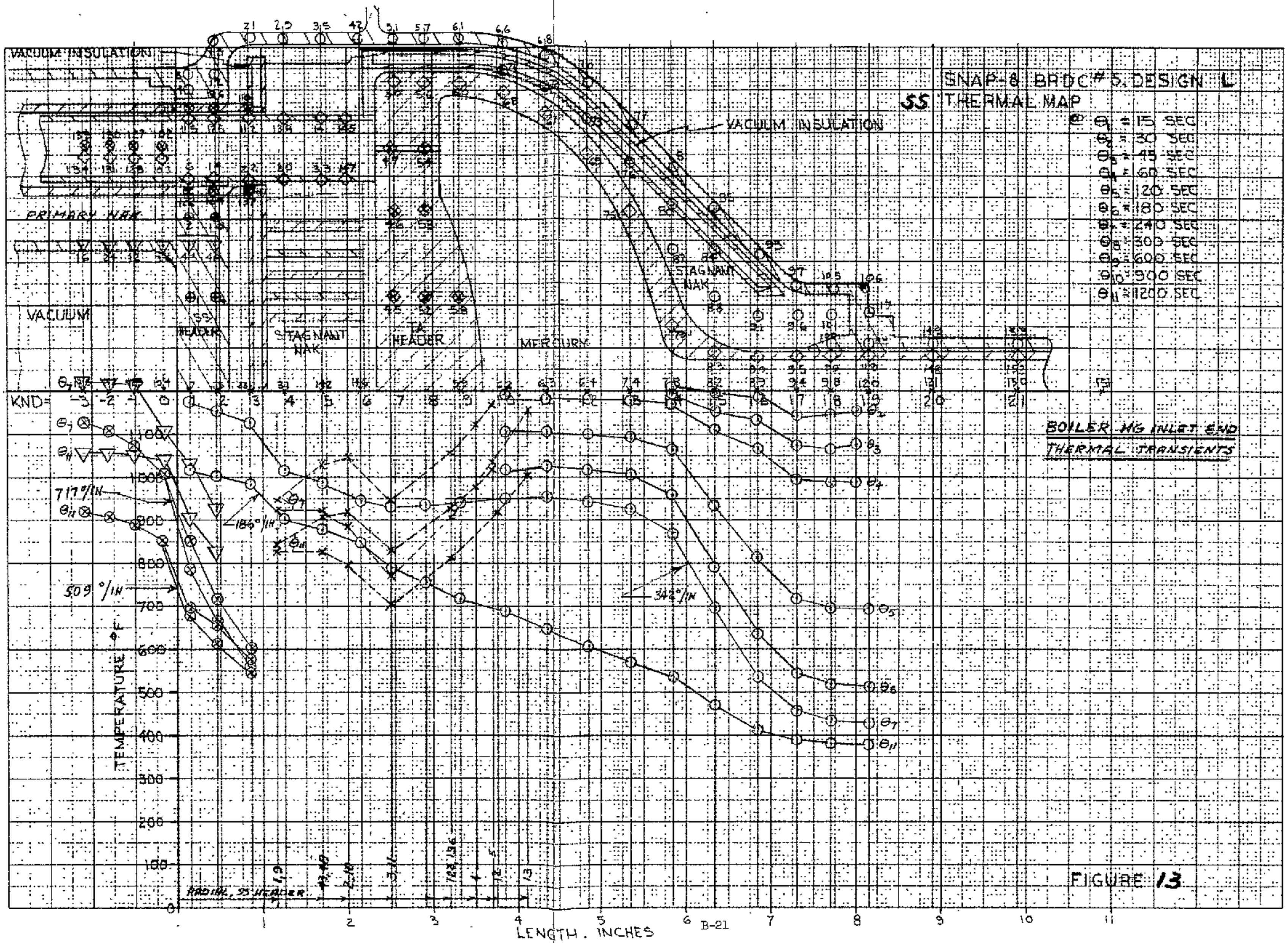

SNAP-8 BRDC #5 DESIGN L
SS THERMAL MAP
@ θ1 = 15 SEC
θ2 = 30 SEC
θ3 = 45 SEC
θ4 = 60 SEC
θ5 = 120 SEC
θ6 = 180 SEC
θ7 = 240 SEC
θ8 = 300 SEC
θ9 = 600 SEC
θ10 = 900 SEC
θ11 = 1200 SEC
VACUUM INSULATION
PRIMARY NAK
VACUUM
SS HEADER
STAGNANT NAK
TA HEADER
MERCURY
BOILER HG INLET END THERMAL TRANSIENTS
717°/IN
509 °/IN
184°/IN
342°/IN
TEMPERATURE °F
LENGTH, INCHES
RADIAL SS HEADER
KND=

FIGURE 13

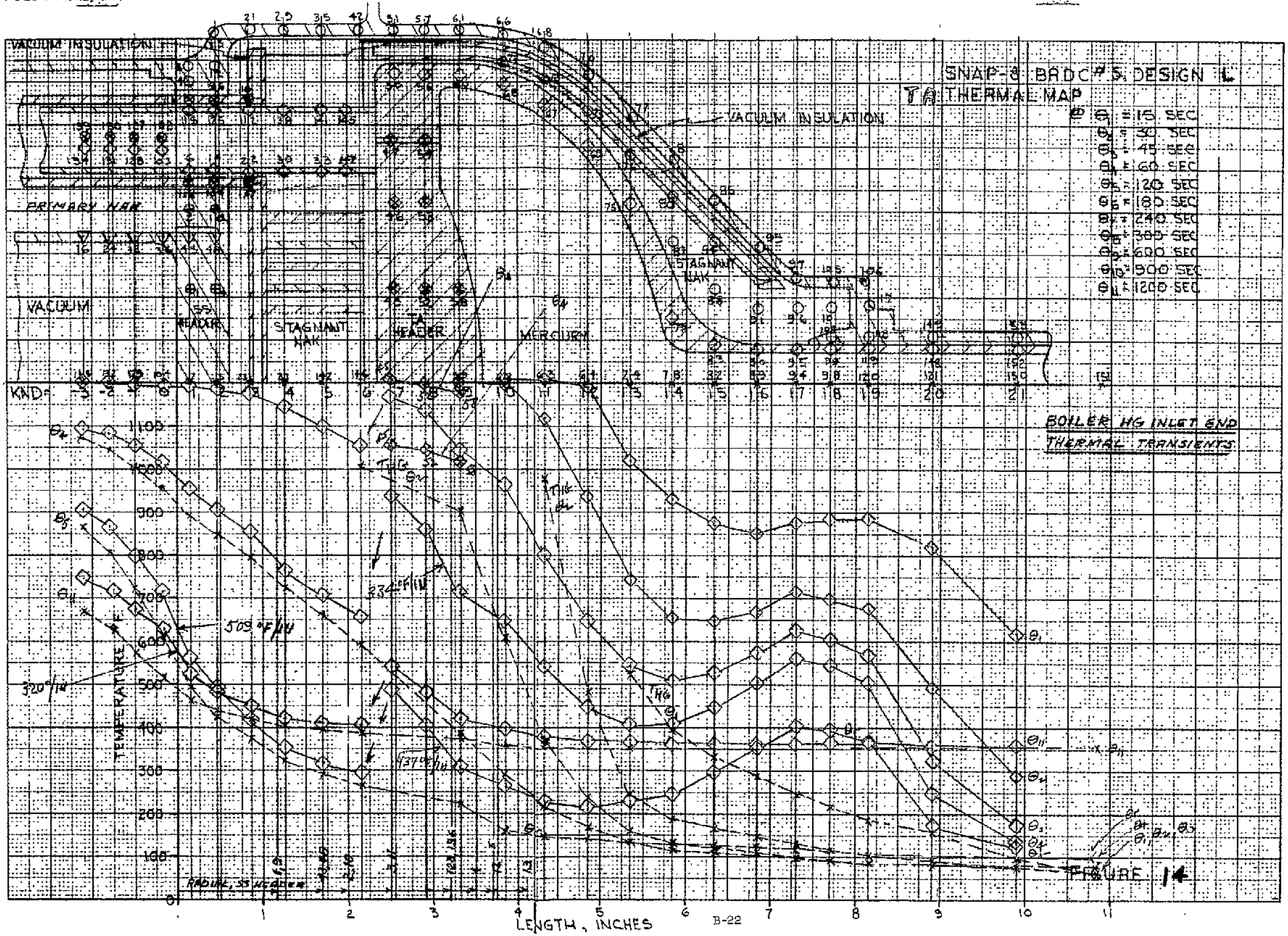
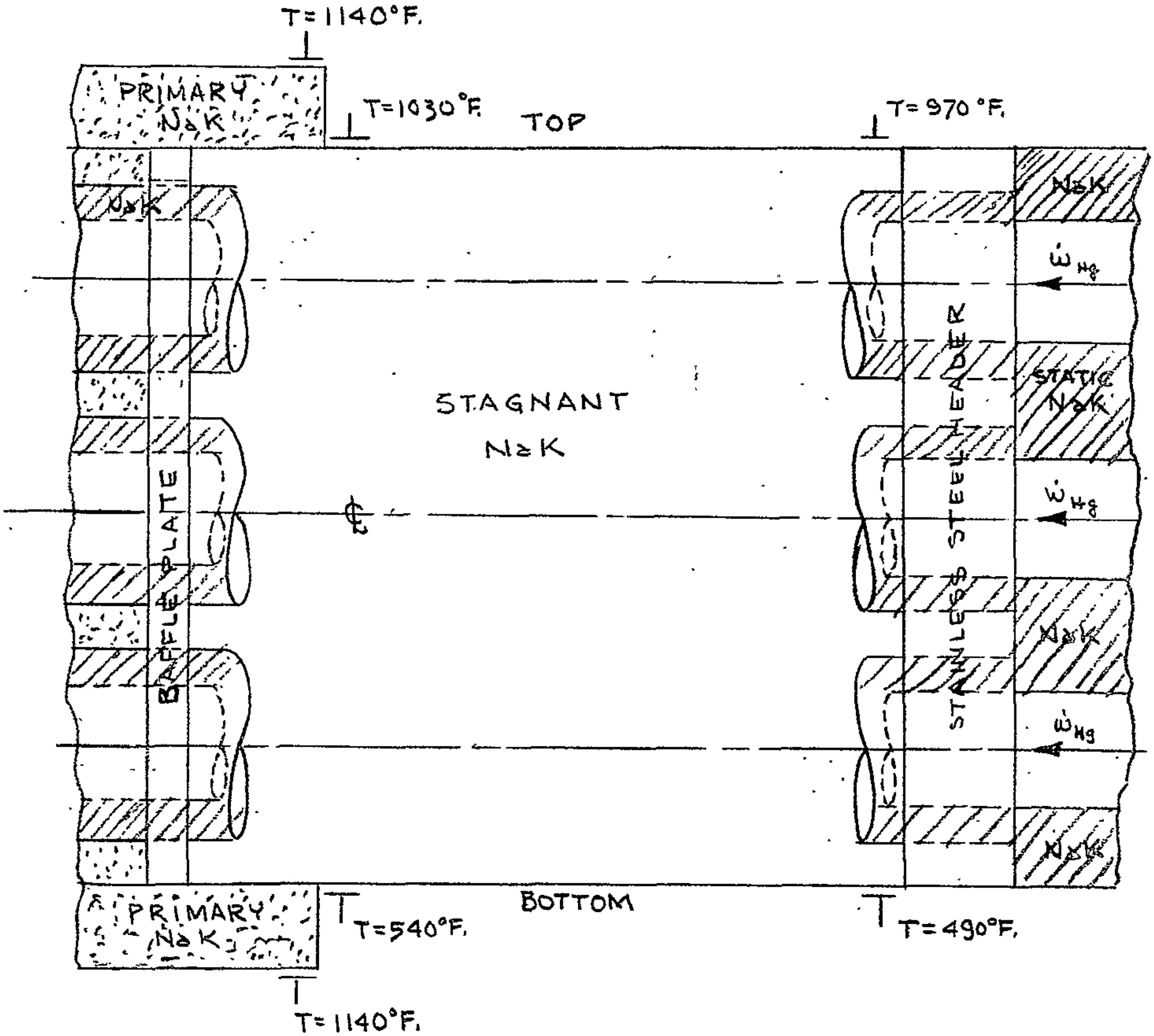

SNAP-8 BRDC #5 DESIGN L
TA THERMAL MAP
θ1 = 15 SEC
θ2 = 30 SEC
θ3 = 45 SEC
θ4 = 60 SEC
θ5 = 120 SEC
θ6 = 180 SEC
θ7 = 240 SEC
θ8 = 300 SEC
θ9 = 600 SEC
θ10 = 900 SEC
θ11 = 1200 SEC
VACUUM INSULATION
PRIMARY NAK
VACUUM
HEADER
STAGNANT NAK
TA HEADER
MERCURY
KND=
BOILER HG INLET END
THERMAL TRANSIENTS
TEMPERATURE °F
LENGTH, INCHES
RADIAL .55 HEADER
509 °F/IN
834 °F/IN
320 °/IN
437 °F/IN

FIGURE 14

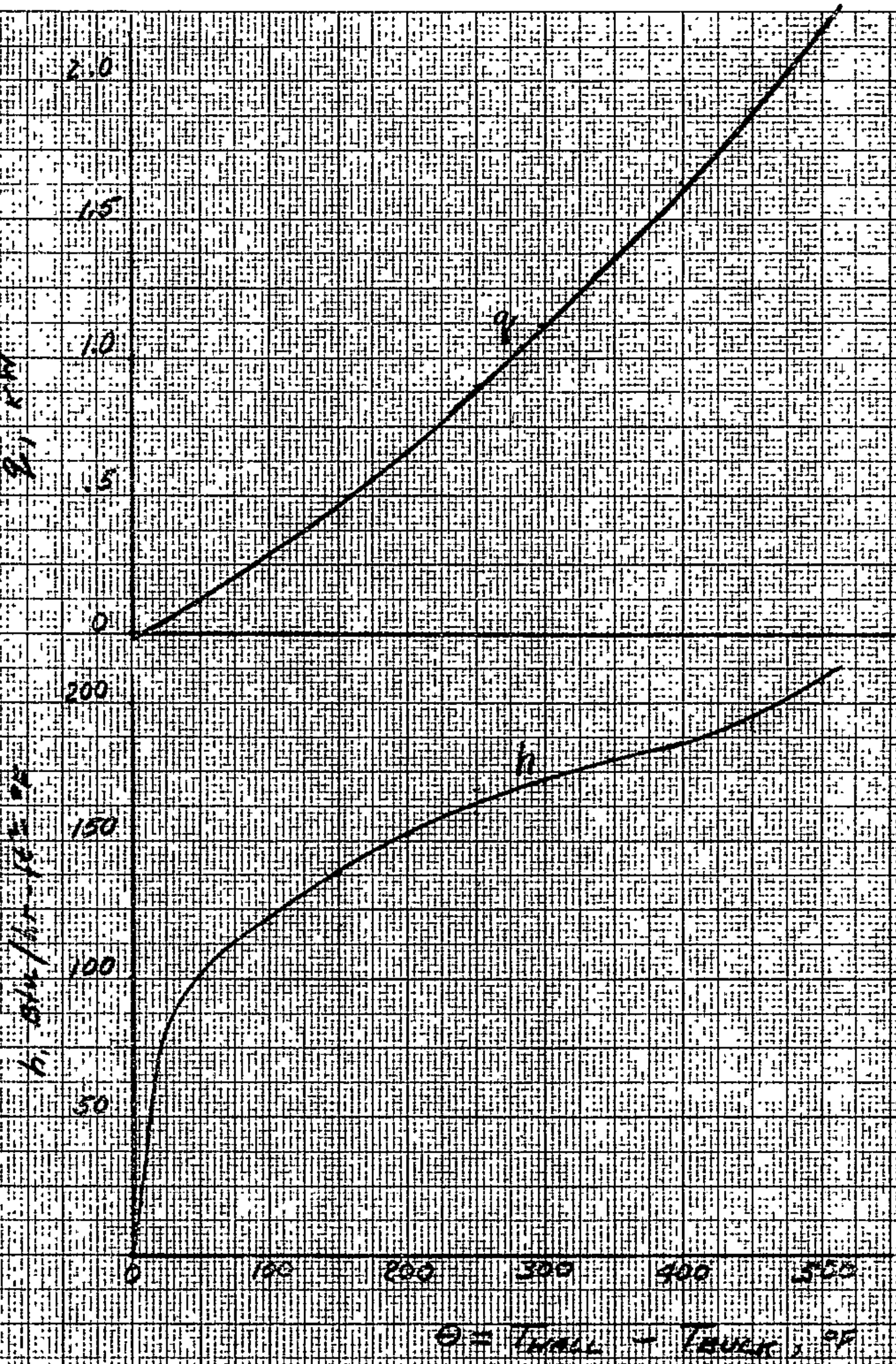
Subject: Interpretation of BRDC #4 Mercury Inlet End NaK Shell-Tube Surface Temperature Measurements

Analysis of boiler BRDC #4 mercury inlet end NaK shell-tube temperature measurement leads to the conclusion that the relatively large stagnant NaK volume contained between the vertical baffle plate and header in the horizontally located NaK shell-tube mercury inlet end is condusive to free convection and body force effects of the NaK. Free convection is induced by a ~~relatively~~ high baffle plate wall temperature (1140°F). The body force (buoyancy) and resulting NaK temperature stratification is caused by the heat sink (Hg tube bundle) placed in the NaK volume. To eliminate non-symmetric NaK shell-tube temperature distribution, the honeycombing of the stagnant NaK volume is recommended for the purpose of providing a conductive heat transfer pass. Typical BRDC #4 temperature distribution is shown in enclosure (1). Utilizing the liquid metal free convection heat transfer correlations, the possible film inductances (h) and heat flow rates (q) are shown in Enclosure (2) for a range of wall-to-bulk temperature differences derived from Enclosure (1).

Based on the above analysis, it is concluded that BRDC boiler #5 with its honeycomb structure in this are and the envelopment of the area with the flowing NaK in the tee and the incorporation of evacuated baffles, that the problem of natural or free convection of the static NaK will be eliminated.



SCHEMATIC VIEW OF BRDC BOILER #5
SKIN TEMPERATURE MEASUREMENTS
AT MERCURY INLET END DURING
TEST



FREE CONVECTION FILM CONDUCTANCE (h) AND HEAT TRANSFER RATE (q) VS. WALL-TO-BULK TEMPERATURE DIFFERENCE (θ)

FREE CONVECTION HEAT TRANSFER ACROSS FLOWING NAK STAGNATION PLATE OF BRDC #1

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS
ENGINEERING DESIGN FILE

PROJECT SNAP-8

ENGINEERING FILE NO.
EDF SERIAL NO. DE 0026
DATE 7-30-70
W. O. NO. 1475-44-0117

SUBJECT

BRDC BOILER NO. 5, DIFFERENTIAL THERMAL EXPANSION BETWEEN STATIC NaK TUBE AND Ta TUBE

ABSTRACT

Analytical calculations to determine the subject differential thermal expansion are presented. The maximum differential thermal expansion at the steady state temperature of 1210°F is 0.287 in. per 180° turn or 0.574 in. total across the boiler.

The oval static NaK tube is designed for a 0.602 in. movement of the tantalum tube within it. This results in a 0.314 in. margin over that required. The extra clearance provides for ease of fabrication and the possibility of over-temperature excursions.

DISTRIBUTION R. Alena, B. Breindel, E.S.Chalpin, C.Hawk, G.L.Lombard, U.A.Pineda, R. W.Marshall, Jr.

COVER SHEET ONLY

J.Hodgson, A.H.Kreeger, L.Lopez

KEY WORDS BRDC Boiler No. 5, Differential Thermal Expansion
Static NaK Tube Ta Tube

AUTHOR		DEPT	REVIEWED	DATE	REVIEWED	DATE
R.Alena	R. Alena	7978	E S Chalpin	8/4/70	R W Marshall	8/4/70

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

QUADRILLE WORK SHEET

DATE 30 July 1970

SUBJECT BRDC BOILER NO. 5 BY R. ALENA WORK ORDER 1475-44-0117

DETERMINATION OF DIFFERENTIAL THERMAL EXPANSION BETWEEN STATIC NaK TUBE & Ta TUBE

A. GIVEN DATA

$\Delta T = 1210°F - 75°F = 1135°F$

MEAN COEFFICIENT OF THERMAL EXPANSION AT 1210°F

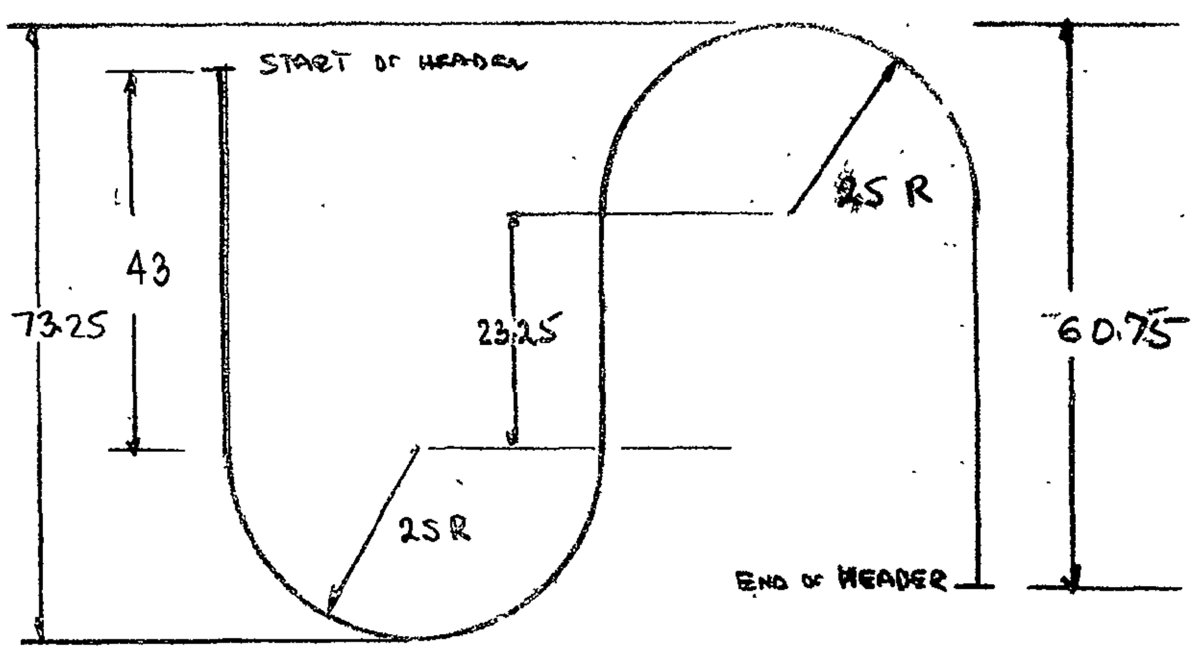
$\alpha_{TANTALUM} = 3.8 \times 10^{-6}$ in/in - °F MIN
3.89×10^{-6} in/in - °F MAX

$\alpha_{CRES} = 10.25 \times 10^{-6}$ in/in - °F MIN
10.80×10^{-6} in/in - °F MAX

MATERIALS:

7.5" OD SHELL —	321 CRES
DUAL TUBES (12)	316 CRES
Hg - .750D TUBES (12)	TANTALUM

B. BOILER #5 DIMENSIONS



73.25" DIMENSION IS THE MAX. LINEAR DIMENSION

C. DIFFERENTIAL GROWTH FOR THE MAX. LINEAR DIMENSION OF THE BOILER (73.25")

$\Delta L_{Ta} = (3.89 \times 10^{-6})(73.25)(1135) = 0.323''$ MAX

$\Delta L_{ss} \; (10.80 \times 10^{-6})(73.25)(1135) = 0.898''$ MIN

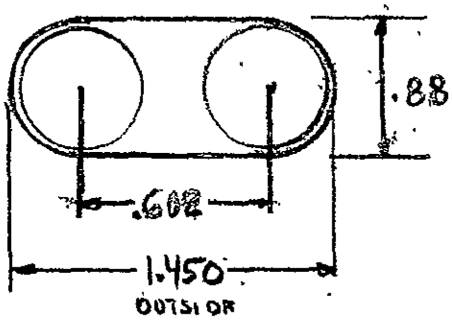
$\Delta L_{max} = 0.575$ in

$\Delta L_{Ta} \; (3.8 \times 10^{-6})(73.25)(1135) = 0.316''$ MAX

$\Delta L_{ss} \; (10.25 \times 10^{-6})(73.25)(1135) = 0.852''$ MIN

$\Delta L_{min} = 0.536$ in

D. ALLOWANCE PROVIDED IN THE OVAL TUBES FOR DIFFERENTIAL THERMAL EXPANSION



OVAL TUBE = WALL .049"
TANTALUM Hg TUBE = .750" OD

1.450 - OUTSIDE
- .098 2 WALLS
1.352
- .750 Hg TUBE
0.602

ACTUAL AMOUNT ALLOCATED FOR DIFFERENTIAL EXPANSION IS 0.602 IN PER ONE TURN OF THE OVAL TUBE
MAX. DIFF. EXPANSION TO ALLOW FOR IS 0.575 IN FOR 2 - 180° TURNS
EXTRA CLEARANCE $= .602 - \frac{.575}{2} = 0.314$ IN. IN OVAL TUBE
USE $1\frac{3}{16}$" O.D. X 0.049 WALL 321 SS TUBE TO FORM OVAL TUBE AS SHOWN ABOVE.

APPENDIX C

MERCURY SIDE BOILER PRESSURE DROP ANALYSES

INTEROFFICE MEMORANDUM

AEROJET NUCLEAR SYSTEMS COMPANY

7996:70:0856:GLL:plb

Date: 1 September 1970

TO: E. S. Chalpin

FROM: G. L. Lombard

SUBJECT: Predicted Boiler Pressure Drop with a Multipassage Plug Insert Length of 2.7 ft and 12 Tubes.

DISTRIBUTION: A. H. Kreeger, A. J. Sellers, File
NASA/LeRC - E. R. Furman

A. INTRODUCTION

The following analysis was made in order to establish the effects of varying multipassage plug insert length, NaK inlet temperature and NaK flow on the boiler Hg-side pressure drop. From the test data on boilers with 4.0 ft, 3.5 ft and 3.0 ft multipassage plug inserts, it was noted that the boiler pressure drop versus mercury flow increases with flow to a maximum value then decreases as the flow is increased further. It has been concluded that this pressure drop versus flow behavior is characteristic of this mercury side geometry, namely, a multipassage plug insert and a bare tube with a swirl wire. From the test operations it was also gleaned that system control, i.e. NaK heater response, was difficult to maintain when the system was operated in the range where the boiler pressure drop decreased with increased mercury flow. Whether this is a detrimental effect when the system is tested with a reactor is not known at this time. However, it is felt that it would be desirable to have a boiler that would have, at all conditions, an increasing pressure drop with increasing mercury flow.

In order to accomplish this it is necessary to place a flow restrictor at the inlet of each boiler tube. The size of the restrictor flow path would be such that when its pressure drop is added to the boiler pressure drop, the total Δ P would increase as the flow was increased. Stated mathematically:

$$\frac{\partial(\Delta P)_T}{\partial \dot{W}_H} \geq 0; \text{ FOR } 0 < \dot{W}_H < \dot{W}_{H(MAX)}.$$

However, before an inlet flow restrictor can be designed for a particular boiler design, the boiler pressure drop versus Hg flow function must be known. The remainder of this report describes the method used to extrapolate data on plug lengths that have been tested to determine performance of shorter plug inserts considered for use in future boilers. Ultimately, the information will allow an optimum choice of restrictor size to be made for a given boiler design.

B. DATA

Plotted in Figure 1 is BRDC Boiler #2 pressure drop (less restrictor ΔP) versus liquid mercury flow at NaK side flow and inlet temperature of 48500. lb/hr and 1310°F, respectively. Figure 2 shows the data taken on the SB-2 Boiler, tested at AGN, San Ramon, at the same NaK conditions. BRDC Boiler #4 data at NaK flows and inlet temperatures from 48000 to 27000 lb/hr and 1300°F to 1150°F, respectively, are presented in Figures 3,4 & 5. Each boiler tested had plug inserts of different length per the following:

Boiler #2	-4.0 ft
Boiler #4	-3.5 ft
SB-2	-3.0 ft

Figure 6 compares the pressure drop versus liquid mercury flow for the three boilers at the same NaK conditions of flow & temperature. It should be noted that the NaK flow and mercury flow are stated in terms of lb/hr/tube so that the pressure drop can be compared on an equal basis regardless of the number of tubes. Also shown in Figure 6 is a dashed line drawn through the peaks or inflection points of each curve. A review of figures 3 to 5 shows that the liquid Hg flow at which these peaks occur is a function of the NaK flow and NaK inlet temperature and from Figure 6 is also a function of plug insert length. It is important in the choice of a flow restrictor to know this peak Δ P and the liquid mercury flow at which it occurs for a given plug insert and different NaK flows and inlet temperatures. The curves shown in Figures 1 & 2 for the #2 and SB-2 boilers, respectively, represents all of the relevant data available for these two boilers.

C. METHOD

1. Neglect the difference in boiler lengths between #2, SB-2 & #4 boilers since the largest percentage of boiler Δ P occurs in the plug insert.

2. Plotted in Figure 7 are curves of peak pressure drop versus plug insert length. The curve for TNBI = 1300°F was established from Figure 6 using the peak pressure drop established by the dashed straight line intersecting the pressure drop versus flow rate curves. The curves for 1250, 1200, and 1150°F were drawn parallel to the 1300°F curve and used Boiler #4 data only, since that was the only data available. (NaK flow is constant at 6860. lb/hr/tube).

3. Figure 8 was generated using the data from Figure 6 for 1300°F and Figure 7. The lines of constant TNBI are drawn parallel to one another. The curve of peak pressure drop vs. peak flow for Boiler #4 was first plotted (from Figure 3). Then Boiler #2 & SB-2 values at 1300°F & 6860 lb/hr/tube were plotted (from Figure 6). Next the constant temperature lines were drawn. Then the peak pressure drop values (from Figure 7) were laid in on the constant temperature lines and connected with the curved lines.

4. Figure 9 was generated in a similar manner to Figure 7. First, the curve for 1300°F and 6860. lb/hr/tube was plotted using Figure 6 points at the intersection of the dashed line and the pressure drop vs. liq. flow curves.

Then the curves for 1250, 1200, 1150°F and 6860. lb/hr/tube were plotted and are the same lines as given in Figure 7. The curves for 5360. & 3930. lb/hr/tube & 1300, 1250, 1200 & 1150°F were drawn parallel to their corresponding curve at 6860. lb/hr/tube using Boiler #4 data points.

5. Figure 10 through 13 show variations of peak pressure drop versus peak liquid mercury flow for TNBI = 1300, 1250, 1200 and 1150°F with variation of NaK flow from 3930 to 6860 lb/hr/tube and plug insert lengths of 2.2 ft to 4.0. As an example, let us look at Figure 10 for 1300°F. First plot the peak pressure drop versus peak liquid flow for the 3.5 ft plug insert (Boiler #4) from Figures 3,4 and 5 for 1300°F and NaK flows of 6860, 5360 & 3930 lb/hr/tube. Next plot from Figure 8 the points for the 4.0 ft, 3.0 ft and 2.2 ft at 1300°F and 6860 lb/hr/tube and connect them with a line (which is straight). Then draw lines for 5360 & 3930 lb/hr/tube parallel to the 6860 lb/hr/tube line through the 3.5 ft plug data. Finally, using Figure 9, pick off the necessary points to complete the plot. A similar procedure is used in generating the remaining plots for 1250, 1200 & 1150°F.

6. Plotted in Figure 14 is the pressure drop versus liquid Hg flow for the new PCS-G statepoint and new boiler with 12 tubes. The blacked-in triangles were interpolated from the plots in Figures 10 through 13 for the 2.7 ft plug. The open triangles are from the BODEPE computer program.

7. Table 1, 2 & 3 are the data listings for Boiler SB-2, #2 & #4 respectively. Also included are the PHBO versus liquid Hg flow curves used as a guide in making corrections to flow rates which seemed to be in error.

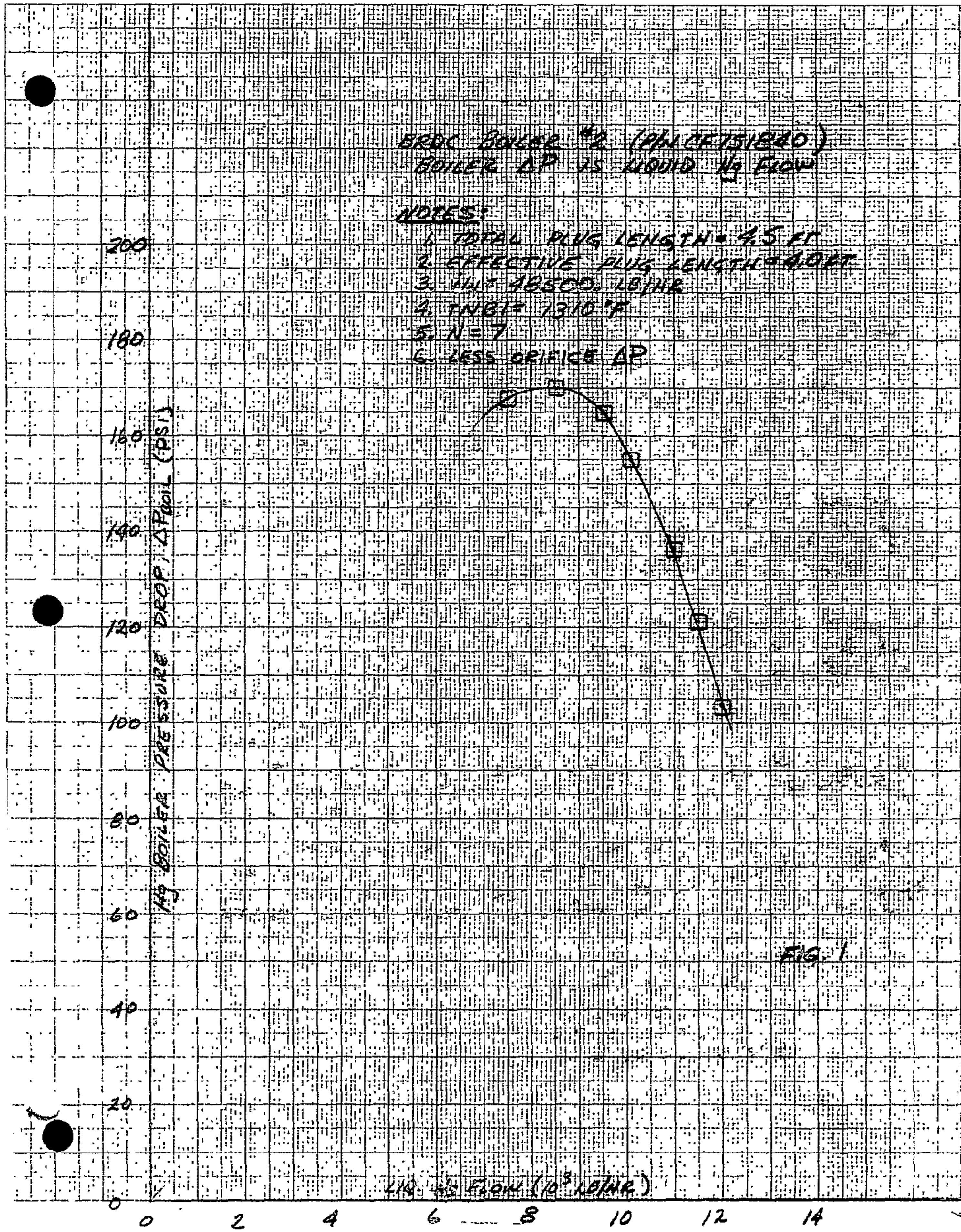
ORIFICE SIZE

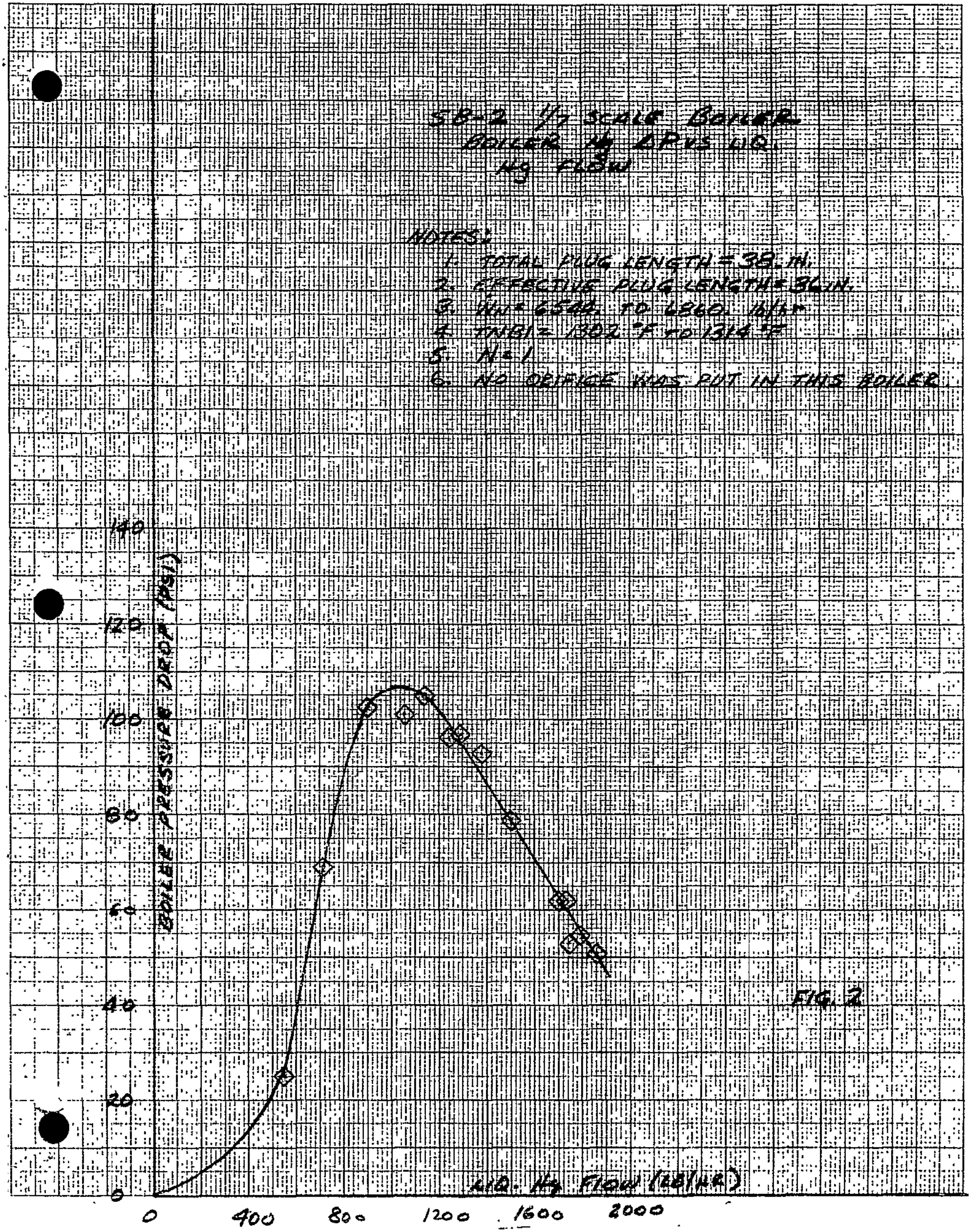
Plotted in Figure 15 is the pressure drop versus liquid mercury flow (%) for the 2.7 ft plug insert, orifice pressure drop and total boiler pressure drop.

It is recommended, if the system can tolerate the total pressure drop at design flow, that the new PCS-G boiler have an orifice with a .050 inch diameter, with a square edge. At 100% design flow for liquid mercury the total pressure drop across the boiler would then be 174. PSID.

G. L. Lombard

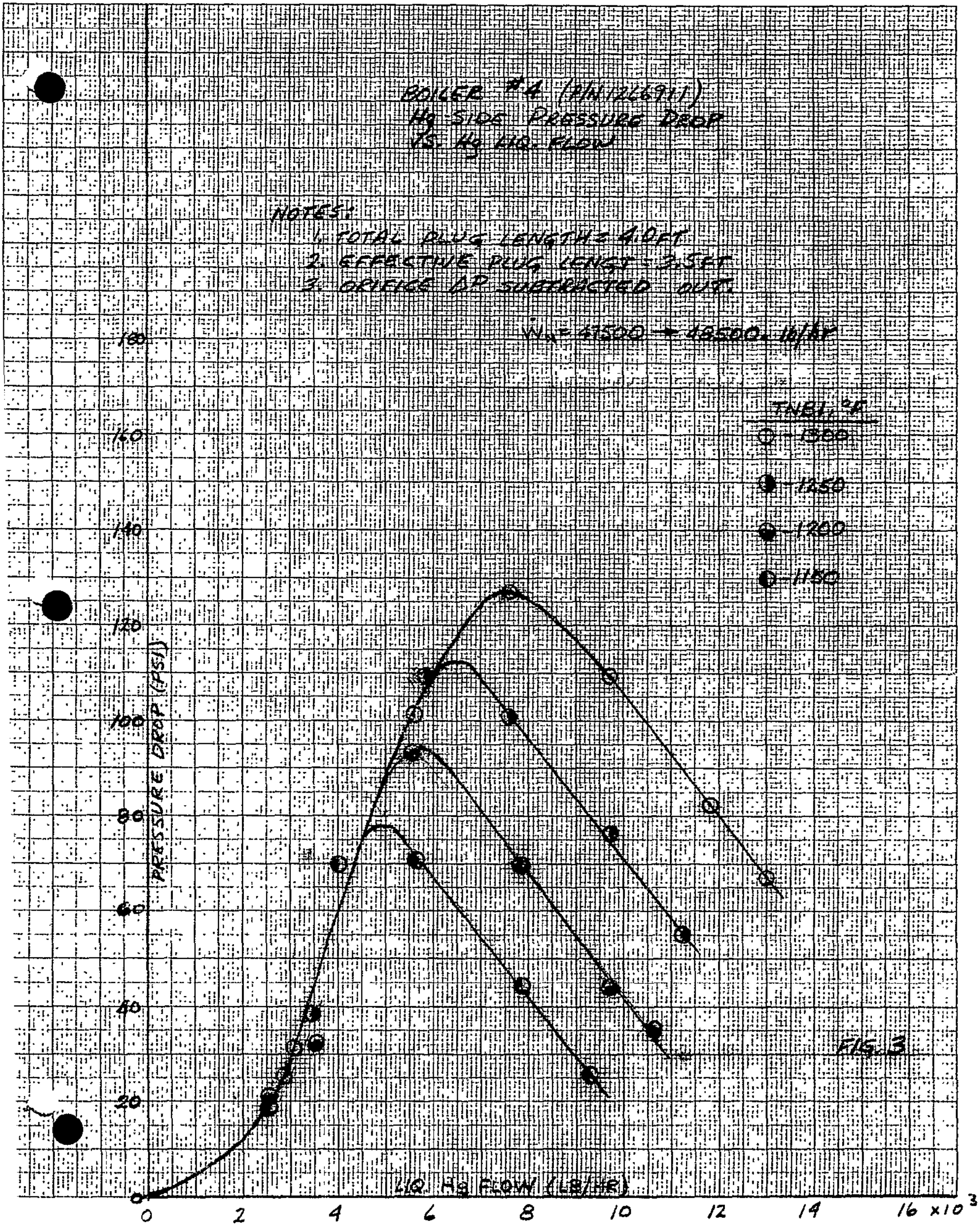
G. L. Lombard
Static Components
Power Systems Operations


BRDC BOILER #2 (P/N CF751880)
BOILER ΔP VS LIQUID Hg FLOW
NOTES:
1. TOTAL PLUG LENGTH = 4.5 FT
2. EFFECTIVE PLUG LENGTH = 4.0 FT
3. WHT 48500. LB/HR
4. TNBI = 1310 °F
5. N = 7
6. LESS ORIFICE ΔP
Hg BOILER PRESSURE DROP, ΔP BOIL (PSI)
0
20
40
60
80
100
120
140
160
180
200
LIQ. Hg FLOW (10³ LB/HR)
0
2
4
6
8
10
12
14
FIG. 1



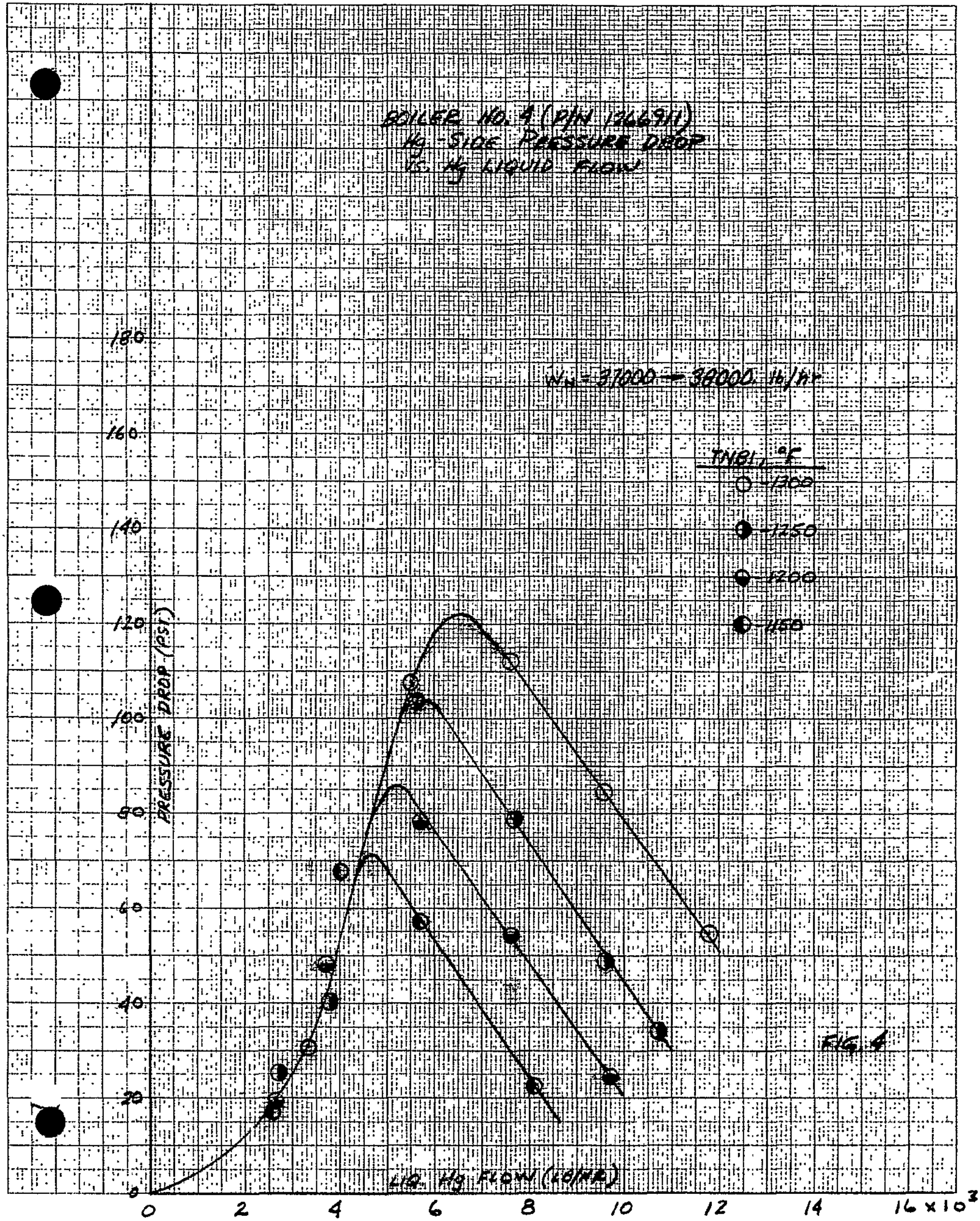
SB-2 1/7 SCALE BOILER
BOILER Hg ΔP VS LIQ.
Hg FLOW
NOTES:
1. TOTAL PLUG LENGTH = 38. IN.
2. EFFECTIVE PLUG LENGTH = 36 IN.
3. WN = 6540. TO 6860. lb/hr
4. TNBI = 1302 °F TO 1314 °F
5. N = 1
6. NO ORIFICE WAS PUT IN THIS BOILER.
BOILER PRESSURE DROP (PSI)
140
120
100
80
60
40
20
0
LIQ. Hg FLOW (LB/HR)
0
400
800
1200
1600
2000

FIG. 2



BOILER #4 (P/N1226911)
Hg SIDE PRESSURE DROP
VS. Hg LIQ. FLOW
NOTES:
1. TOTAL PLUG LENGTH = 4.0 FT
2. EFFECTIVE PLUG LENGTH = 3.5 FT
3. ORIFICE ΔP SUBTRACTED OUT.
Ẇ = 41500 → 48500 lb/hr
TNBI, °F
-1300
-1250
-1200
-1150
PRESSURE DROP (PSI)
180
160
140
120
100
80
60
40
20
0
LIQ. Hg FLOW (LB/HR)
0
2
4
6
8
10
12
14
16 ×10³

FIG. 3


BOILER NO. 4 (P/N 1266911)
Hg-SIDE PRESSURE DROP
vs. Hg LIQUID FLOW
WN = 37000 — 38000 lb/hr
TNB11, °F
-1300
-1250
-1200
-1150
PRESSURE DROP (PSI)
LIQ. Hg FLOW (LB/HR)
0 20 40 60 80 100 120 140 160 180
0 2 4 6 8 10 12 14 16 x10³
FIG. 4

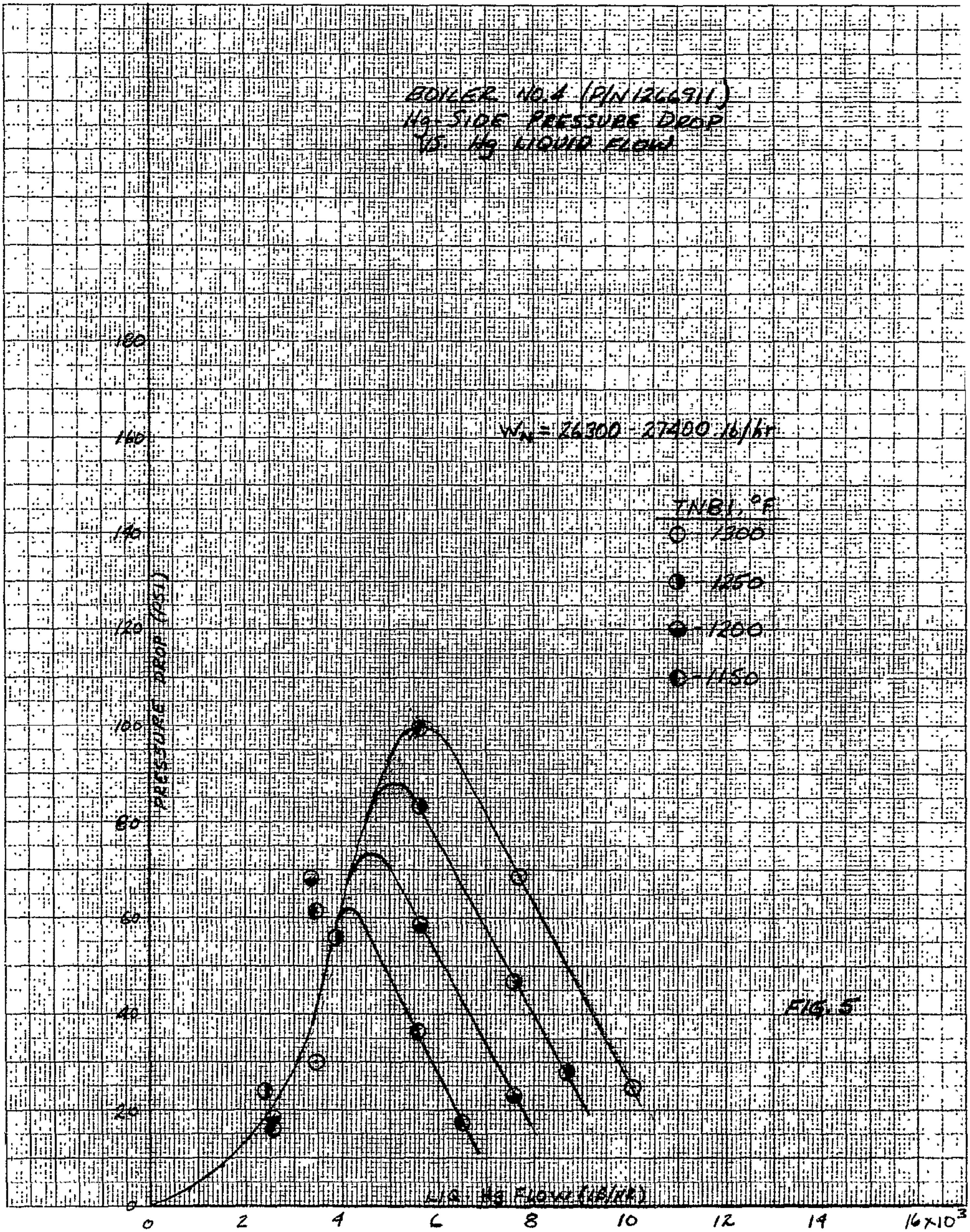

BOILER NO.4 (P/N 1266911)
Hg-SIDE PRESSURE DROP
VS. Hg LIQUID FLOW
W_N = 26300 - 27400 lb/hr
TNBI, °F
1300
1250
1200
1150
PRESSURE DROP (PSI)
LIQ. Hg FLOW (LB/HR)
0
20
40
60
80
100
120
140
160
180
2
4
6
8
10
12
14
16×10^3

FIG. 5

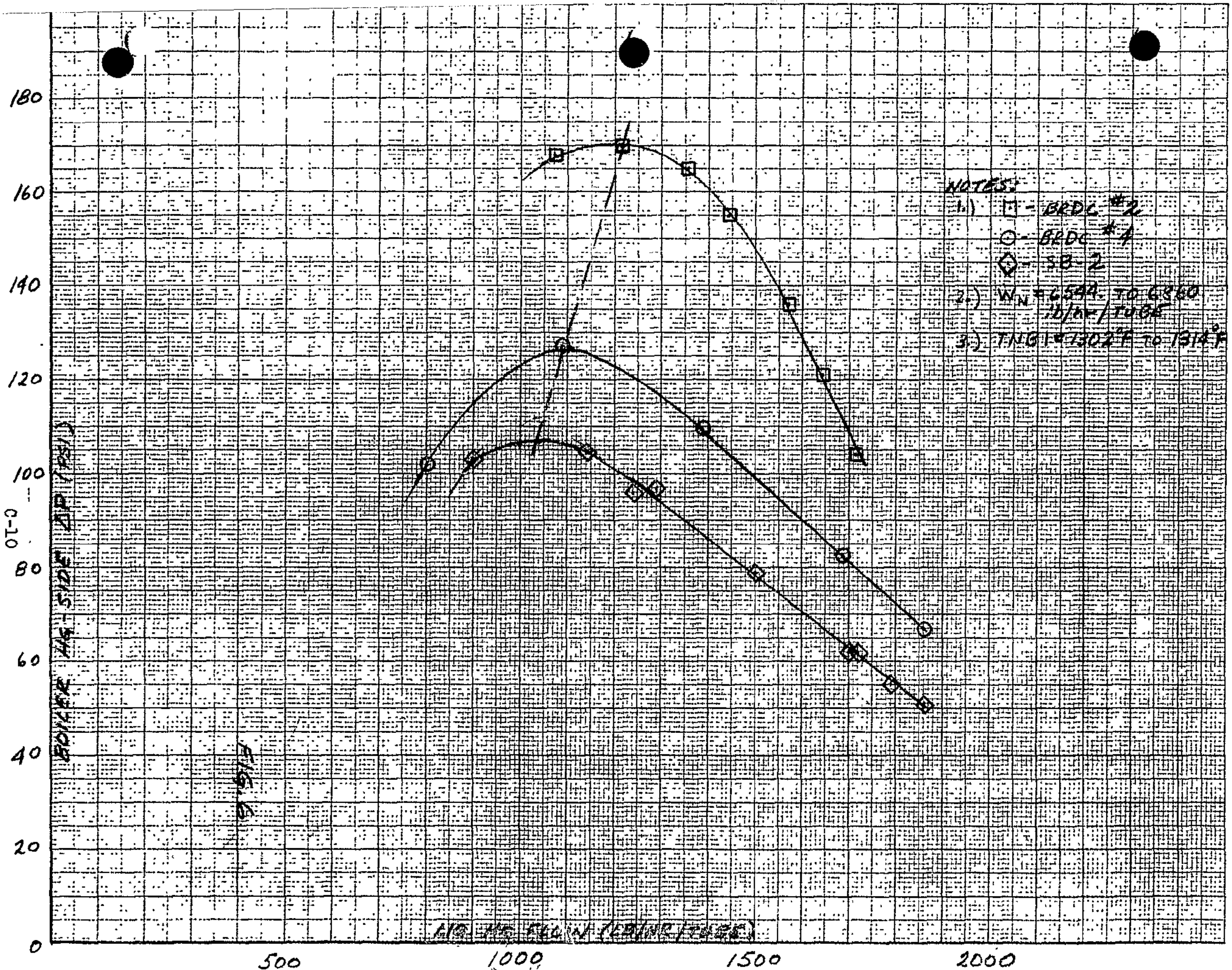

180
160
140
120
100
80
60
40
20
0
500
1000
1500
2000
BOILER HG-SIDE ΔP (PSI)
HG MASS FLOW (LB/HR/TUBE)
NOTES:
1.) □ - BRDC #2
⊙ - BRDC #4
◇ - SB-2
2.) W_N = 6544 TO 6860 lb/hr/TUBE
3.) TNG1 = 1302°F TO 1314°F

FIG. 6

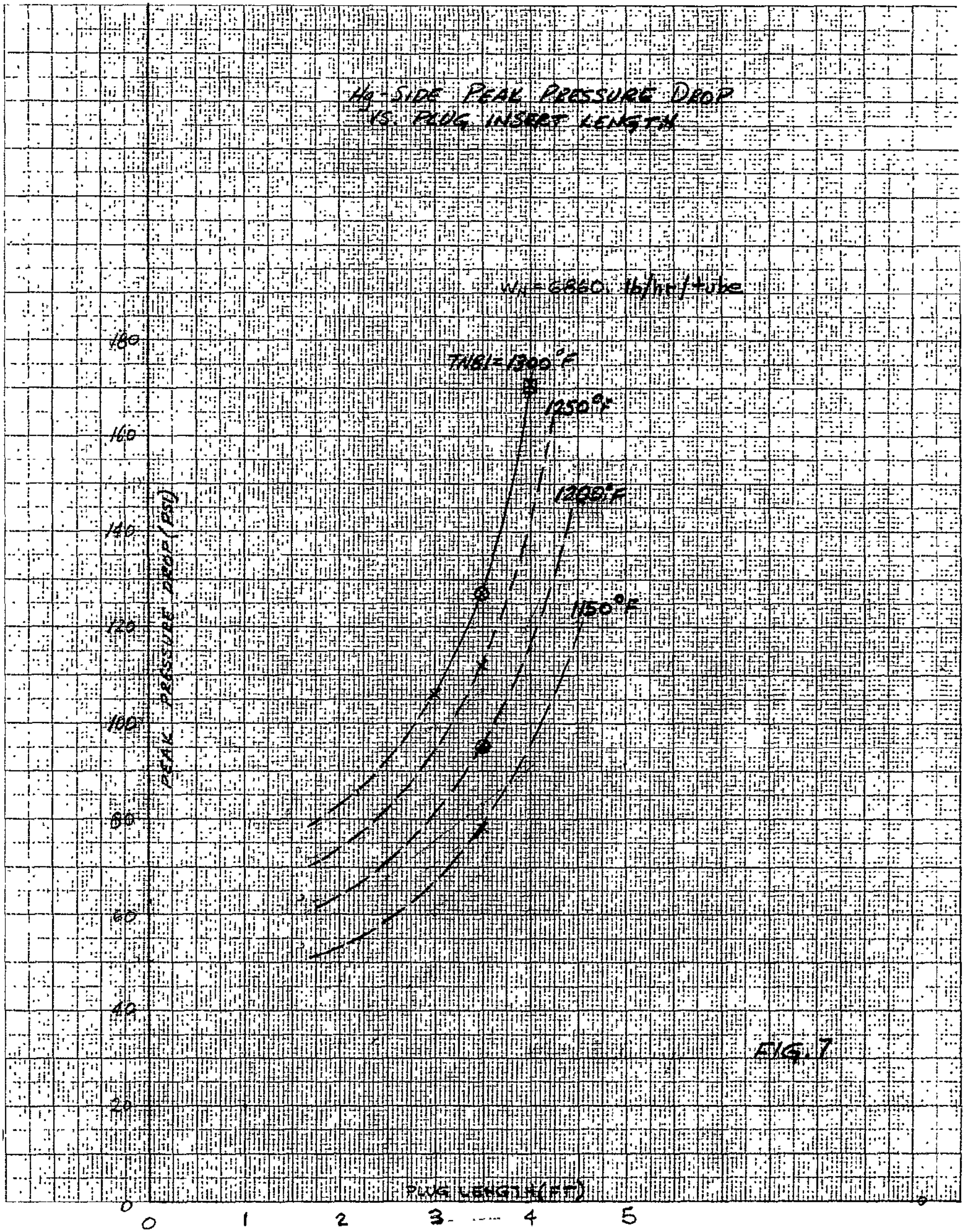

Hg-SIDE PEAK PRESSURE DROP
VS. PLUG INSERT LENGTH
W_N = 6860 lb/hr/tube
TNBI = 1300°F
1250°F
1200°F
1150°F
PEAK PRESSURE DROP (PSI)
PLUG LENGTH (FT)
0
20
40
60
80
100
120
140
160
180
0
1
2
3
4
5

FIG. 7

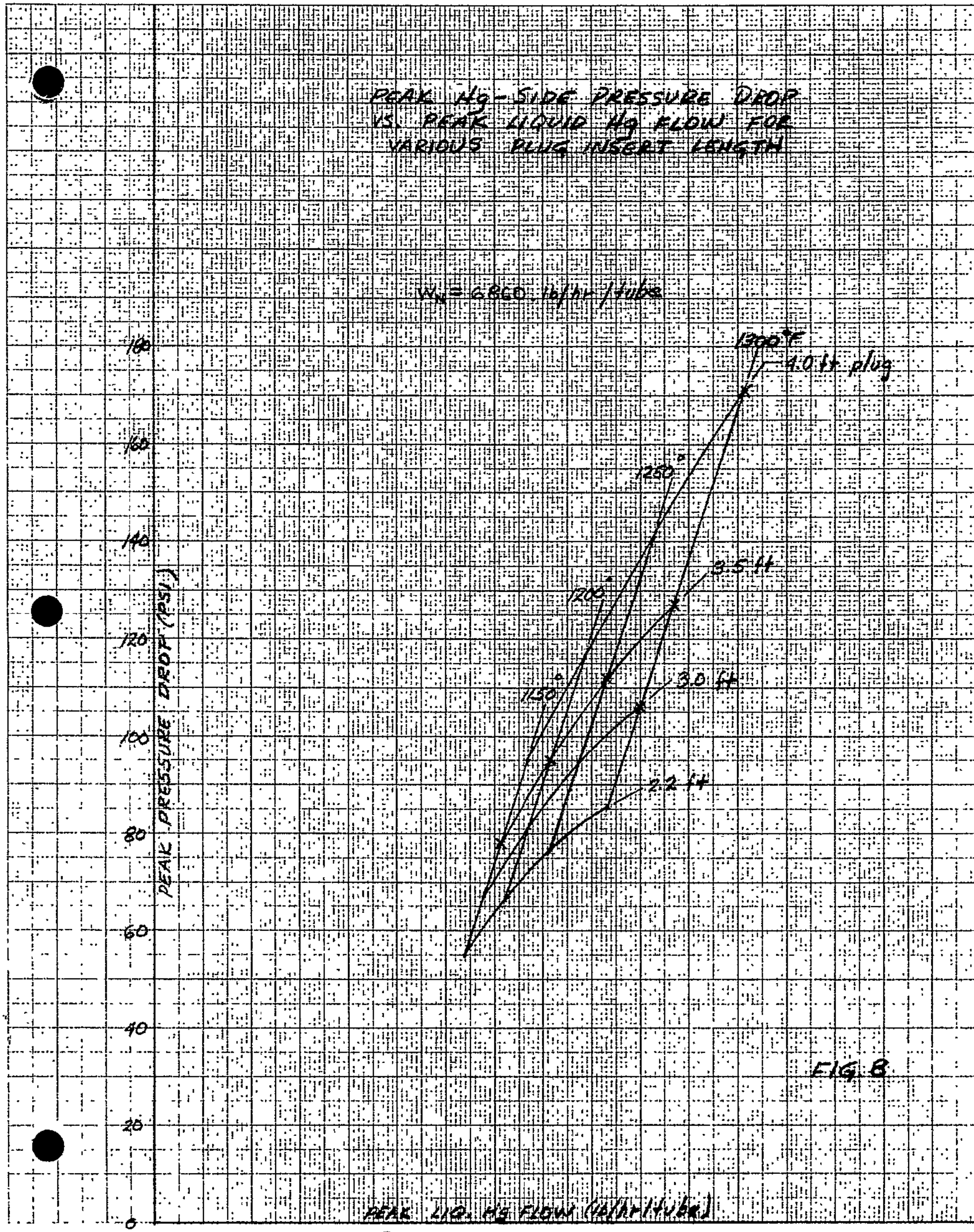
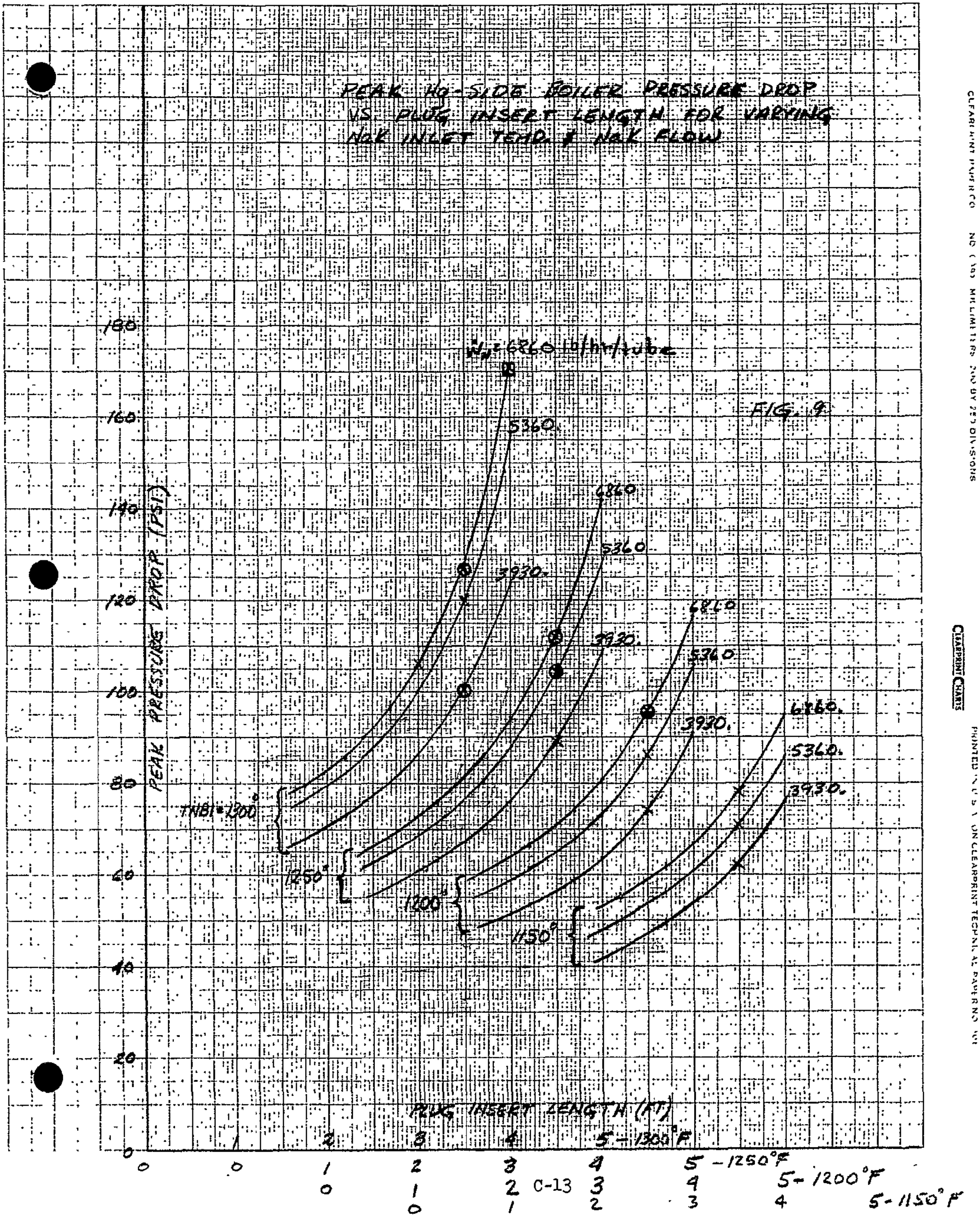
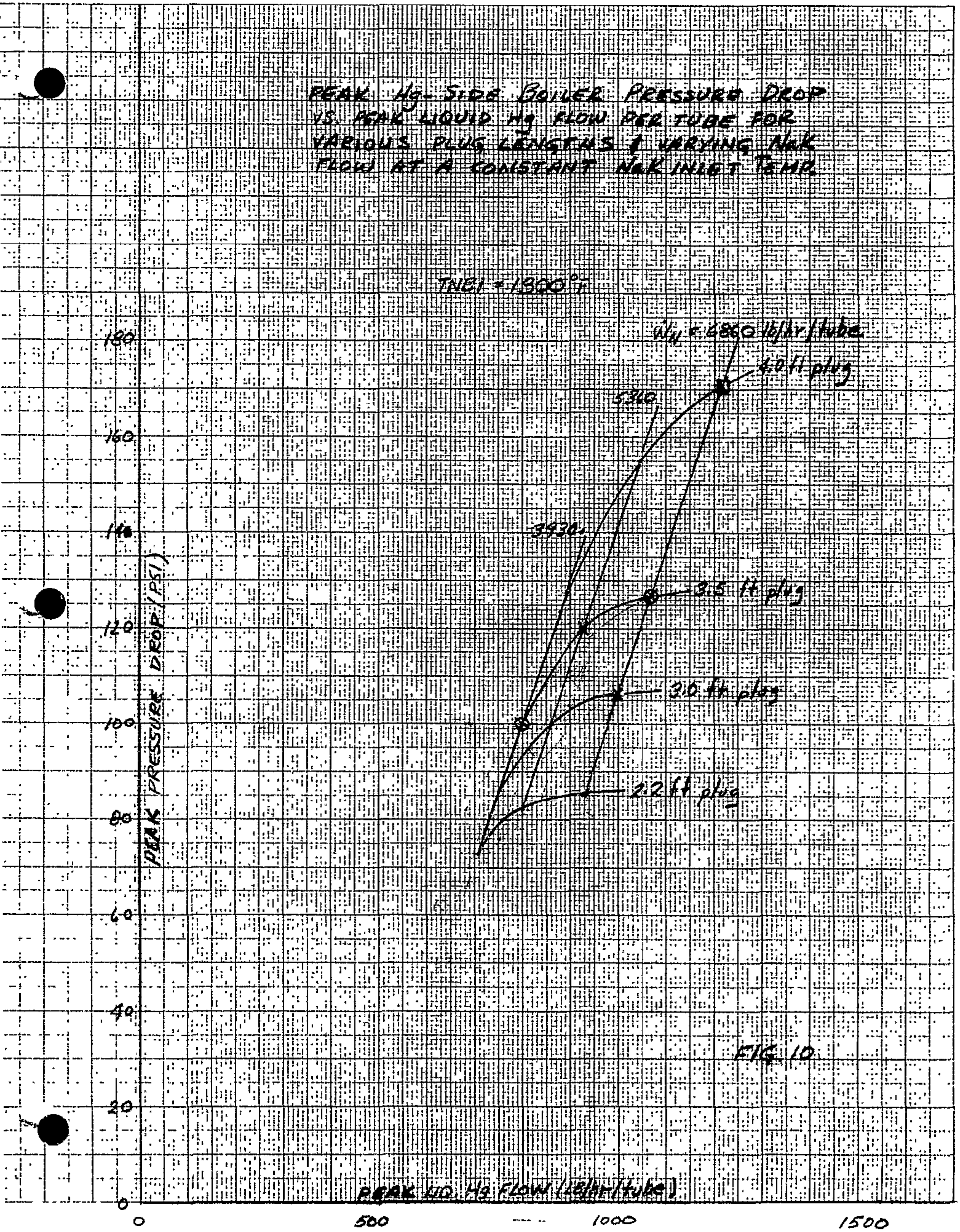

PEAK Hg-SIDE PRESSURE DROP
VS. PEAK LIQUID Hg FLOW FOR
VARIOUS PLUG INSERT LENGTH
W_v = 6860. lb/hr/tube
1300°F
4.0 ft plug
1250°
3.5 ft
1200°
1150°
3.0 ft
2.2 ft
PEAK PRESSURE DROP (PSI)
PEAK LIQ. Hg FLOW (lb/hr/tube)
0
20
40
60
80
100
120
140
160
180
0
500
1000
1500

FIG. 8


PEAK H₂O-SIDE BOILER PRESSURE DROP VS. PLUG INSERT LENGTH FOR VARYING NaK INLET TEMP. & NaK FLOW
FIG. 9
PEAK PRESSURE DROP (PSI)
PLUG INSERT LENGTH (FT)
WN = 6860 lb/hr/tube
5360
3930
6860
5360
3930
6860
5360
3930
6860
5360
3930
TNBI = 1200°
1250°
1200°
1150°
5 – 1300°F
5 – 1250°F
5 – 1200°F
5 – 1150°F


PEAK Hg-SIDE BOILER PRESSURE DROP
VS. PEAK LIQUID Hg FLOW PER TUBE FOR
VARIOUS PLUG LENGTHS & VARYING NaK
FLOW AT A CONSTANT NaK INLET TEMP.
TNEI = 1300°F
W_N = 4860 lb/hr/tube
4.0 ft plug
5360
3930
3.5 ft plug
3.0 ft plug
2.2 ft plug
180
160
140
120
100
80
60
40
20
0
PEAK PRESSURE DROP (PSI)
PEAK LIQ. Hg FLOW (LB/hr/tube)
0
500
1000
1500
FIG 10

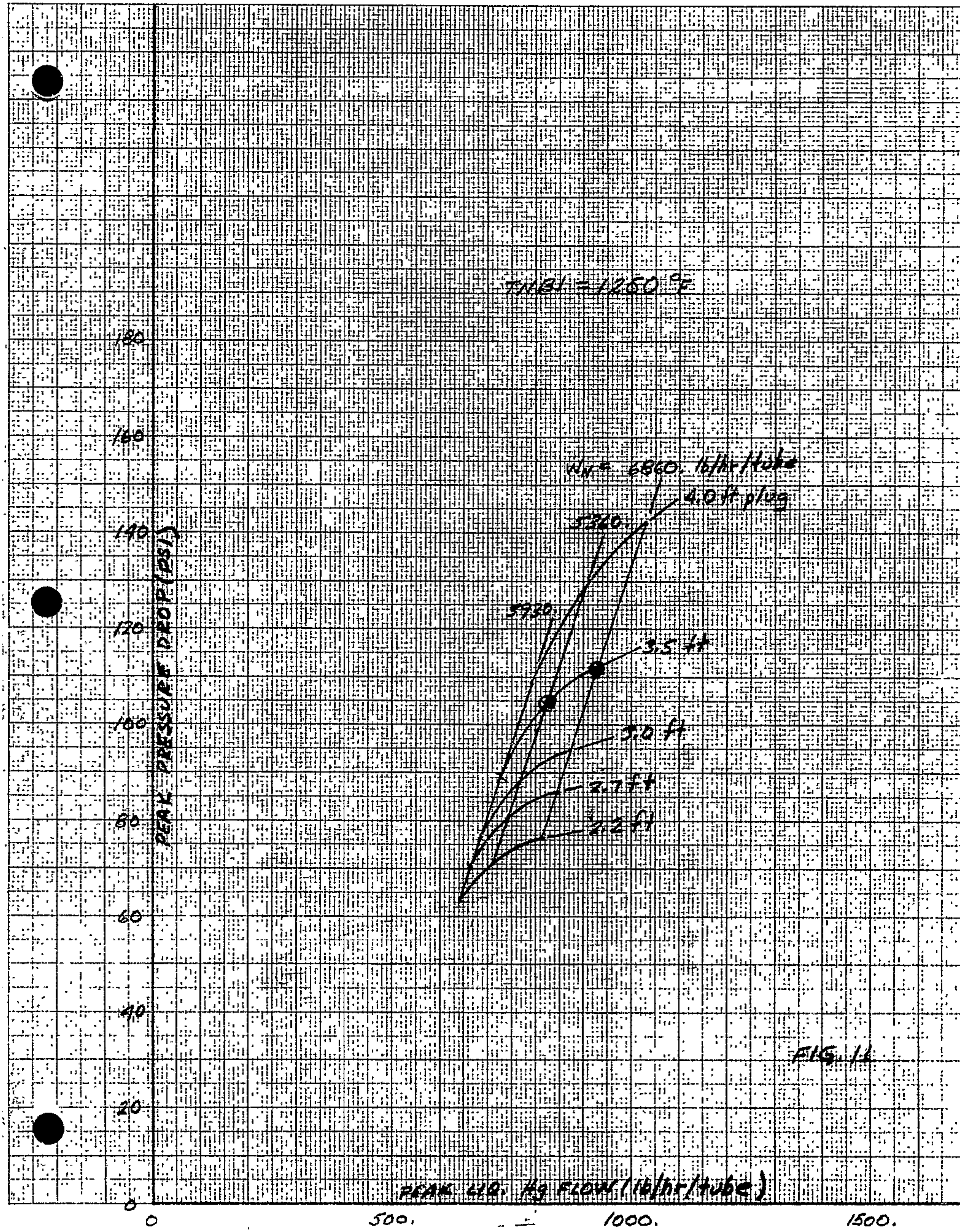

TNBI = 1250 °F
WN = 6860. lb/hr/tube
4.0 ft plug
5320.
5930.
3.5 ft
3.0 ft
2.7 ft
2.2 ft
PEAK PRESSURE DROP (PSI)
PEAK LIQ. Hg FLOW (lb/hr/tube)
0
20
40
60
80
100
120
140
160
180
500.
1000.
1500.

FIG. 16

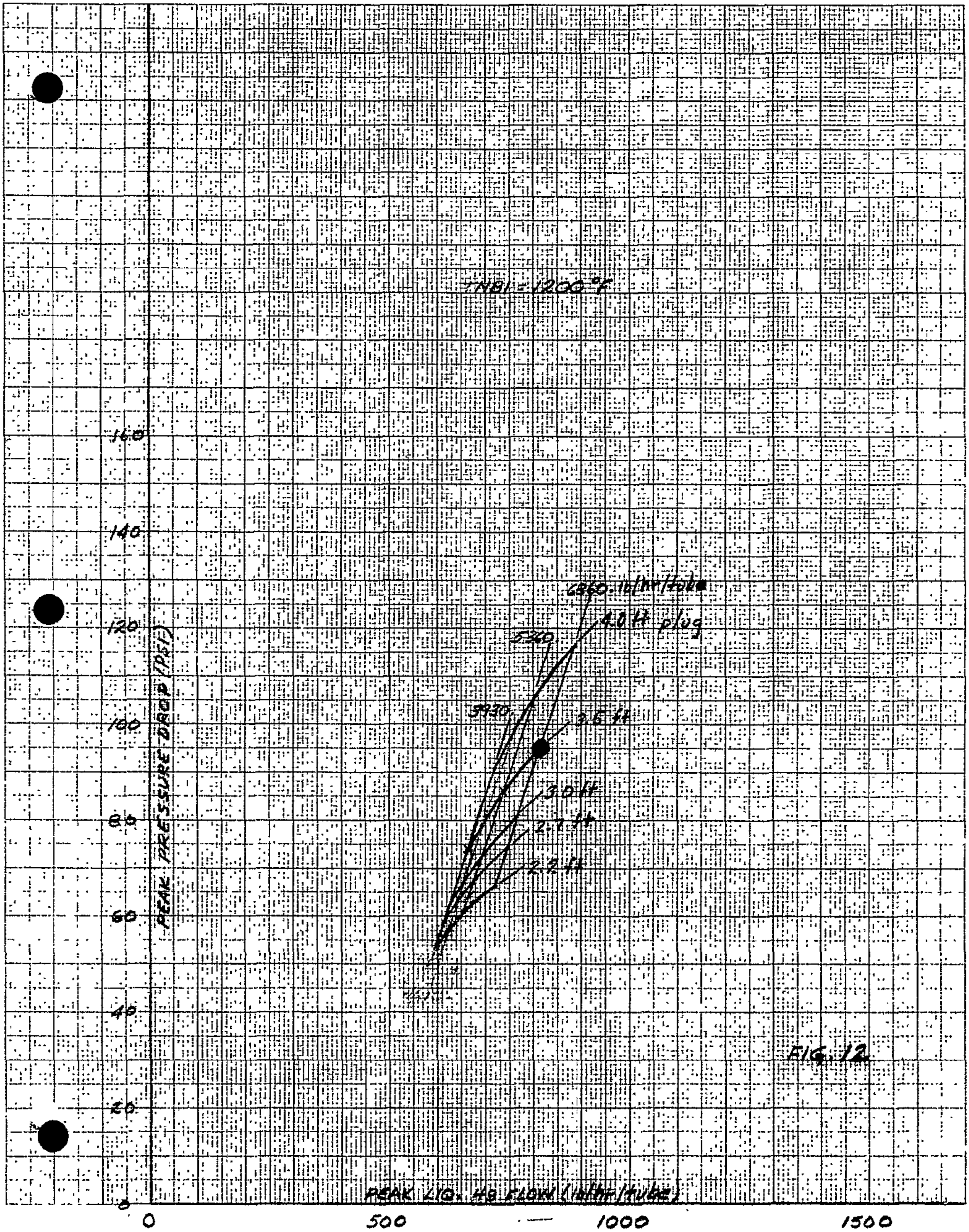

TNBI = 1200°F
6860 lb/hr/tube
4.0 ft plug
5340
5930
3.5 ft
3.0 ft
2.7 ft
2.2 ft
PEAK PRESSURE DROP (PSI)
PEAK LIQ. H2 FLOW (lb/hr/tube)
160
140
120
100
80
60
40
20
0
0
500
1000
1500

FIG. 12

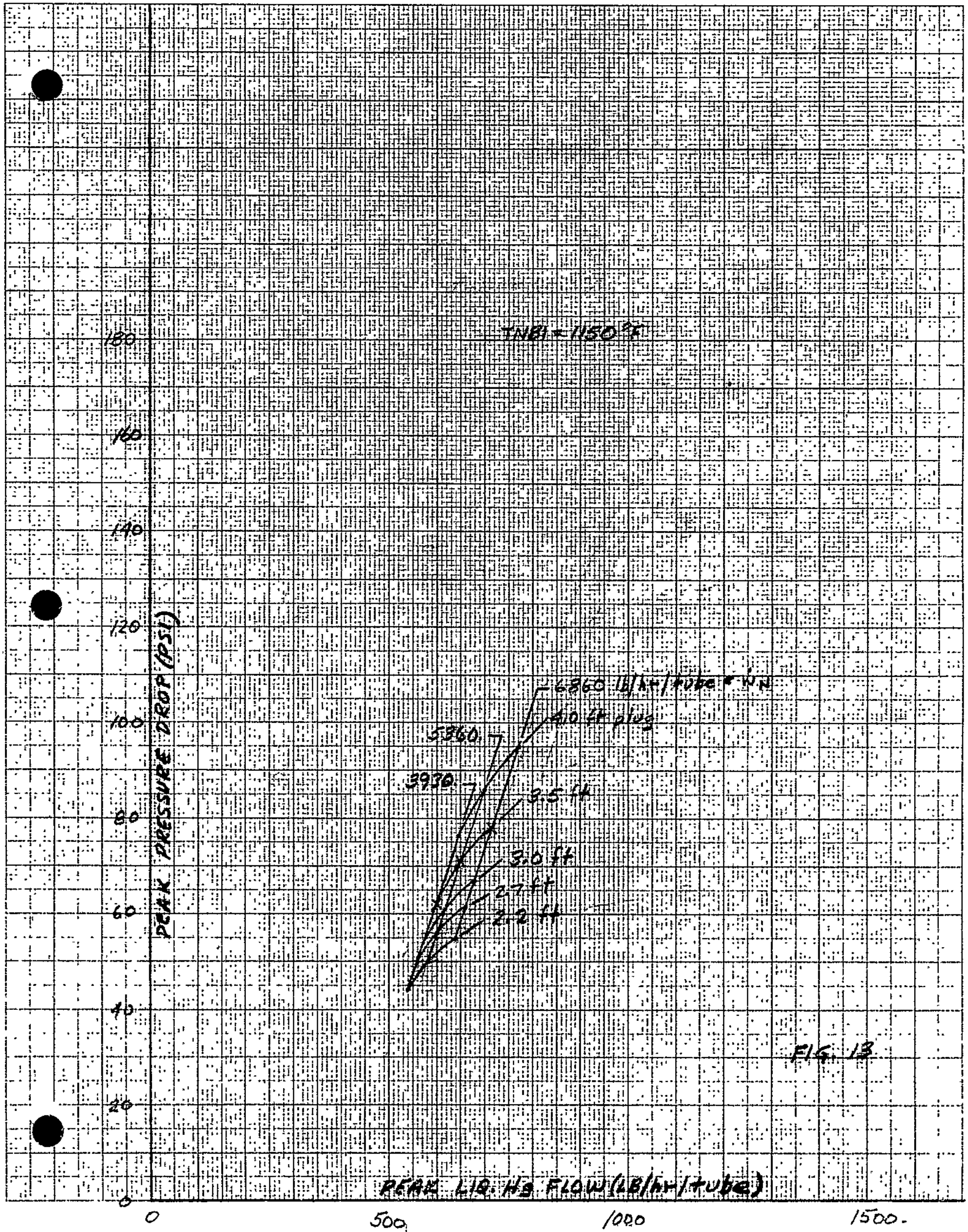

TNBI = 1150°F
6860 lb/hr/tube = W_N
4.0 ft plug
5360
3930
3.5 ft
3.0 ft
2.7 ft
2.2 ft
PEAK PRESSURE DROP (PSI)
PEAK LIQ. Hg FLOW (LB/hr/tube)
180
160
140
120
100
80
60
40
20
0
0
500
1000
1500

FIG. 13

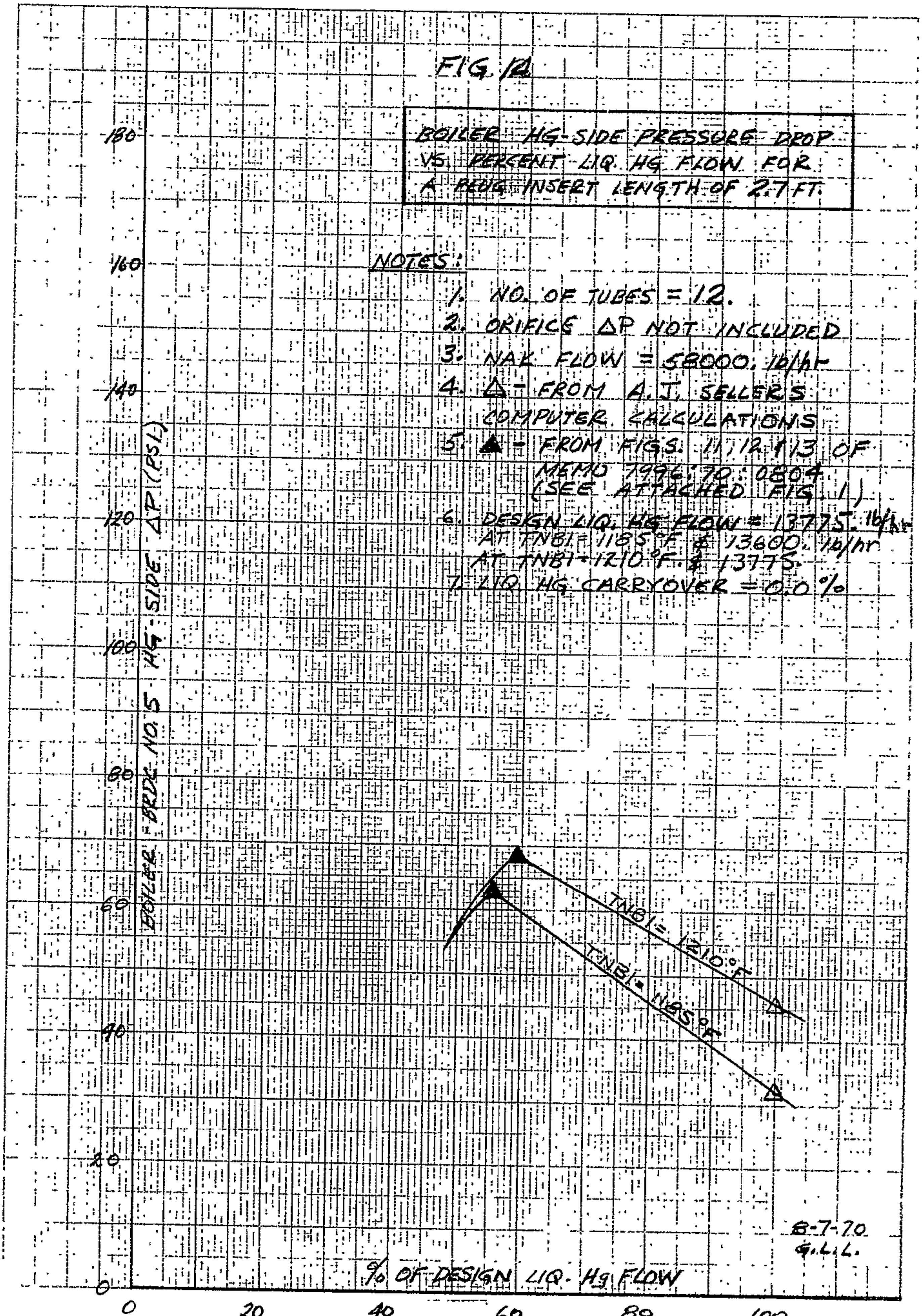
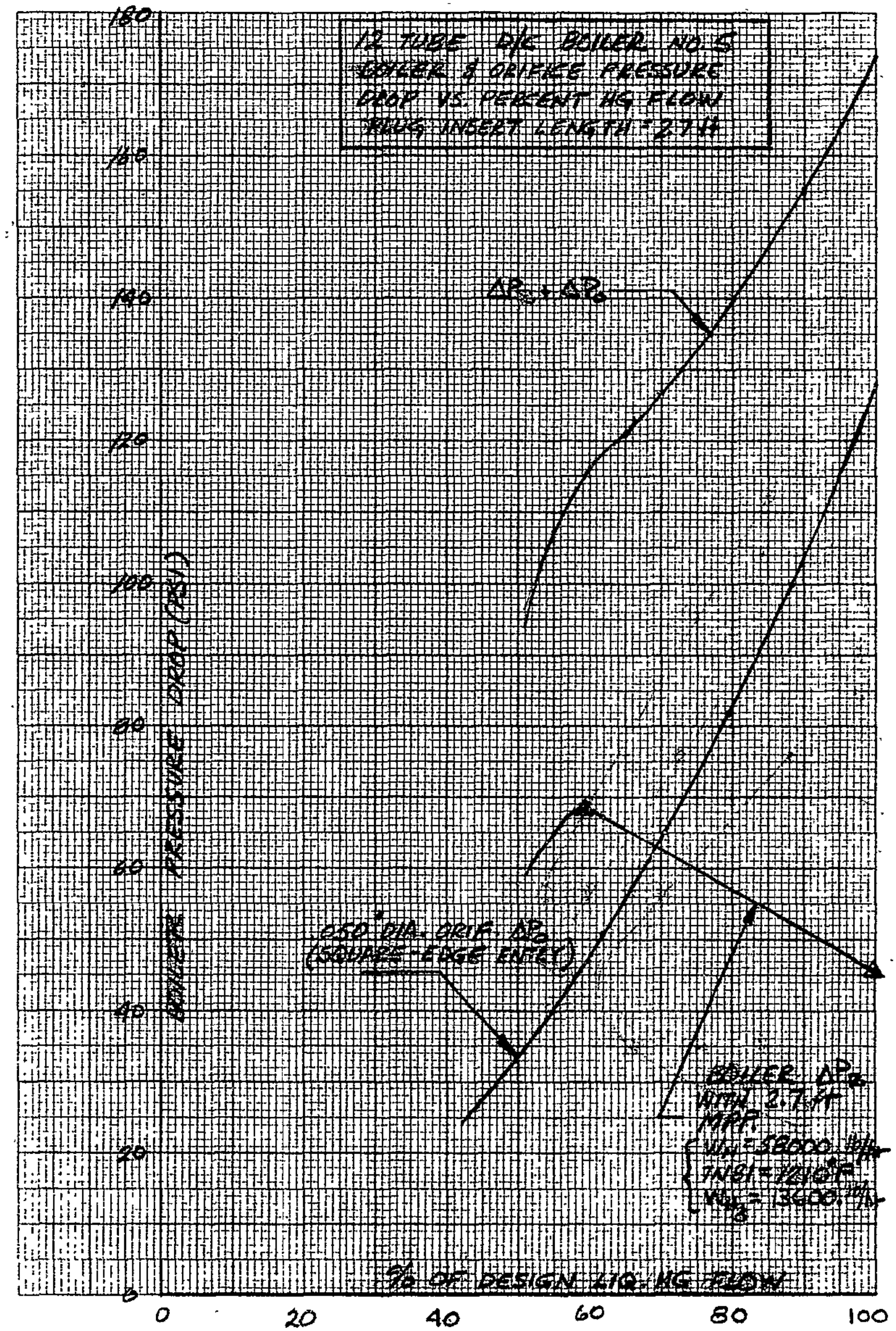


FIG. 12
BOILER HG-SIDE PRESSURE DROP VS. PERCENT LIQ. HG FLOW FOR A PLUG INSERT LENGTH OF 2.7 FT.
NOTES:
1. NO. OF TUBES = 12.
2. ORIFICE ΔP NOT INCLUDED
3. NAK FLOW = 58000. lb/hr
4. △ - FROM A.J. SELLERS COMPUTER CALCULATIONS
5. ▲ - FROM FIGS. 11, 12 & 13 OF MEMO 7996:70:0804 (SEE ATTACHED FIG. 1)
6. DESIGN LIQ. HG FLOW = 13775. lb/hr AT TNBI = 1185°F & 13600. lb/hr AT TNBI = 1210°F & 13775.
7. LIQ. HG CARRYOVER = 0.0 %
TNBI = 1210°F
TNBI = 1185°F
BOILER "BRDC" NO. 5 HG-SIDE ΔP (PSI)
% OF DESIGN LIQ. Hg FLOW
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
8-7-70
G.L.L.



8-7-70
G.L.L.

FIG. 15

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

SUBJECT BOILER Hg-SIDE ΔP

BY G. LOMBARD

PAGE 1 OF 1 PAGES

DATE

WORK ORDER

BRDC BOILER NO. 2 (P/N CF751840)

PCS-1 TEST DATA

W_N	T_{NBI}	$\dot{W}_{H(L)}$	ΔP_{TOT}	$\Delta P_{ORIF.}$	$\Delta P_{BOIL.}$
48500.	1310°F	7500.	200.	32.	168.
		8500	211.	41.	170.
		9500	216.	51.	165.
		10100	214.	59.	155.
		11000	205.	69.	136.
		11500	196.	75.	121.
		12000	186.	82.	104.

TABLE 1

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

QUADRILLE WORK SHEET

PAGE 1 OF 1 PAGES

DATE

WORK ORDER

BY G. LOMBARD

SUBJECT Boiler Hg-Side ΔP

STK. NO. D-1-103

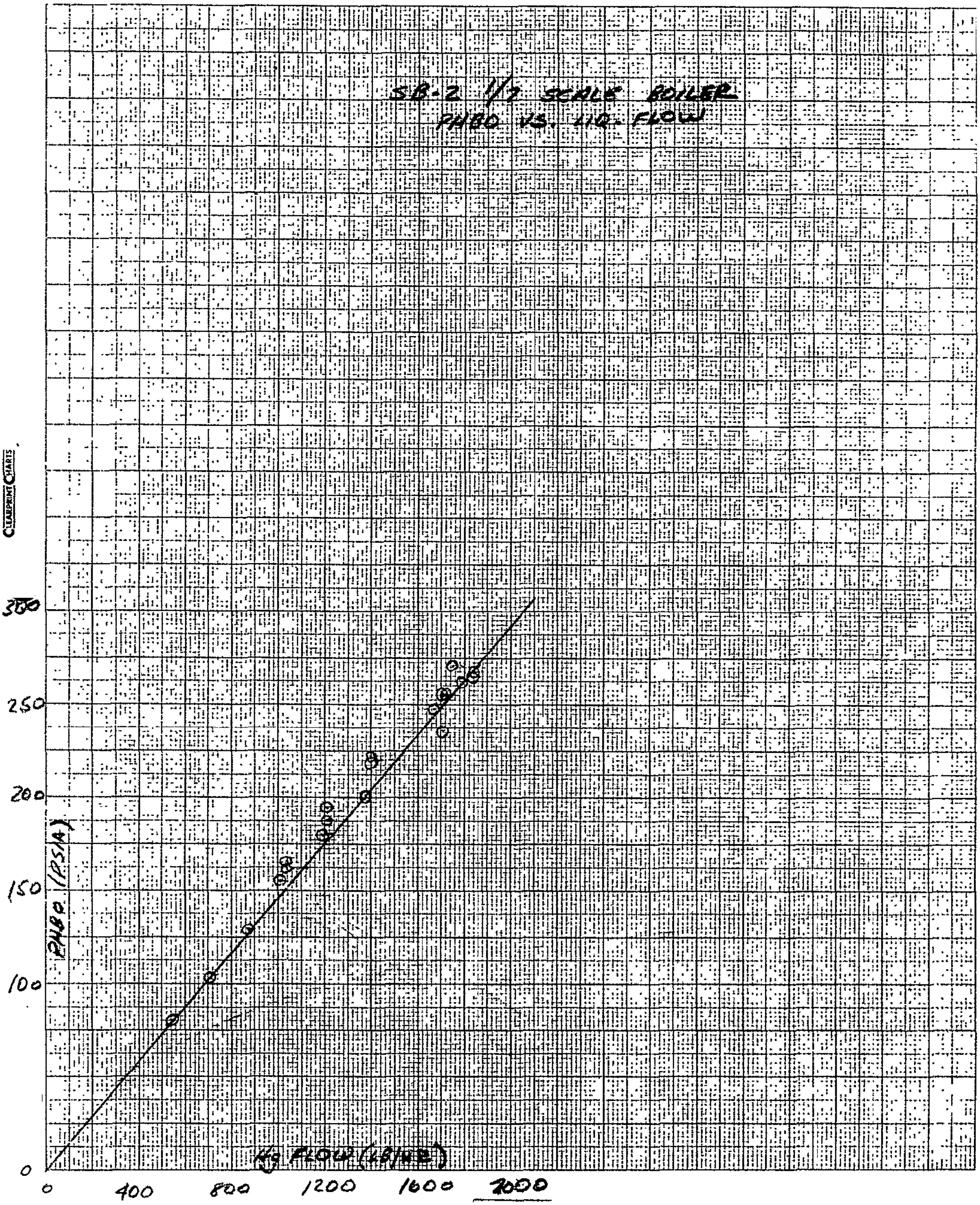
SB-2 BOILER TEST DATA
TESTED AT 1/7 SCALE
LOOP - AGN

D.P.	$\dot{W}_N$	TNBI	$\dot{W}_{H}(L)$	ΔP_{BOIL}	P_{HBO}
4B-12	6780.	1306.	553. ✓	25.	80/80
4B-9	6873.	1310.	706. ✓	69.	103/103.
4B-5	6717.	1309.	867. (900)	103.	129./129.
4C-34	6756.	1314.	1014. (1060)	101.	155./155.
4A-28	6806.	1304.	1042. (1120)	105.	162/166
4A-25	6696.	1306.	1204. (1290/~~1330~~)	97.0	188/194
4C-29	6760.	1302.	1192. (1240)	96.0	180./180
4B-17	6661	1307.	1377. ✓	93.0	199/201.
4A-22	6725.	1305.	1398. (1580)	79.0	222./220.
4-2	6620.	1309.	1671. (1700)	62.0	248/252
4A-1	6860.	1308.	1712. (1740)	53.0	236/256
4A-11	6757.	1308.	1791. ✓	55.0	262./262
4A-13	7014.	1310.	1838. ✓	56.0	268/266
4A-17	6544.	1308.	1753. (1860)	51.0	271./271.
4B-14	6612.	1308.	1720. (1740)	62.0	255/255.

NOTES:
1. NO ORIFICE
2. ONE TUBE BOILER

TABLE 2

01-071-002


SB-2 1/7 SCALE BOILER
PHBO VS. LIQ. FLOW
PHBO (PSIA)
Hg FLOW (LB/HR)
0
100
150
200
250
300
0
400
800
1200
1600
2000

BOILER NO. 4 - P/N 1266911
PERFORMANCE DATA
PCS-1 TEST

DATA PT.	$\dot{W}_N$	TNBI	TNBO	ΔP_N	$\dot{W}_{H(L)}$	THBI	THBO	P_{HBI}	P_{HBO}	$\Delta P_{H(T)}$	$\Delta P_{H(0)}$	$\Delta P_{H(N)}$
1	48500	1304.8	1117.7	2.38	13000.	380.	1250.8	391.4	261.6	128.9	61.5	67.4
2	48500.	1305.1	1134.1	2.40	11800.	379.5	1248.1	372.9	239.1	133.8	51.0	82.8
3	48300.	1305.0	1162.1	2.35	9700.	377.0	1243.0	345.6	201.2	145.6	36.0	109.6
4	48000.	1303.4	1189.1	2.33	7600.	374.0	1235.2	309.5	161.1	149.4	22.4	127.0
5	48100.	1303.4	1219.9	2.14	5600	370.0	1229.7	233.4	119.7	113.8	12.2	101.6
6	47600.	1300.0	1256.7	2.20	3070.	324.1	1191.2	100.6	65.9	34.7	3.4	31.3
7	47600.	1307.3	1267.5	2.20	2880.	296.8	1173.2	91.7	61.3	28.7	3.1	25.6
8	37300.	1301.0	1072.4	1.39	11800.	392.0	1249.9	338.7	238.9	100.5	46.0	54.5
9	37600.	1303.4	1116.1	1.42	9600.	389.9	1251.8	316.6	200.0	119.3	34.4	84.9
10	37100.	1303.5	1151.8	1.44	7600.	385.4	1243.7	294.2	160.3	134.8	22.4	112.4
11	38000.	1298.5	1189.8	1.36	5500.	370.0	1227.2	237.5	118.1	119.9	12.0	107.9
12	37600.	1297.2	1232.6	1.33	3330.	338.9	1200.0	108.1	72.5	35.0	4.0	31.0
13												
14	26500.	1294.8	1003.6	0.74	10050.	390.2	1227.1	267.5	206.4	62.4	37.6	24.8
15	26500.	1295.3	1066.5	0.76	7700.	385.6	1236.8	251.9	161.3	91.8	23.0	68.8
16.	26500.	1297.3	1127.1	0.66	5600.	370.0	1223.5	231.6	120.3	112.1	12.2	99.9
17	27400.	1296.8	1194.1	0.69	3450.	309.3	1196.3	110.7	75.6	34.3	4.2	30.1
18												
19	48400.	1251.1	1081.8	2.45	11250.	378.8	1200.0	336.9	235.8	101.6	46.5	55.1
20	48200	1252.3	1111.9	2.34	9600.	376.4	1197.3	306.8	196.8	113.1		
21	48100.	1250.5	1139.2	2.37	7600.	372.0	1185.0	278.0	155.6	123.4	22.4	101.0
22	48000.	1259.8	1174.1	2.17	5590. (5800)	361.1	1190.3	241.4	120.2	122.1	12.1 (13.0)	110.0 (109)
23	47100.	1261.0	1205.3	2.16	3450.	278.2	1168.0	120.4	80.3	42.5	4.2	38.3
24	47600.	1251.6	1211.1	2.14	2330.	235.8	1134.3	85.5	57.2	29.0		
25	37300.	1247.2	1038.8	1.39	10800.	377.5	1193.0	292.0	217.5	77.3	43.0	34.3
26	37000.	1245.8	1057.8	1.45	9600.	376.0	1195.9	277.3	197.2	83.0	34.4	48.6
27	37000.	1245.5	1093.7	1.35	7700.	385.7	1189.4	257.9	156.6	102.1	23.0	79.1
28	37000.	1261.9	1150.9	1.32	5610.	363.1	1191.4	232.7	119.7	115.9	12.3	103.6
29	36800.	1249.8	1172.7	1.30	3380. ([illegible])	279.3	1158.6	124.7	80.2	45.5	4.0 (5.0)	41.5 (40.5)
30	37000.	1251.6	1198.7	1.34	2380. ([illegible])	234.0	1133.9	84.6	57.4	28.4	2.5 ([illegible])	25.9 ([illegible])
31	27100.	1253.0	999.7	0.67	8700.	378.6	1195.8	233.8	178.8	56.8	28.5	28.3
32	27000.	1253.3	1027.8	0.69	7600.	376.4	1193.3	226.6	157.0	69.4	22.4	47.0
33	26400.	1253.4	1085.0	0.65	5600.	368.5	1185.4	215.4	119.2	95.6	12.2	83.4
34	26000.	1246.1	1130.4	0.65	3460. ([illegible])	277.7	1155.0	140.0	80.7	61.6	4.2 ([illegible])	57.4 (55.1)
35	26000.	1248.6	1168.0	0.66	2430.	234.0	1131.1	82.3	57.5	26.0	2.6	23.4

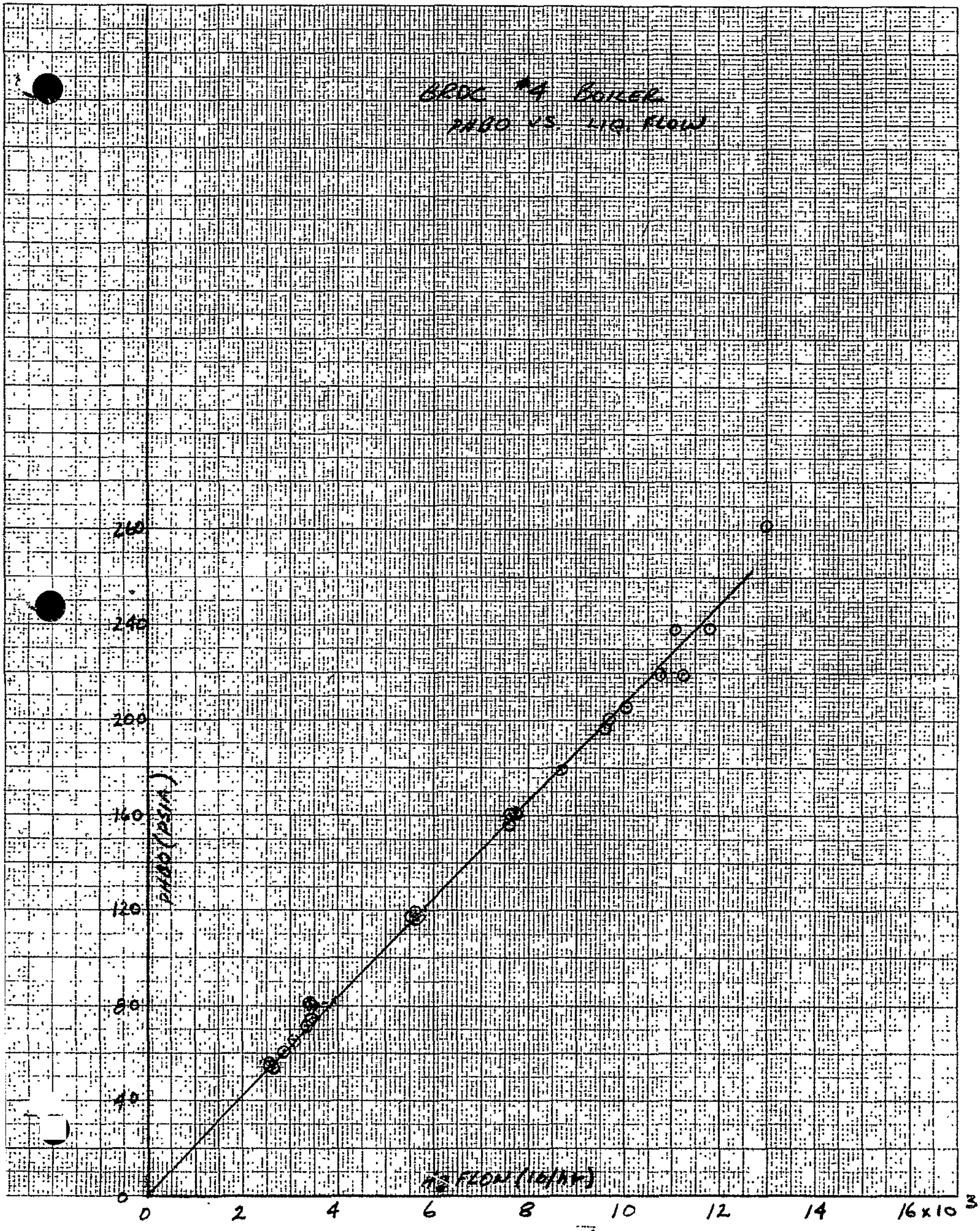
TABLE 3

DATA PT.	W_N	TNBI	TNBO	ΔP_N	$\dot{W}_{H(L)}$	THBI	THBO	PHBI	PHBO	$\Delta P_{H(T)}$	$\Delta P_{H(O)}$	$\Delta P_{H(H)}$
36	48400.	1199.9	1040.8	2.42	11250. ([illegible])	377.8	1130.6	296.4	220.4	76.9	46.5 ([illegible])	30.4 ([illegible])
37	48200.	1198.4	1053.6	2.42	9700.	376.1	1150.0	273.7	195.7	80.2	36.0	44.2
38	48200.	1197.2	1085.0	2.45	7850.	372.0	1144.2	249.4	157.8	93.3	23.6	69.7
39	48100.	1201.1	1118.8	2.17	5550.	368.2	1136.0	221.8	117.5	105.4	12.0	93.4
40	48100.	1199.2	1146.6	2.16	3520.	318.0	1111.8	112.8	75.7	37.3	4.5	32.8
41	48000.	1202.7	1165.6	2.14	2560.	269.0	1088.1	78.9	54.5	24.2	2.6	21.6
42	37800.	1198.7	1015.8	1.51	9700.	378.1	1138.0	253.2	194.8	60.8	36.0	24.8
43	37700.	1195.1	1050.5	1.51	7600.	374.9	1138.4	235.8	153.0	76.8	22.4	544
44	37000.	1197.9	1083.6	1.21	5700.	368.9	1133.2	212.1	119.2	91.8	13.0	78.8
45	37000.	1194.0	1123.6	1.21	3450. ([illegible])	321.7	1107.5	129.0	75.5	52.9	4.5 ([illegible])	48.4 (68.3)
46	36900.	1198.4	1147.9	1.19	2650.	271.2	1085.0	77.3	54.2	22.8	3.0	19.8
47	26600.	1199.8	981.3	0.63	7600.	376.0	1142.3	201.6	154.0	45.5	22.4	23.1
48	26300.	1199.6	1031.3	0.56	5620.	366.2	1127.8	190.0	117.4	70.8	12.1	58.7
49	26000.	1197.9	1086.9	0.57	3370.	277.8	1102.5	148.1	76.3	72.5	4.0	68.5
50	26500.	1197.5	1102.7	0.61	2550.	239.4	1072.9	76.2	56.6	21.0	2.6	18.4
51	48500.	1145.1	1015.8	2.45	9300.	375.5	1092.2	239.1	183.1	57.9	32.0	25.9
52	48200.	1151.1	1049.6	2.44	7850.	372.0	1100.6	224.0	153.4	68.5	23.6	44.9
53	48400.	1154.4	1071.9	2.14	5660.	368.0	1092.0	201.9	116.3	83.5	12.5	71.0
54	48500.	1153.0	1097.9	2.12	3420. (4000)	277.4	1067.7	154.4	80.7	76.9	4.2 (6.?)	72.7 (70.9)
55	48100.	1148.2	1110.4	2.11	2550.	232.0	1041.1	75.7	55.7	20.9	2.6	18.3
56	37800.	1148.1	994.2	1.48	8100.	374.0	1095.2	217.8	161.7	47.7	25.0	22.7
57	37300.	1153.0	1040.1	1.20	5700.	368.0	1093.0	190.2	117.4	70.6	13.0	57.6
58	37200.	1151.5	1077.2	1.25	3420. ([illegible])	278.2	1065.5	152.1	80.7	74.0	4.2 (6.0)	69.8 (68.0)
59	37200.	1145.2	1094.8	1.26	2575.	234.0	1043.5	75.6	56.2	19.9	2.8	17.1
60												
61												
62	26300.	1143.1	1033.3	0.58	3450.	282.4	1061.4	142.0	77.8	66.1	4.5	61.6
63	26300.	1152.0	1073.8	0.60	2600.	234.0	1043.5	75.6	56.4	18.7	2.7	16.0

TABLE 3 (CONT'D)

DATA PT.	$\dot{W}_N$	TNBI	TNBO	ΔP_N	$\dot{W}_{H(L)}$	THBI	THBO	PHBI	PHBO	$\Delta P_{H(T)}$	$\Delta P_{H(O)}$	$\Delta P_{H(M)}$
64	33400.	1221.8	1074.4	1.02	6500.	370.0	1163.4	226.3	135.6	90.1		
65	33500.	1220.5	1052.8	1.04	7610.	377.0	1165.7	234.4	156.1	79.0		
66	33600.	1221.1	1030.3	1.06	8700.	379.0	1167.2	243.6	176.7	67.6		
67	33300.	1194.9	1048.8	1.02	6600.	370.7	1138.0	212.4	135.3	76.6		
68	33700.	1201.4	1035.6	1.03	7600.	375.7	1148.0	223.5	153.4	69.5		
69	34200.	1203.8	1018.0	1.09	8700.	379.3	1151.4	235.9	176.8	61.1		
70	33700.	1174.3	1030.4	1.00	6600.	370.8	1120.7	202.9	134.3	66.3		
71	33800.	1177.9	1011.9	1.07	7600.	377.6	1123.0	212.4	154.6	56.4		
72	34000.	1176.9	991.2	1.07	8610.	379.4	1111.8	220.7	172.2	48.4		

TABLE 3 (CONT'D)


BRDC #4 BOILER
PHBO VS. LIQ. FLOW
PHBO (PSIA)
FLOW (lb/hr)
0
40
80
120
160
200
240
260
0
2
4
6
8
10
12
14
16 x 10³

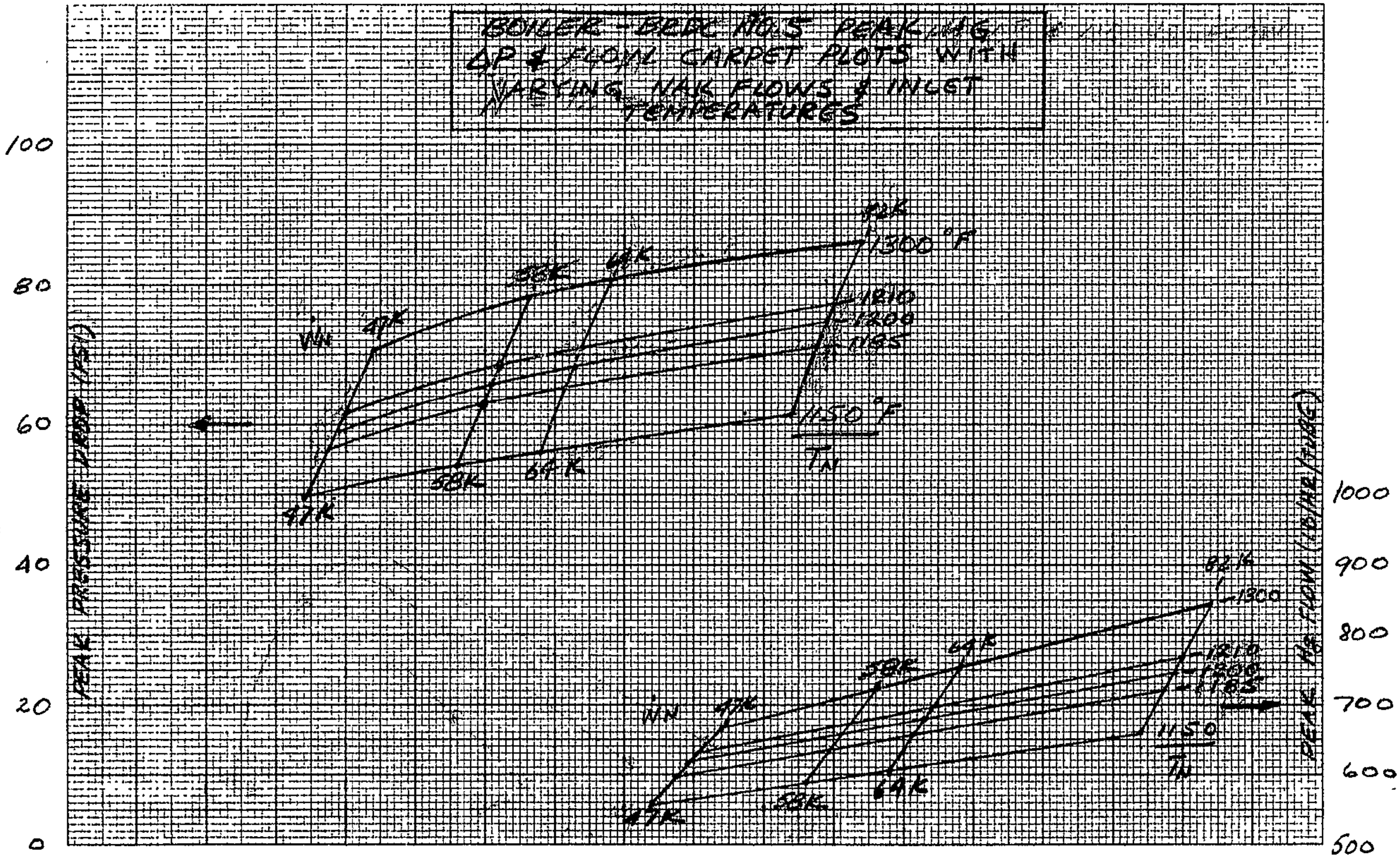


FIG. 1

8-7-70
G.L.L.

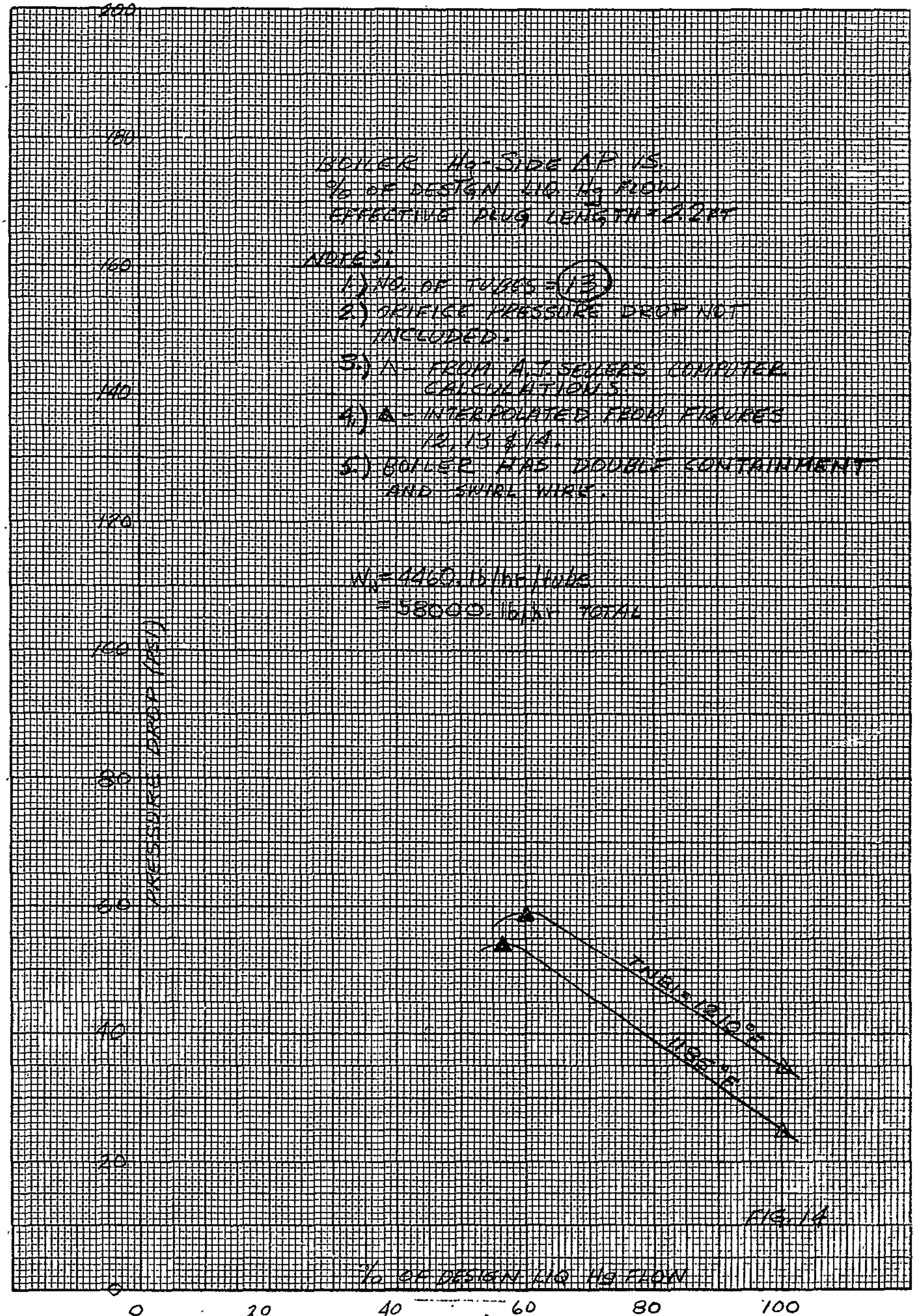
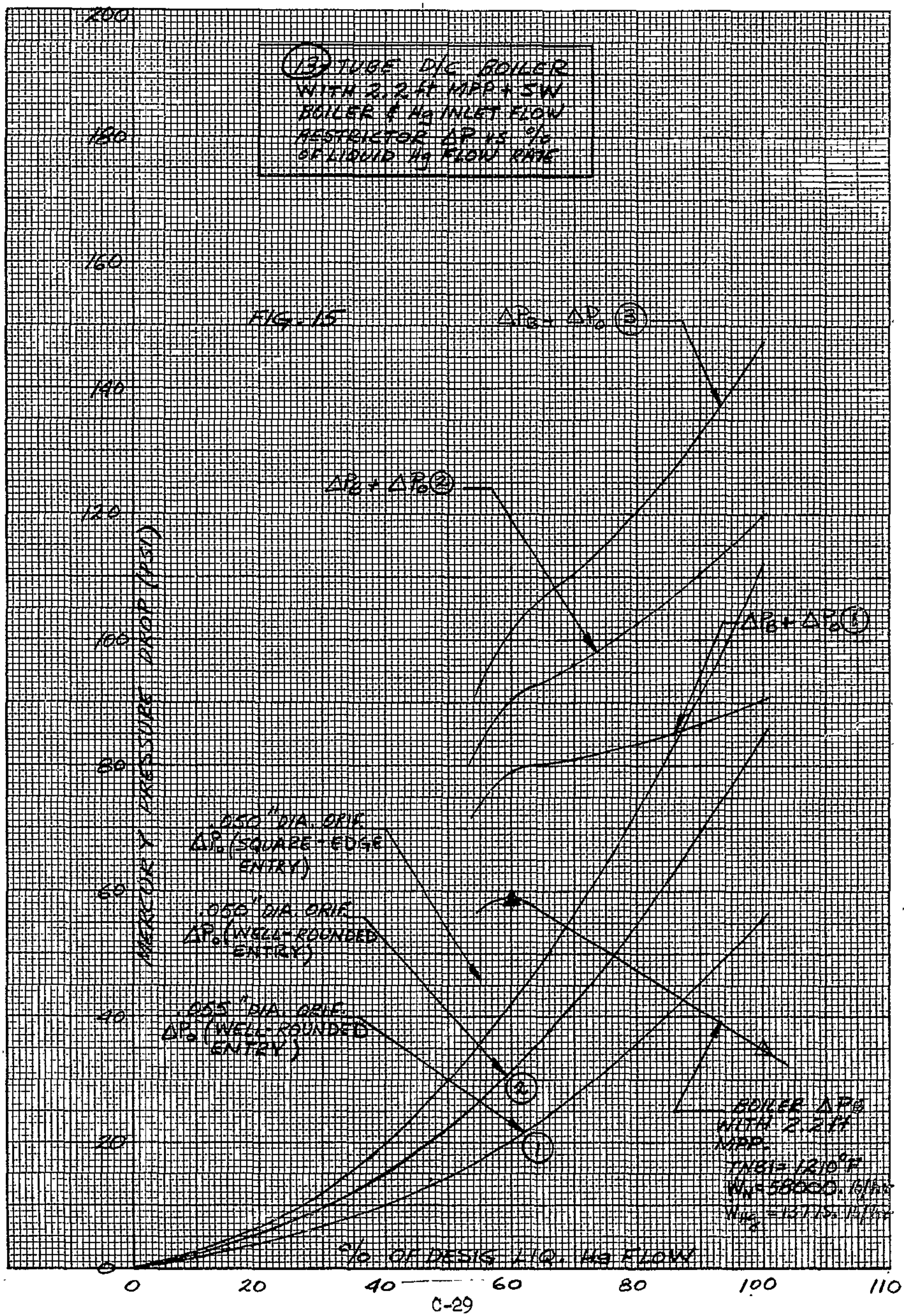

BOILER Hg-SIDE ΔP VS.
% OF DESIGN LIQ. Hg FLOW
EFFECTIVE PLUG LENGTH = 22 FT
NOTES:
1.) NO. OF TUBES = 13
2.) ORIFICE PRESSURE DROP NOT INCLUDED.
3.) ∆ - FROM A.J. SELLERS COMPUTER CALCULATIONS.
4.) ▲ - INTERPOLATED FROM FIGURES 12, 13 & 14.
5.) BOILER HAS DOUBLE CONTAINMENT AND SWIRL WIRE.
W = 4460. lb/hr/tube
= 58000. lb/hr TOTAL
T NBL = 1210°F
1185°F
PRESSURE DROP (PSI)
% OF DESIGN LIQ Hg FLOW
200
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100

FIG. 14


13 TUBE D/C BOILER
WITH 2.2 ft MPP + SW
BOILER & Hg INLET FLOW
RESTRICTOR ΔP vs %
OF LIQUID Hg FLOW RATE
FIG-15
ΔPB + ΔPo (3)
ΔPB + ΔPo (2)
ΔPB + ΔPo (1)
.050" DIA. ORIF.
ΔPo (SQUARE-EDGE ENTRY)
.050" DIA. ORIF.
ΔPo (WELL-ROUNDED ENTRY)
.055" DIA. ORIF.
ΔPo (WELL-ROUNDED ENTRY)
(2)
(1)
BOILER ΔPB
WITH 2.2 ft
MPP.
TNBI = 1210°F
WN = 5800. lb/hr
WHg = 13715. lb/hr
MERCURY PRESSURE DROP (PSI)
% OF DESIG LIQ. Hg FLOW
0
20
40
60
80
100
120
140
160
180
200
0
20
40
60
80
100
110

PREDICTED WATER FLOW PRESSURE DROP
OF
SWAGED PLUG INSERT AND TUBE ASSY'S

THE METHOD OF ANALYSIS UTILIZES THE REYNOLDS NUMBER ANALOGY.

$$RE_{H_2O} = RE_{Hg(LIQ)} \qquad (1)$$

$$\left(\frac{V D_e \rho}{\mu}\right)_{H_2O} = \left(\frac{V D_e \rho}{\mu}\right)_{Hg(LIQ)} \qquad (2)$$

$$V = \dot{W} / A\rho \qquad (3)$$

SUBSTITUTING (3) INTO (2) GIVES:

$$\left(\frac{\dot{W} D_e}{A \mu}\right)_{H_2O} = \left(\frac{\dot{W} D_e}{A \mu}\right)_{Hg(LIQ)} \qquad (4)$$

SINCE D_e/A IS CONSTANT:

$$\left(\frac{\dot{W}}{\mu}\right)_{H_2O} = \left(\frac{\dot{W}}{\mu}\right)_{Hg(LIQ)} \qquad (5)$$

THE TOTAL PRESSURE DROP ACROSS THE PLUG INSERT CAN BE EXPRESSED AS THE SUM OF THE FRICTION LOSS, AND ENTRANCE/EXIT EFFECTS LOSSES. SUCH THAT:

$$\Delta P = \Delta P_{FRICT.} + \Delta P_{ENT./EX.}, \text{ psid} \qquad (6)$$

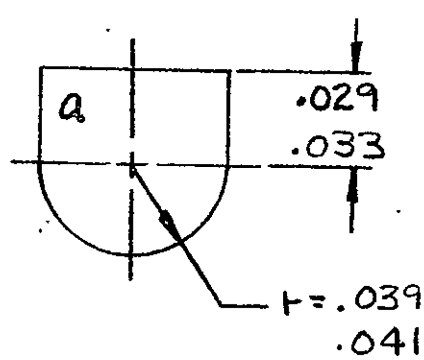
$$\Delta P_{FRICT.} = f_{ex}\,(L_e/D_e)\left[G^2/(2)(g_c)(\rho)(144)\right], \text{ psi} \qquad (7)$$

WHERE f_{ex} = FRICTION FACTOR DETERMINED EXPERIMENTALLY. *FROM REFERENCE 1.*
L_e = EQUIVALENT FLOW PATH LENGTH, IN.
D_e = EQUIVALENT DIAMETER, IN.
G = MASS VELOCITY = $\dot{W}/A$, LB/SEC-FT^2
ρ = FLUID DENSITY, LB/FT^3
g_c = GRAVITY CONSTANT, FT/SEC^2

$$\Delta P_{ENT/EX} = K_{ex}\,(L_e/D_e)\left[G^2/(2)(g_c)(\rho)(144.)\right], \text{ psi} \qquad (8)$$

WHERE K_{ex} = *ENTRANCE & EXIT LOSS COEFFICIENT EXPERIMENTALLY DETERMINED IN REFERENCE 1 FOR A 5-GROOVE MULTIPASSAGE PLUG INSERT AND EXTRAPOLATED FOR 16 PASSAGES. SEE FIGURE 1.*

THE FLOW PATH GEOMETRY IS AS FOLLOWS:



CROSS-SECTION OF A SINGLE GROOVE.

STK. NO. D-1-103

MINIMUM AREA, PERIMETER & EQUIVALENT DIA.

$a_1 = .00464$ SQ. IN.

$p_1 = .2586$ IN.

$De_1 = .0716$ IN. $= 4a_1/p_1$

MAXIMUM AREA, PERIMETER & EQUIVALENT DIA.

$a_2 = .00534$ SQ. IN.

$p_2 = .2768$ IN

$De_2 = .0770$ IN

THE EQUIVALENT FLOW PATH LENGTH IS:

$L_e = 35.6$ IN.

FLUID PROPERTIES :

$T_{H_2O} = 70°F$
$\rho_{H_2O} = 62.3$ LB/FT^3
$\mu_{H_2O} = 2.37$ LB/HR-FT

$T_{Hg} = 350°F$
$\rho_{Hg} = 822°F$
$\mu_{Hg} = 2.6$ LB/HR·FT

SUBJECT BRDC BOILER NO. 5 BY G. LOMBARD WORK ORDER

CALCULATION OF WATER ΔP BASED ON
MINIMUM FLOW PASSAGE DIMENSIONS

$$RE_{H_2O} = 1.76 \times 10^4 (\dot{W}_{H_2O}) \text{ , DIM.}$$

$$G_{H_2O} = 1.94 \times 10^3 (\dot{W}_{H_2O}) \text{ , LB/SEC-FT}^2$$

$$\left[G^2_{H_2O}/(2)(g_c)(\rho)(144.)\right] = 6.51 (\dot{W}_{H_2O})^2 \text{ , PSI}$$

$$\frac{L_e}{D_{e_1}} = 497.$$

$$\dot{W}_{H_2O} = 0.912 (\dot{W}_{Hg}) \text{ , LB/SEC}$$

FLOW RATES:

$\dot{W}_{Hg}$ (TOTAL) LB/HR	$\dot{W}_{Hg}$ LB/SEC-TUBE	$\dot{W}_{H_2O}$ LB/SEC-TUBE
6000.	.139	.127
10000.	.232	.212
14000.	.325	.296

WATER FLOW ΔP BASED ON <u>MINIMUM</u> DIMENSIONS

$\dot{W}_{H_2O}$	$6.51(\dot{W}_{H_2O})^2$	$f_{ex}\frac{L_e}{D_e}$	K_{ex}	$\Delta P_{FRICT.}$	$\Delta P_{EN/EX}$	ΔP
.127	.105	22.4	12.0	2.35	1.26	3.61
.212	.293	18.4	12.0	5.39	3.52	8.91
.296	.570	15.9	12.0	9.07	6.84	15.91

$\dot{W}_{H_2O}$	RE_{H_2O}	f_{ex}
.127	2240.	.045
.212	3730.	.037
.296	5210.	.032

SUBJECT BRDC BOILER NO. 5 BY G. LOMBARD WORK ORDER

CALCULATION OF WATER ΔP BASED ON
MAXIMUM FLOW PASSAGE DIMENSIONS.

$$RE_{H_2O} = 1.615 \times 10^{4} (\dot{W}_{H_2O}) \text{, DIM.}$$

$$G_{H_2O} = 1.685 \times 10^{3} (\dot{W}_{H_2O}) \text{, LB/SEC-FT}^2$$

$$\left[G_{H_2O}^2 / (2)(g_c)(\rho)(144.)\right] = 4.93 (\dot{W}_{H_2O})^2 \text{, PSI}$$

$$\frac{Le}{De_2} = 462.$$

WATER FLOW RATES ARE THE SAME AS
GIVEN ON PAGE 4.

WATER FLOW ΔP BASED ON MAXIMUM DIMENSIONS

$\dot{W}_{H_2O}$	$4.93\dot{W}_{H_2O}^2$	$f_{ex}\frac{L_e}{De_2}$	K_{ex}	ΔP_{FRICT}	$\Delta P_{EN/EX}$	ΔP
.127	.080	20.9	12.0	1.67	0.96	2.63
.212	.222	17.6	12.0	3.91	2.66	6.57
.296	.432	15.25	12.0	6.60	5.20	11.80

$\dot{W}_{H_2O}$	RE_{H_2O}	f_{ex}
.127	2050.	.0452
.212	3420.	.0380
.296	4780.	.0330

01-071-002

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

DATE SEPT. 3, 1970

SUBJECT BRDC BOILER NO. 5 BY G. LOMBARD WORK ORDER

THE MAXIMUM & MINIMUM PREDICTED WATER FLOW PRESSURE DROP VALUES ARE PLOTTED IN FIGURE 2.

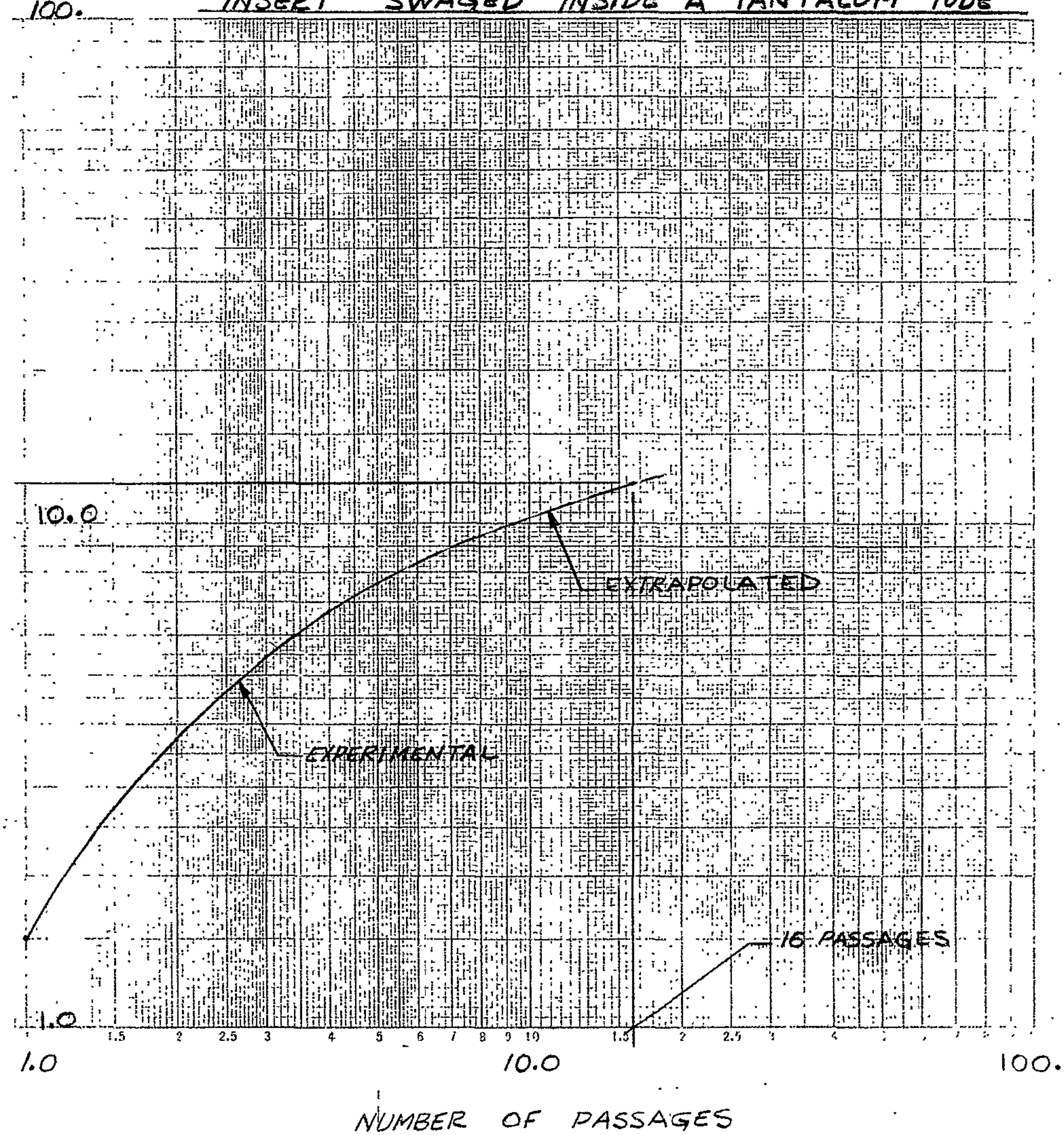
REFERENCES:

1. SELLERS, A.J., FORCED CONVECTION MERCURY BOILING - EXPERIMENTAL INVESTIGATION USING A HELICAL MULTIPASSAGE PLUG INSERT IN A ONCE THROUGH BOILER, AGC TECHNICAL MEMORANDUM 4934:67:459 DATED 31 MARCH 1967.

STK. NO. D-1-103

FIGURE 1.

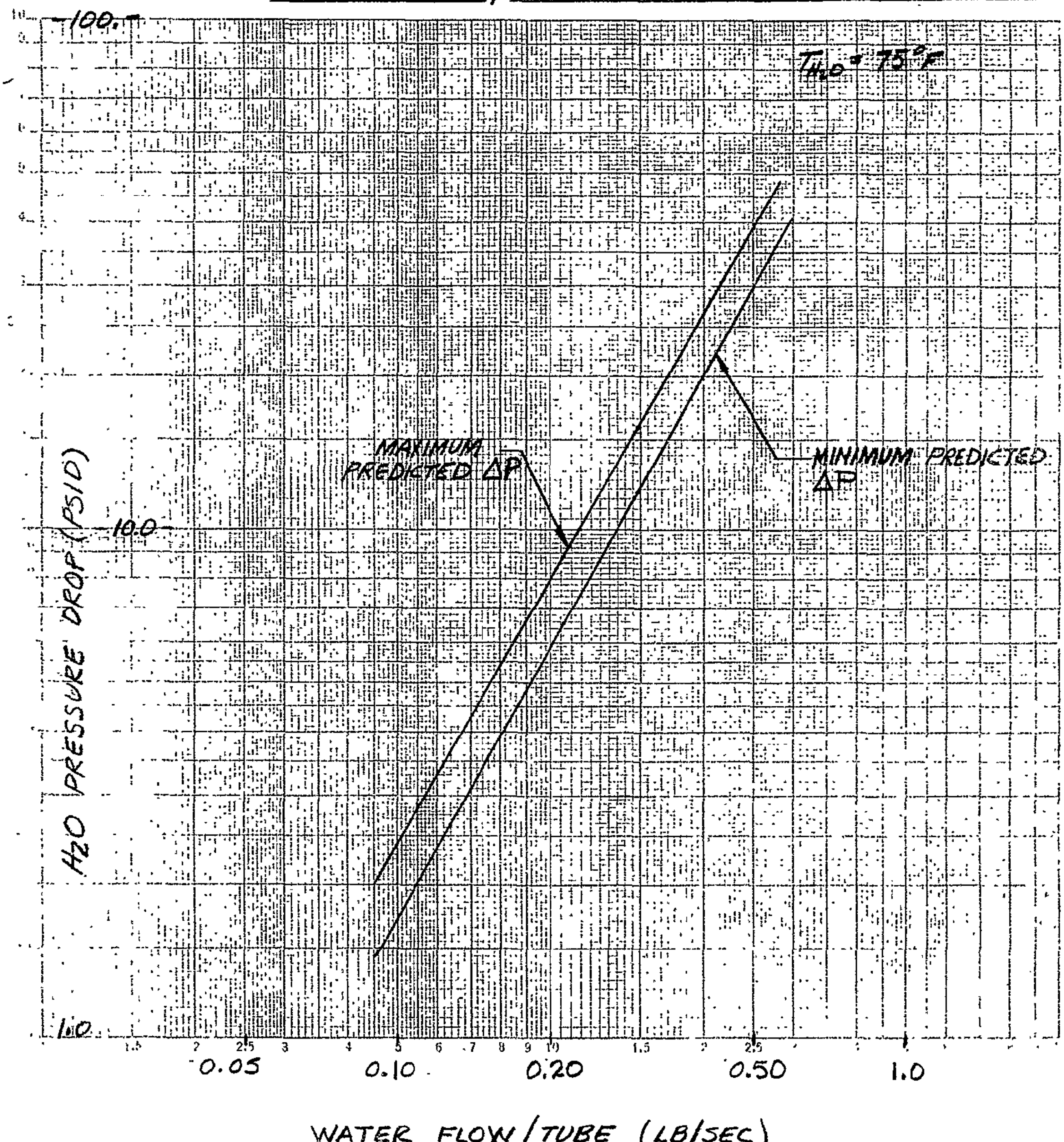
LOSS COEFFICIENT, K_{EX}, VERSUS THE NUMBER OF PASSAGES FOR A MULTI-PASSAGE PLUG INSERT SWAGED INSIDE A TANTALUM TUBE



3 SEPT. 1970
G. LOMBARD

FIGURE 2.

PREDICTED WATER FLOW ΔP VS WATER FLOW FOR BRDC BOILER NO. 5 SWAGED PLUG INSERT/TUBE ASSEMBLY - P/N 1268



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APPENDIX D

BRDC BOILER NO. 5, PRESSURE DROP THROUGH NaK SIDE OF THE BOILER

NaK - SIDE HYDRAULIC TEST RESULTS

ON A PLASTIC MODEL OF

BRDC BOILER NO. 5

G. L. Lombard, Static Components

INTRODUCTION

The purpose of hydraulically testing a shell-side model of the SNAP-8 NaK-to-Hg boiler is to confirm the NaK flow mixing characteristics and pressure drop requirements are met by the current design. Tests similar to those discussed herein were conducted on BRDC Boiler No. 4 which was a 7-tube design. The results of these tests accurately predicted NaK-side pressure drop. It was demonstrated that a helical wire turbulator, wound about the tube bundle was definitely advantageous in promoting turbulent mixing of the NaK fluid and subsequent uniform circumferential temperature distribution.

Pressure drop tests were performed at water flow rates based on the Reynolds number analogy with the loss coefficient expressed in terms of the shell-side velocity head. Dye injection tests to demonstrate shell-side mixing capabilities were performed with water velocities equivalent to NaK velocities.

The remainder of this report presents the tests performed, results and methods of analyzing the data.

SUMMARY

Results of the dye injection tests run at water velocities of 5.0, 4.0, and 3.0 feet per showed that the fluid is mixed and that the wire coil pitch and wire diameter of 6.0 inches and .125 inch, respectively, are satisfactory.

The loss coefficients for the tube bundle supports, wire coils and inlet & exit manifolds are summarized below (values are based on shell-side velocity head) :

1. $K_{sp} = 0.50$/Spacer @ $70000 < Re < \infty$

2. $K_{man.} = 5.65$/Manifold @ $70000 < Re < \infty$

3. $K_{coil} = 0.50$/ft of Coil @ $70000 < Re < \infty$

The total boiler NaK-side pressure drop at 58,000. lb/hr and temperature equal to 1135 F is 1.69 psid. This value is well within the system requirement of 3.0 psid.

In conclusion, the NaK-side fluid dynamics of the proposed design are satisfactory.

PRESSURE DROP TESTS

A full scale cross-sectional model boiler containihg three (3) tube bundle supports, twelve (12) flattened oval tubes, two (2) helical wire coils (one right-hand, one left-hand and both with a 6.0 inch pitch) wound around the 3.5 inch O.D center tube and the tube bundle and the inlet/exit manifolds is shown in Figure 1. The pressure drop readings were measured across three sections of the test piece as shown in Figure 1.

The water flow rates were determined on a equal Reynolds number as given by the following:

$$RE_{H2O} = RE_{NaK}$$

and

$$\dot{W}_{H_2O} = \dot{W}_{NaK} (\mu_{H_2O} / \mu_{NaK})$$

The physical properties of NaK and water are as follows:

Water temperature	75 °F
Density	62.26 lb/cu. ft.
Viscosity	2.20 lb/hr-ft.
NaK temperature	1135 °F (Average)
Density	45.3 lb/cu. ft.
Viscosity	0.38 lb/hr.-ft.

therefore:

$$\dot{W}_{H_2O} = 5.80\ \dot{W}_{NaK}$$

Data of pressure drop across sections 1 - 2, 2 - 5 and 3 - 4 are listed in Table 1 over a range of flows from 32.0 lb/sec to 91.0 lb/sec. Listed in Table 2 are the calculated loss coefficients (based on the shell-side velocity head) and Reynolds numbers for the different water flows. It should be noted that the coil loss coefficient excludes friction. The coil pressure losses were obtained by subtracting the pressure loss (3-4) multiplied by 3.0 (the total number of spacers between 2-5) and ~~axial~~ ΔP_{AX} from pressure loss (2-5) as follows:

$$\Delta P_{CO} = \Delta P_{2-5} - 3\left(\Delta P_{3-4}\right) - \Delta P_{ax}\ ,\ \text{psi}$$

Plotted in Figures 3 and 4 are manifold pressure drop, wire coil and spacer pressure drops, respectively, versus water flow in lb/sec. In Figure 5, the shell-side velocity head, H_s, is plotted versus water flow for convenience when calculating the head loss coefficients. Figures 6,7 and 8 give manifold spacer and wire turbulator coil loss coefficients versus Reynolds number.

To generalize the wire turbulator coil loss calculations for NaK flow the coefficient is expressed on a per foot of axial coil length basis. Table 3 gives the equations for Reynolds number and H_s used in the analysis.

In the following calculationsthe NaK-side pressure loss for a full-scale BRDC Boiler No. 5 is made for $\dot{W}n$=58000.lb/hr and an average temperature of 1135°F

NaK density	45.3 lb/cu.ft.
NaK viscosity	0.38 lb/hr.-ft.

Velocity: $V_n = (58000/3600)(144.0/14.25)(1/45.3) = 3.60$ ft/sec.

Reynolds No. : $RE_n = (3.60)(.915)(45.3/0.38)(300.) = 117700$

Shell-side velocity head: $H_s = (3.60)^2(45.3)/(2g_c 144.) = .0633$ psi

Spacer pressure loss:

$\Delta P_{sp} = nK_{sp}\ H_s$, psi where n = 7 spacers

$\Delta P_{sp} = (7.0)(0.50)(.0633) = 0.222$ psid

Inlet & Outlet manifold loss:

$\Delta P_{man.} = nK_{man}(H_s)$, psi where n = 2 manifolds

$\Delta P_{man.} = (2)(5.65)(.0633) = 0.715$ psi

NaK turbulator coils loss:

$\Delta P_c = (L)(F_c)(H_s)$, psi where L = 10.0 feet

$\Delta P_c = (10.)(0.5)\ (.0633) = 0.317$ psi

Frictional pressure loss:

$\Delta P_f = (f_{ax})\left(\frac{L}{D}\right) H_s$, psi where fax = .0171
L = 21. ft
D = 0.915 in

$\Delta P_f = (.0171)\ (12.)(21.)(.0633)/(0.915) = 0.298$ psi

Pressure loss due to "S" bends:

$\Delta P_b = (nK_b)(H_s)$, psi

Where K_b = function of R/d ; R = 25 in; d = 1.88 in

R/d = 13.3 and from ref. 1 page 318, Fig 137

K_b = 1.08 ; and n = the number of 180° bends = 2.0

$\Delta P_b = (2)(.0633)(1.08) = 0.137$ psid

The predicted total NaK-side pressure loss across the boiler is:

$\Delta P_t = 0.222 + 0.715 + 0.317 + 0.298 + 0.137$ psid

$\Delta P_t = 1.69$ psid

Shown in Figure 9 is predicted NaK-side pressure drop versus NaK flow.

NaK - Side Mixing Tests

Fluid mixing was observed by injecting dye (food coloring) into the fluid stream as shown in Figure 2. These tests were performed at water velocities and Reynolds numbers tabulated below at a water temperature of $76^{\circ}F$.

H_2O Velocity, ft/sec	RE_{H_2O}
5.0	39100.
4.0	31200.
3.0	23400.

Visual observation of the fluid stream after injection revealed that complete mixing occurred within 1.5 feet downstream of the injection point at 5.0 ft/sec within 2.5 feet at 3.0 ft/sec. Mixing characteristics of the inlet and outlet manifolds were also observed at the same velocities as listed above. Complete mixing in the manifolds was evident. Photographs were taken during the dye injection tests as a means of recording these tests.

In comparing the Reynolds number at which the dye injection tests were performed they are substantially lower than the design value of 117700 ($\dot{W}$ = 58000. lb/hr) This was done for two reasons. One, at low Reynolds numbers, i.e. at water velocities equal to NaK velocities, observation of mixing is facilitated. Second, if adequate mixing was observed at these lowReynolds numbers then, at design conditions, good mixing would be assured in the boiler.

CONCLUSIONS

1. The expected NaK-side pressure drop for this design (1.69 psid) is well within the system requirement of 3.00 psid.

2. The design of the NaK turbulator coils is satisfactory for the purpose of promoting fluid mixing during boiler operation over a range of NaK flows from 30000 to 58000 lb/hr.

REFERENCES

1. Vennard, John K., Elementary Fluid Mechanics

01-071-002

QUADRILLE WORK SHEET

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SUBJECT BRDC BOILER NO.5
PLASTIC FLOW MODEL

BY G. LOMBARD

DATA TABULATION:

TABLE 1

$\dot{W}_{H2O}$ (LB/SEC)	$\Delta P_{①②}$ (PSI)	$\Delta P_{③④}$ (PSI)	$\Delta P_{②⑤}$ (PSI)	$^{*}\Delta P_{AX}$ (PSI)	ΔP_{COIL} (PSI)
32.0	1.05	0.101	1.51	0.426	0.78
35.8	1.30	0.126	1.87	0.519	0.98
41.0	1.70	0.160	2.40	0.660	1.26
48.0	2.25	0.215	3.22	0.871	1.70
53.0	2.90	0.255	3.85	1.038	2.05
60.0	3.55	0.326	4.90	1.288	2.63
68.0	4.65	0.408	5.31	1.610	3.31
75.0	5.60	0.50	7.41	1.913	4.00
81.0	6.60	0.58	8.64	2.19	4.71
90.5	8.20	0.716	10.67	2.67	5.85

$\Delta P_{①②} = \Delta P_{MAN.}$

$\Delta P_{③④} = \Delta P_{SP}$

* $\Delta P_{AX} = f_{AX} \frac{L}{D} H_S$; $f_{AX} = .316 / Re^{.25}$ FOR 8.1 FT $= L$

$\Delta P_{COIL} = \Delta P_{②⑤} - \Delta P_{AX} - 8.0\,(\Delta P_{③④})$

STK. NO. D-1-10

TABLE 2 - LOSS COEFFICIENTS

W_{H_2O} (LB/SEC)	RE_{H_2O}	$\Delta P_{MAN.}$ (PSI)	$\Delta P_{SP.}$ (PSI)	ΔP_{COIL} (PSI)	① $f_{AX.}$	② $K_{MAN.}$	③ $K_{SP.}$	④ F_{COIL}
32.0	40350.	1.05	0.101	0.78	.0223	5.83	.561	.535
35.8	45080.	1.30	0.126	0.98	.0217	5.78	.560	.538
41.0	51600.	1.70	0.160	1.26	.0210	5.74	.540	.525
48.0	60500.	2.25	0.215	1.70	.0202	5.54	.529	.516
53.0	66800.	2.90	0.255	2.05	.0197	5.85	.518	.510
60.0	75600.	3.55	0.326	2.63	.0191	5.60	.513	.511
68.0	85600.	4.65	0.408	3.31	.0185	5.68	.497	.500
75.0	94500.	5.60	0.50	4.00	.0180	5.60	.500	.494
81.0	102000.	6.60	0.58	4.71	.0177	5.66	.498	.500
90.5	114000.	8.20	0.716	5.85	.0172	5.62	.481	.495

① $f_{AX} = 0.316 / RE^{.25}$ BLASIUS FRICTION FACTOR

② $K_{MAN.} = \Delta P_{MAN.} / H_{SHELL}$ & REPRESENTS LOSS COEFFICIENT FOR ONE MANIFOLD.

③ $K_{SP.} = \Delta P_{SP.} / H_{SHELL}$ & REPRESENTS THE LOSS COEFFICIENT FOR ONE SPACER.

④ $F_{COIL} = \Delta P_{COIL} / (8.1)(H_{SHELL})$ WHERE 8.1 FT WAS THE LENGTH OF WIRE COIL BETWEEN PRESSURE TAPS ② & ⑤

⑤ H_{SHELL} = SHELL-SIDE VELOCITY HEAD (PSI), UPON WHICH ALL EXPERIMENTAL LOSS COEFFICIENTS ARE BASED.

SUBJECT BRDC BOILER NO. 5 PLASTIC FLOW MODEL BY G. LOMBARD

TABLE 3 - EQUATIONS

REYNOLDS NUMBER:

$$RE = \left(V, \frac{ft}{sec}\right)\left(D_E, in\right)\left(\rho, \frac{lb}{ft^3}\right)\left(\frac{1}{\mu, \frac{lb}{ft\text{-}hr}}\right)\left(3600 \frac{sec}{hr}\right)\ldots$$

$$\ldots\left(\frac{1}{12.0 \frac{in}{ft}}\right)$$

$$RE = (300.)(V)(D_E)(\rho)/\mu$$

VELOCITY HEAD:

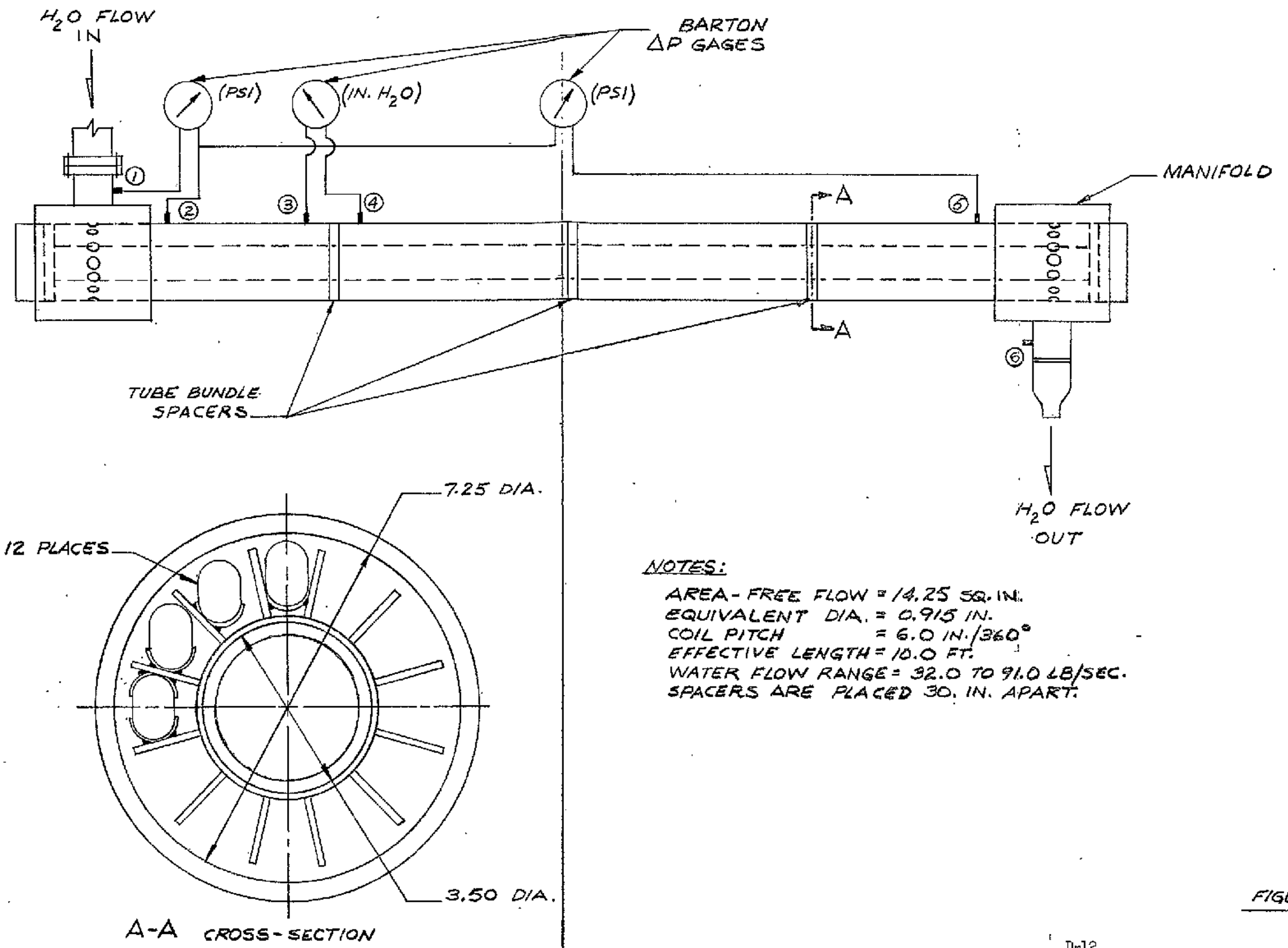
$$H = \left(V, \frac{ft}{sec}\right)^2\left(\rho, \frac{lb}{ft^3}\right) \Big/ \left[\left(2 g_c, \frac{ft}{sec^2}\right)\left(144 \frac{in^2}{ft^2}\right)\right], psi$$

$$H = (V)^2(\rho)/9270., psi$$

DARCY-WEISBACH EQUATION:

$$\Delta P = f \frac{L}{D_E} H, psi$$

OR $$\Delta P = K \cdot H, psi \quad \text{WHERE} \quad K = f \frac{L}{D_E}$$



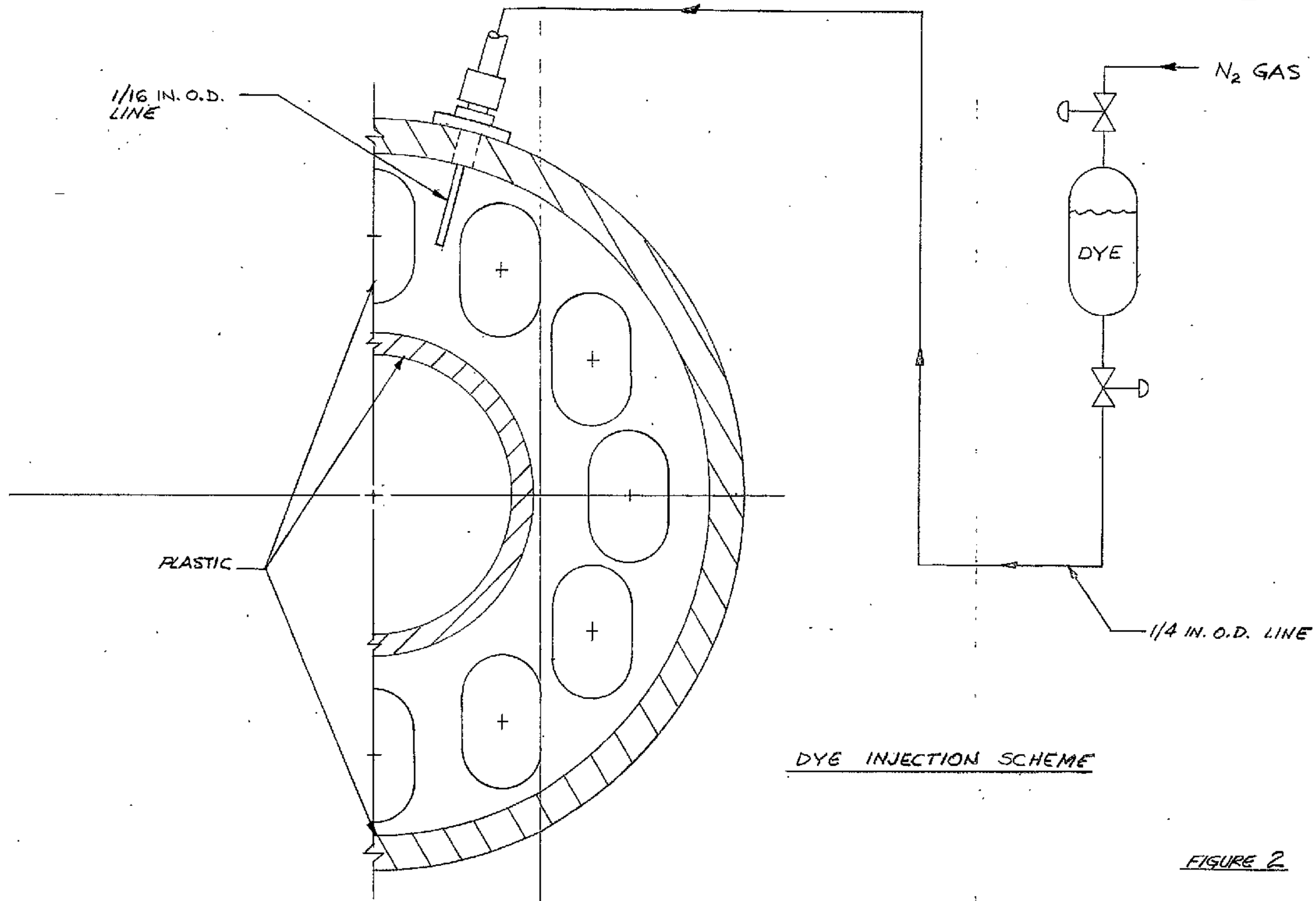
NOTES:

AREA - FREE FLOW = 14.25 SQ. IN.
EQUIVALENT DIA. = 0.915 IN.
COIL PITCH = 6.0 IN./360°
EFFECTIVE LENGTH = 10.0 FT.
WATER FLOW RANGE = 32.0 TO 91.0 LB/SEC.
SPACERS ARE PLACED 30. IN. APART.

FIGURE 1

FOLDOUT FRAME 1

FOLDOUT FRAME 2



DYE INJECTION SCHEME

FIGURE 2

32-04

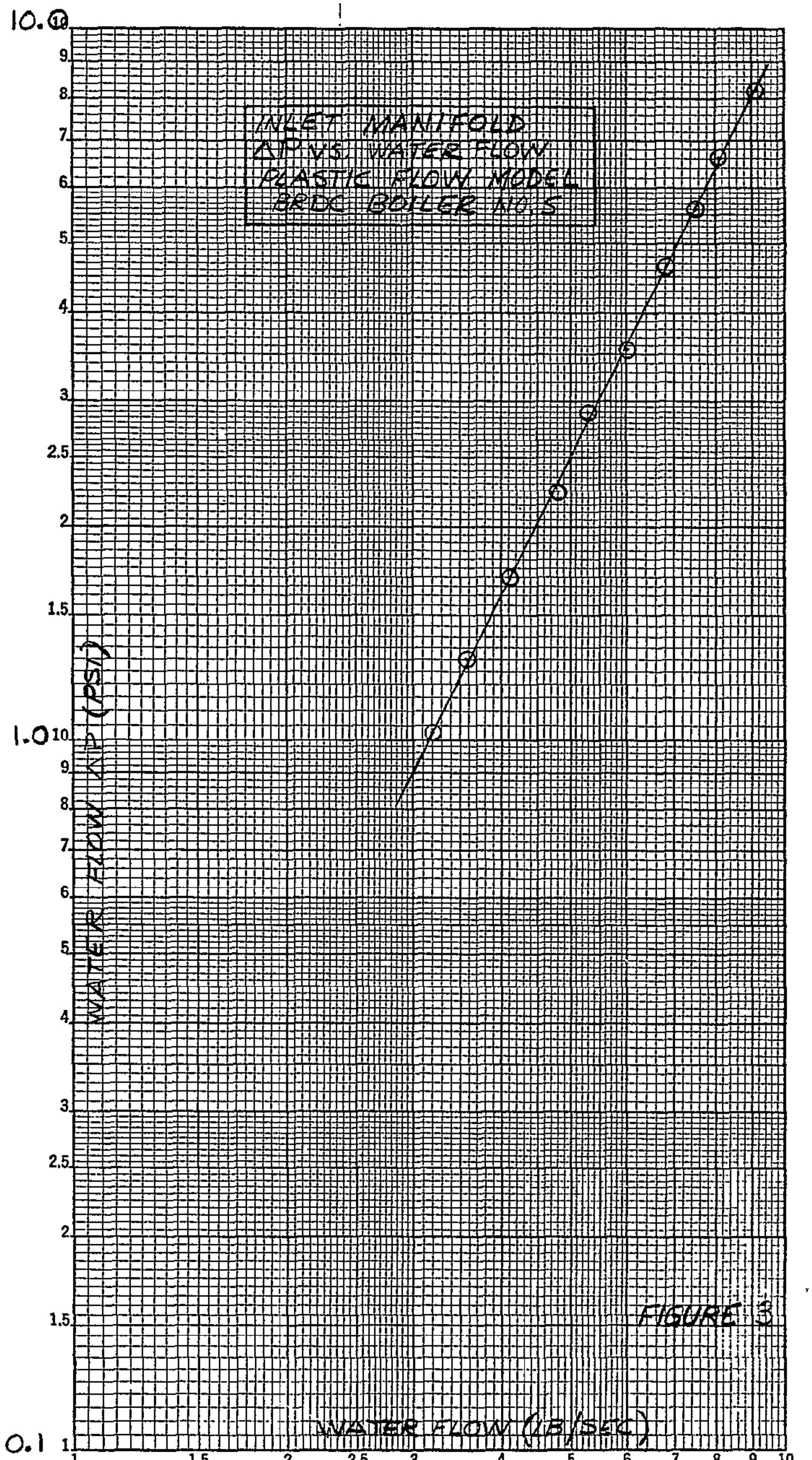
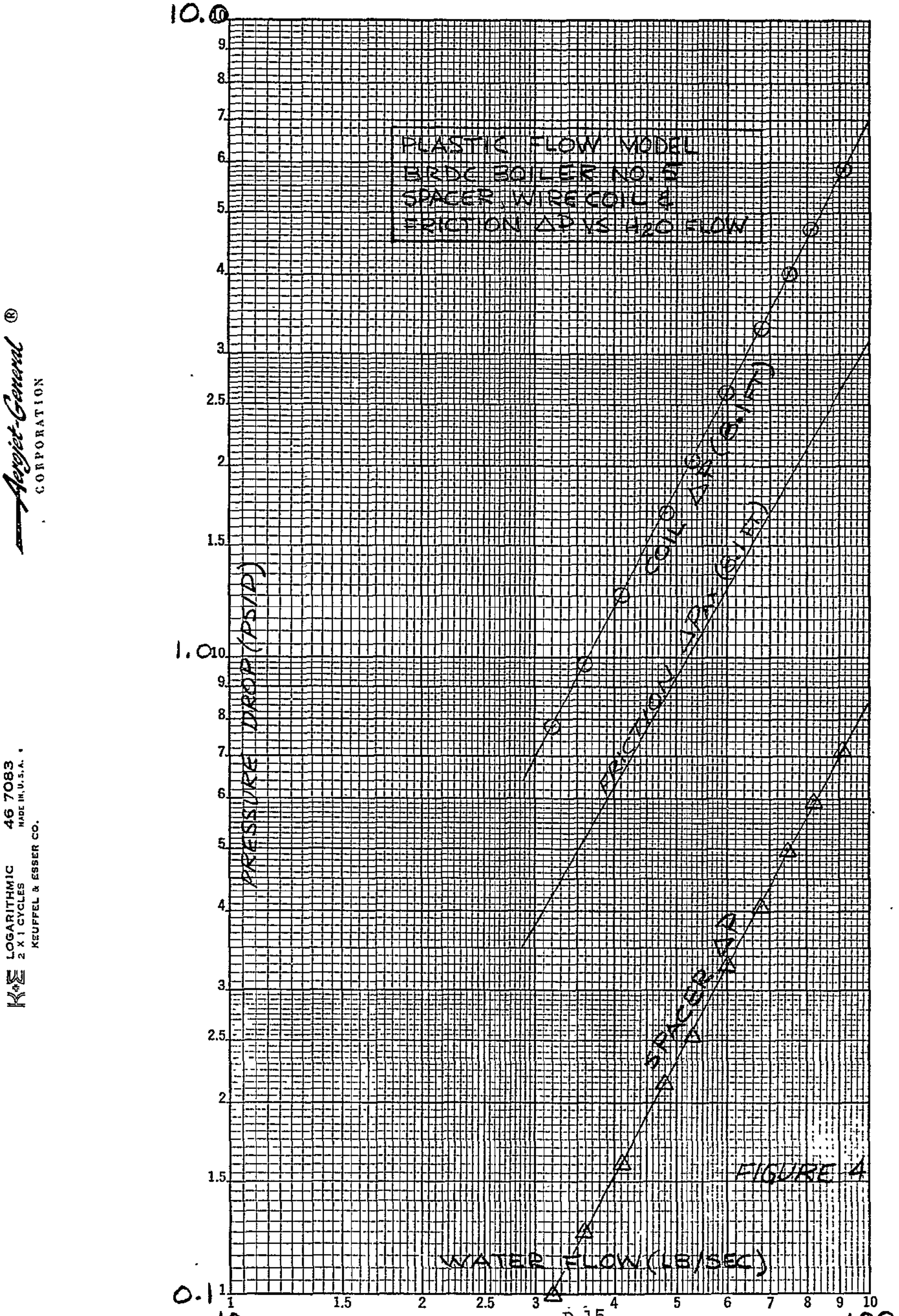

INLET MANIFOLD
ΔP VS. WATER FLOW
PLASTIC FLOW MODEL
BRDC BOILER NO. 5
WATER FLOW ΔP (PSI)
WATER FLOW (LB/SEC)
10.0
1.0
0.1
10.
100.

FIGURE 3


PLASTIC FLOW MODEL
BRDC BOILER NO. 5
SPACER, WIRE COIL &
FRICTION ΔP VS H2O FLOW
PRESSURE DROP (PSI/D)
COIL ΔP (0.1 FT)
FRICTION ΔP (0.1 FT)
SPACER ΔP
FIGURE 4
WATER FLOW (LB/SEC)
10.0
1.0
0.1
10.
100.
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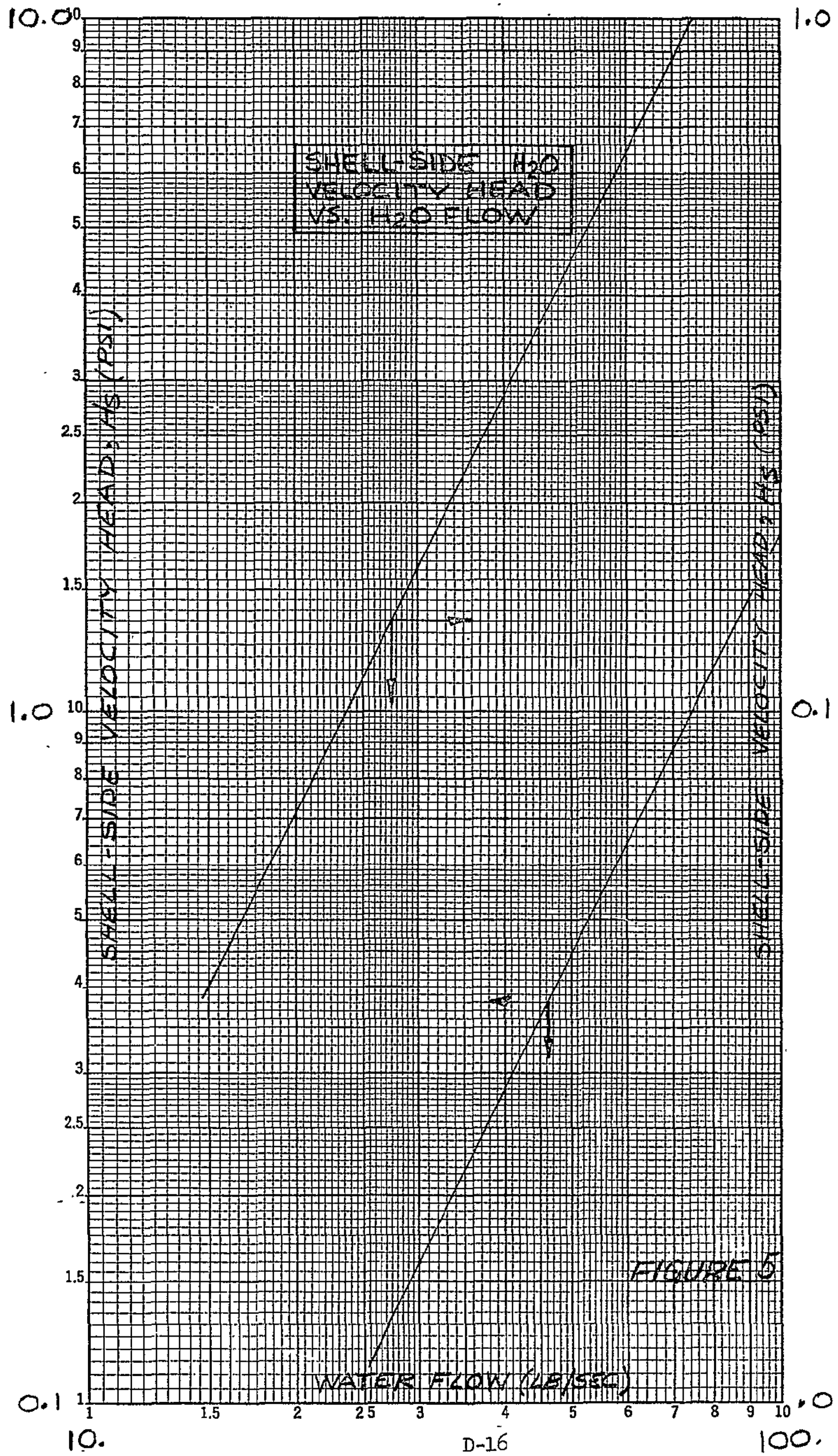
K+E LOGARITHMIC 2 X 1 CYCLES KEUFFEL & ESSER CO. 46 7083 MADE IN U.S.A.


SHELL-SIDE H2O
VELOCITY HEAD
VS. H2O FLOW
SHELL-SIDE VELOCITY HEAD, HS (PSI)
SHELL-SIDE VELOCITY HEAD, HS (PSI)
WATER FLOW (LB/SEC)
10.0
1.0
0.1
1.0
0.1
.01
10.
100.
FIGURE 5

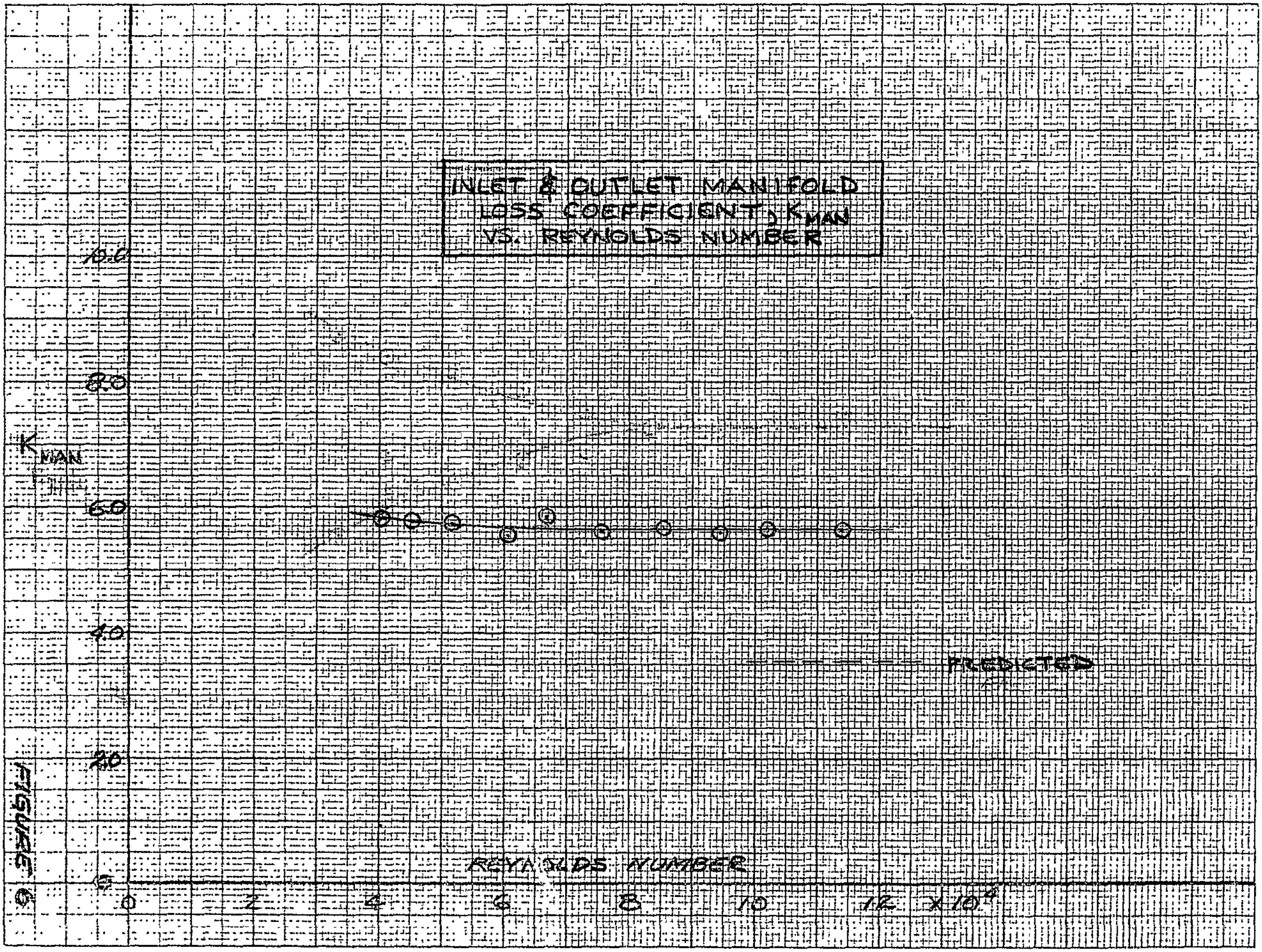

INLET & OUTLET MANIFOLD
LOSS COEFFICIENT, K_{MAN}
VS. REYNOLDS NUMBER
K_{MAN}
10.0
8.0
6.0
4.0
2.0
0
PREDICTED
REYNOLDS NUMBER
0
2
4
6
8
10
12
$\times 10^4$

FIGURE 6

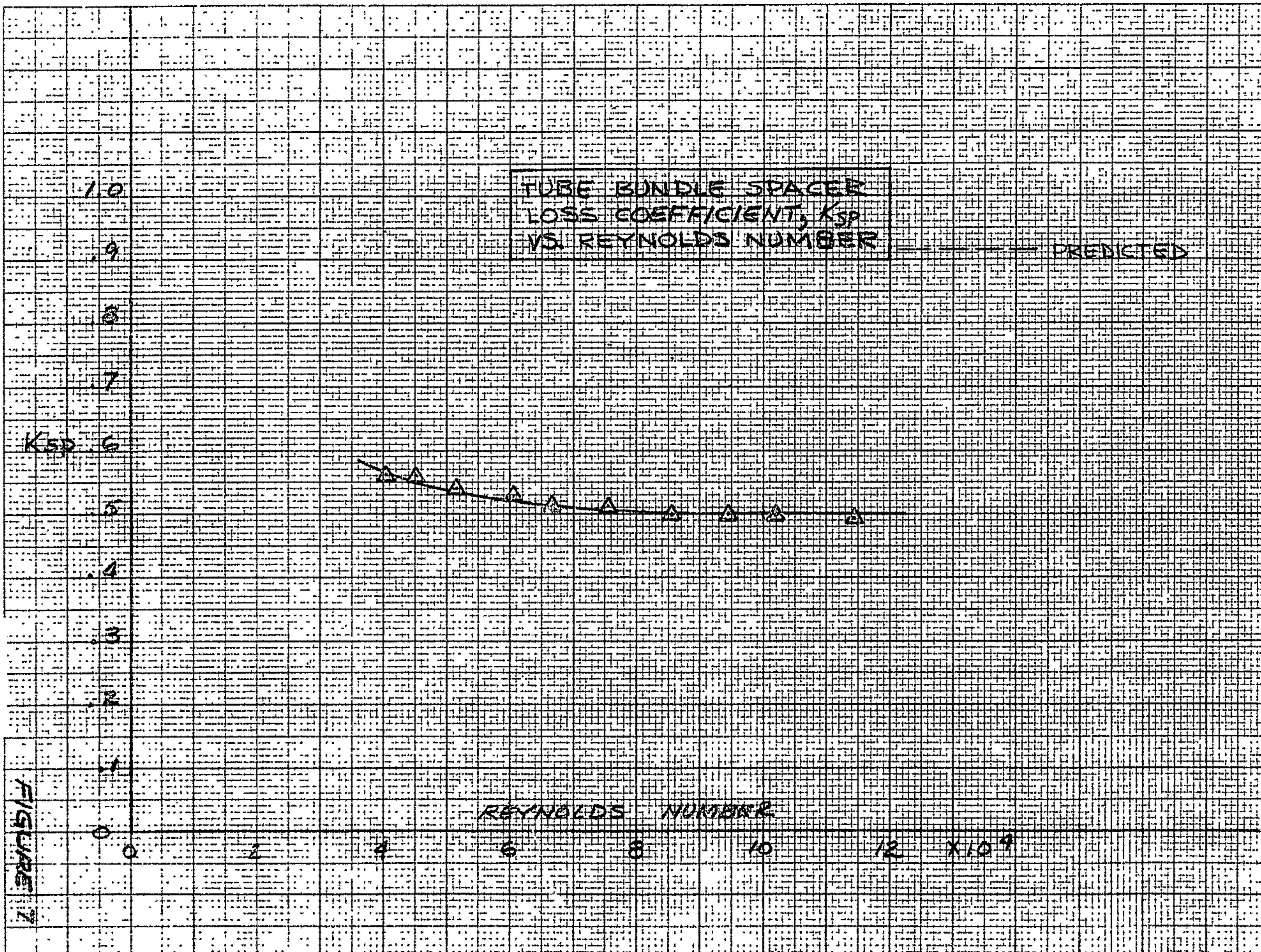

TUBE BUNDLE SPACER
LOSS COEFFICIENT, K_{SP}
VS. REYNOLDS NUMBER
PREDICTED
K_{SP}
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
2
4
6
8
10
12
X10^4
REYNOLDS NUMBER

FIGURE 7

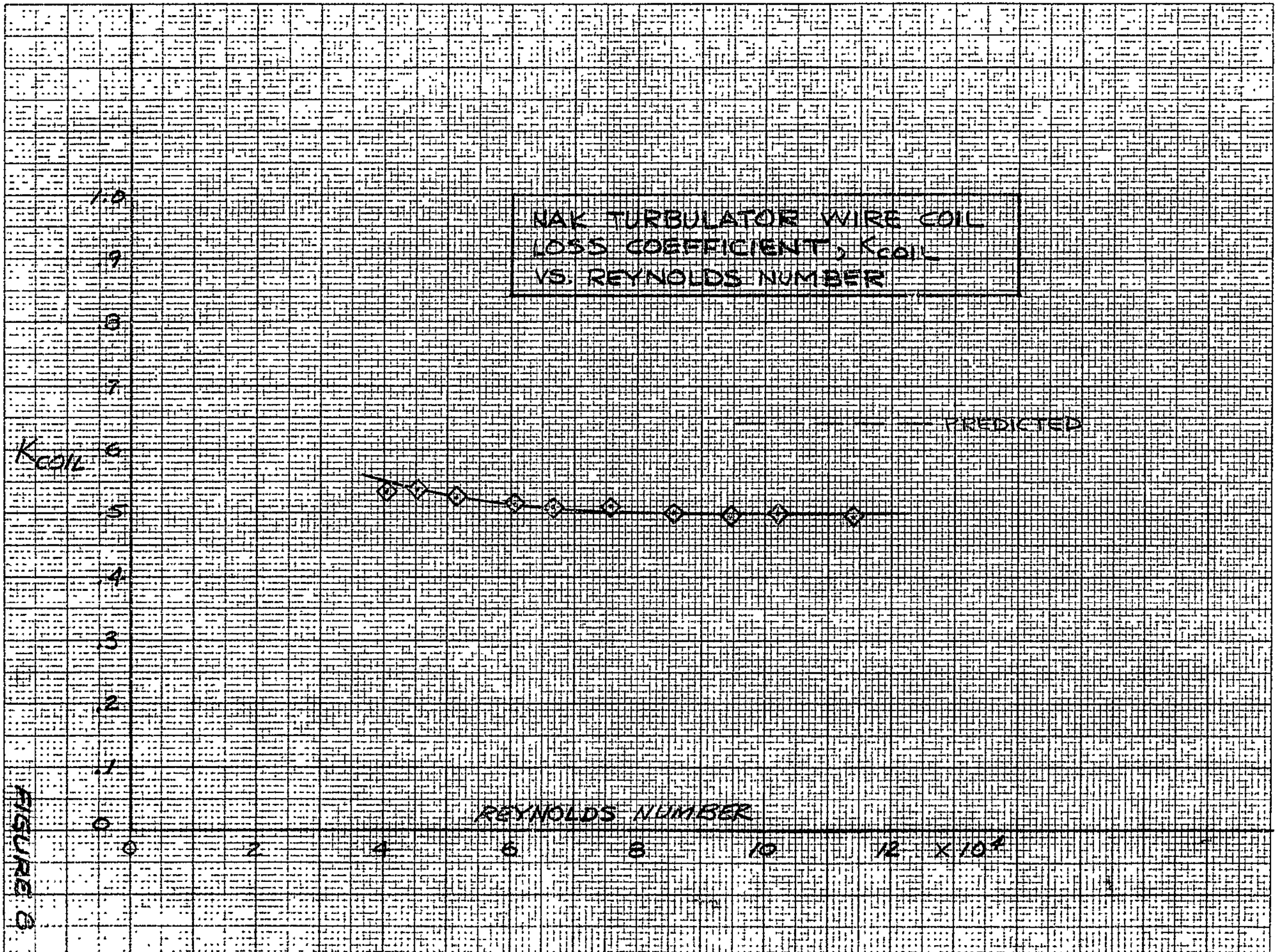
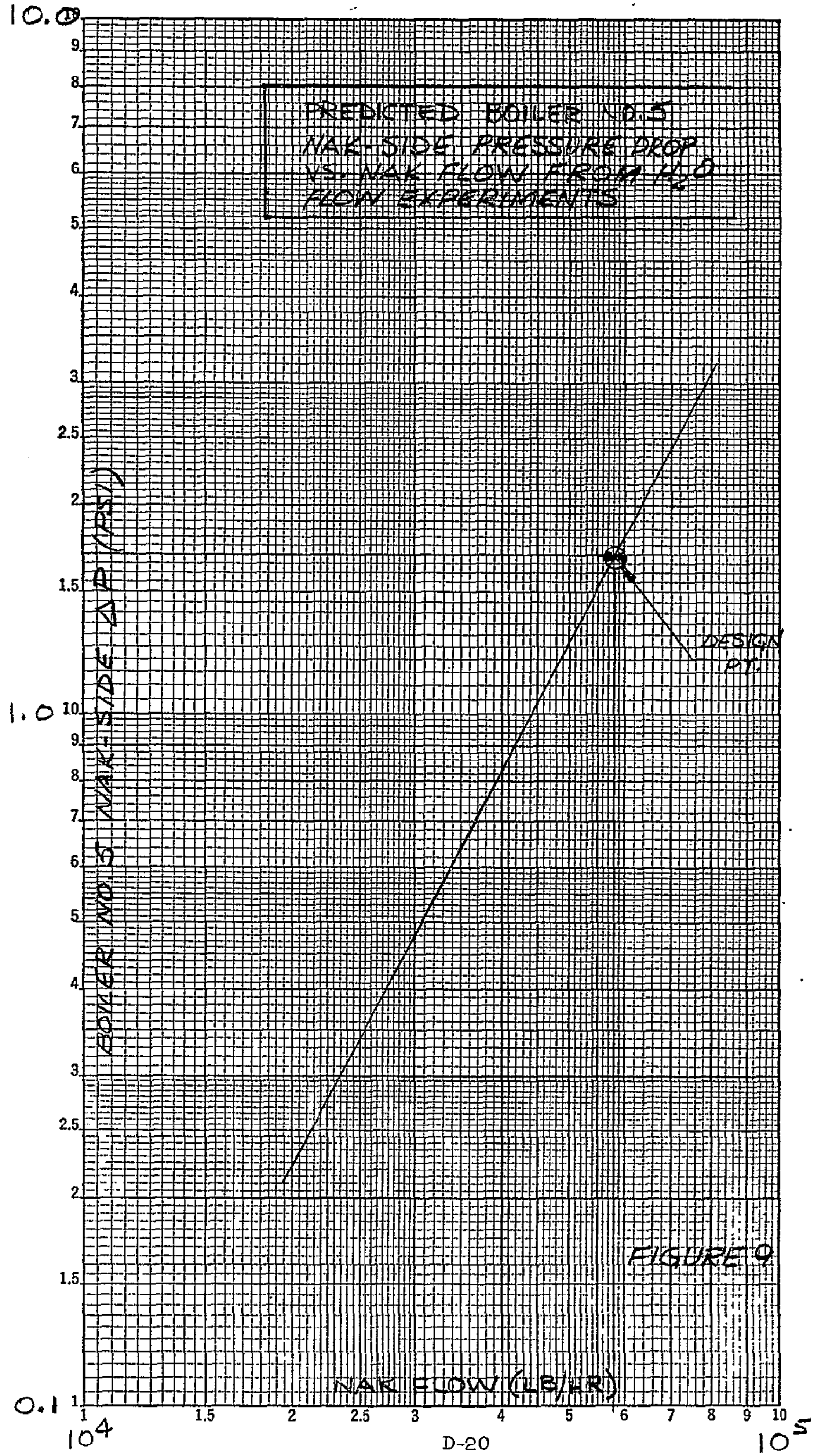

NAK TURBULATOR WIRE COIL
LOSS COEFFICIENT, K_{COIL}
VS. REYNOLDS NUMBER
PREDICTED
K_{COIL}
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
0
2
4
6
8
10
12
$\times 10^4$
REYNOLDS NUMBER

FIGURE 8


PREDICTED BOILER NO.5
NAK-SIDE PRESSURE DROP
VS. NAK FLOW FROM H_2O
FLOW EXPERIMENTS
BOILER NO.5 NAK-SIDE ΔP (PSI)
10.0
1.0
0.1
DESIGN PT.
FIGURE 9
NAK FLOW (LB/HR)
10^4
10^5

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DATE 7-30-70
W. O. NO. 1475-44-0117

PROJECT SNAP-8

SUBJECT
BRDC BOILER NO. 5, PRESSURE DROP THROUGH NaK-SIDE OF THE BOILER

ABSTRACT

Analytical calculations to determine the subject pressure drop are presented.

The overall pressure drop through the NaK side of the Boiler was calculated to be 1.50 PSID. The allowable PCS-G requirement is 3.0 PSID.

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KEY WORDS BRDC Boiler No. 5, NaK-Side Pressure Drop

AUTHOR		DEPT	REVIEWED	DATE	REVIEWED	DATE
R.Alena	R. Alena	7978	E S Chalpin	8/4/70	R W Marshall Jr	8/4/70

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QUADRILLE WORK SHEET

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AZUSA, CALIFORNIA

SUBJECT BRDC BOILER No 5 BY R. ALENA DATE July 30, 1970 WORK ORDER 1475-44-0117

I INTERMEDIATE LOOP - PRESSURE DROP THRU NaK-SIDE OF THE BOILER

A. GIVEN DATA

NaK FLOW RATE: 57,020 lb/HR ; $\dot{W}_N$ = 15.82 lb/sec

$T_{NaK\ IN}$ = 1210°F
$T_{NaK\ OUT}$ = 1041°F
> $T_{NaK\ AV}$ = 1,125°F

NaK PHYSICAL PROPERTIES AT 1,125°F - (REF. HANDBK H-100, IV-2, REV C)

DENSITY ρ_{NaK} = 45.3 lb/FT³
ABS. VISCOSITY μ_{NaK} = 0.38 lb/HR-FT

BOILER No 5 GEOMETRIC DATA - (REV. ENCLOSURE 1)

FREE FLOW AREA A_F = 15.01 in²
FREE FLOW AREA AT SPACERS A_{FS} = 11.16 in²
WETTED AREA A_W = 18.48 in²
WETTED PERIMETER P_W = 80.6 in
HYDRAULIC DIAMETER D_H = 0.915 in

BOILER LENGTH = 39.50 + 2π×25 + 23.25 + 32.25 = 252 in or 21 FT

No of TUBES IN BUNDLE = 12
No of TUBE BUNDLE SUPPORTS = 7

B. SHELL SIDE VELOCITY HEAD

1) NaK VELOCITY (V_N)

$$V_N = \frac{\dot{W}\ \frac{lb}{sec} \times \frac{144\ in^2}{FT^2}}{\rho\left(\frac{lb}{FT^3}\right) \times A_F\ (IN^2)} = \frac{15.82 \times 144}{45.3 \times 15.01} = \underline{3.4\ FT/Sec}$$

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2.) VELOCITY HEAD (H_N)

$$H_N = \frac{\rho_N V_N^2}{2g} = \frac{\frac{lb}{FT^3} \times \frac{FT^2}{Sec^2}}{\frac{FT}{Sec^2}} = \frac{lb}{FT^2} \times \frac{FT^2}{144 in^2}$$

$$= \frac{45.3 \times (3.4)^2}{2 \times 32.2 \times 144} = \underline{0.0568 \text{ PSI}}$$

C. REYNOLDS NUMBER

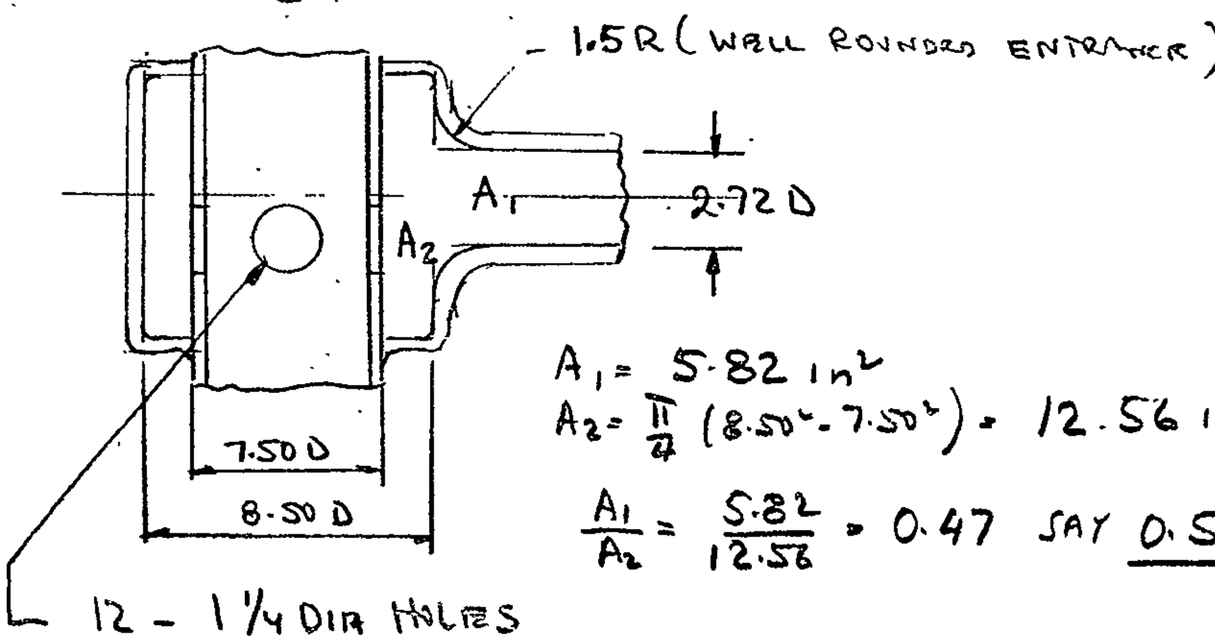
$$Re = \frac{\rho_N D_H V_N}{\mu_N} = \frac{3600}{12} \left[\frac{45.3 \times 0.905 \times 3.4}{0.38} \right]$$

$$= 300 [367] = \underline{110,000} \quad \text{(TURBULENT FLOW)}$$

D. PRESSURE DROP THRU NaK-SIDE OF BOILER

1.) INLET AND OUTLET PRESSURE LOSSES.

THE NaK INLET AND OUTLET GEOMETRY IS IDENTICAL.



$A_1 = 5.82 \text{ in}^2$

$A_2 = \frac{\pi}{4}(8.50^2 - 7.50^2) = 12.56 \text{ in}^2$

$\frac{A_1}{A_2} = \frac{5.82}{12.56} = 0.47$ SAY $\underline{0.5}$

THE SIZE OF THE 12 HOLES THRU THE 7.5 DIA SHELL BE BASED ON THE SAME RATIO OF FREE AREA TO HOLES ARE AS FOR BOILER # 4

BOILER # 4 (REF. ΔP ANALYSIS FOR BOILER No. 4 BY. G. LOMBARD)

A_{FREE} (NO SUPPORTS) = $10.78 \, in^2$
A_{FREE} (AT SUPPORTS) = $6.65 \, in^2$

OR $A_{F \cdot AT\,SUPP} = 61.8\%$ OF $A_{F\,NO\,SUPP.}$

RADIAL HOLES = 6 - 1½ in DIA.

$A_H = 6 \times 1.767 = 10.6 \, in^2$

OR $A_H = \frac{10.6}{10.78} = \underline{0.985}$ of A_{FREE} (NO SUPPORTS)

BOILER # 5 (REF. ENCLOSURE 1)

A_{FREE} (NO SUPPORTS) = $15.01 \, in^2$
A_{FREE} (AT SUPPORTS) = $11.11 \, in^2$

OR $A_{F\,AT\,SUPP} = 73.8\%$ OF A_{FREE} (NO SUPP.)

<u>USE</u> 12 HOLES OF 1¼ DIA.

$A_H = 12 \times 1.227 = 14.7 \, in^2$

OR $A_H = \frac{14.7}{15.01} = 0.98$ OF A_{FREE} (NO SUPPORTS)

THIS IS SAME AS FOR BOILER # 4

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$\Delta P_{IN} = K_{IN} \times H_N$
$\Delta P_{OUT} = K_{OUT} \times H_N$

SINCE NaK INLET & OUTLET ARE SIMILAR
$K_{IN} = K_{OUT}$
AND $\Delta P_{IN} = \Delta P_{OUT}$

DETERMINATION OF K_{IN} OR K_{OUT}

NOTE: K_{IN-OUT} FOR BOILER #4 IS 5.0 (BASED ON TEST DATA)

$K_{IN-OUT} = K_{ENTRANCE\ OR\ EXIT} + K_{SUDDEN\ CHANGE\ IN\ CROSS\ SECTION}$
$+ K_{FLOW\ THRU\ 12\ ORIFICES} + K_{90°\ BEND}$

FROM REF. 1. pages 83 THRU 90

$K_{ENTRANCE\ OR\ EXIT} = 0.5$

$K_{SUDDEN\ CHANGE\ IN\ CROSS\ SECTION}$
SINCE $A_1/A_2 = 0.5$ $K_{ENLARGEMENT} = K_{CONTRACTION} = 0.28$

$K_{FLOW\ THRU\ 12\ ORIFICES}$

ASSUME THAT THE TOTAL NaK FLOW IS EVENLY DIVIDED AMONG THE 12 HOLES.

CONSIDER THE HOLES AS THIN-PLATE, SQUARE-EDGE ORIFICES.

FOR $Re = 110,000$ AND $\frac{A_{HOLES}}{A_{FREE}} = 0.98$

ORIFICE FLOW COEFFICIENT $C = 0.78$

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CONVERSION OF C TO 'K' FACTOR

$$Q = A c \sqrt{2 g H_L}$$

$$H_L = \frac{Q^2}{A^2 c^2 2g} \quad \text{BUT} \quad Q = AV$$

$$\text{OR} \quad H_L = \frac{1}{c^2} \rho \frac{V^2}{2g} \quad \text{OR} \quad \frac{1}{c^2} H_N$$

$$\text{THEREFORE} \quad K_0 = \frac{1}{c^2} = \frac{1}{(0.78)^2} = \underline{1.64}$$

$$K_{90^\circ \text{ BEND}} = 1.1$$

$$K_{\text{IN-OUT}} = 0.5 + 0.28 + 1.64 + 1.1 = 3.52$$

THEREFORE

$$\Delta P_{IN} = 3.52 \times 0.0568 = \underline{0.20 \text{ PSI}}$$

$$\Delta P_{OUT} = 3.52 \times 0.0568 = \underline{0.20 \text{ PSI}}$$

2. PRESSURE LOSS THRU 2 - 180° BENDS

$$R = 25.0 \text{ IN}$$

$$d = \tfrac{1}{2}(D_{01} - D_{i(0)}) = (7.26 - 3.5)/2 = 1.88 \text{ in}$$

$$R/d = 25/1.88 = 13.3 \qquad N = 2 \ (2 \text{ BENDS})$$

FROM REF. 2 page 218, FIG. 97

$$\text{FOR } R/d = 13.3 \quad K_b = 2 \times 0.38 = 0.76$$

STK. NO. D-1-103

$$\Delta P_b = N \times K_b \times H_N = 2 \times 0.76 \times 0.0568 = \underline{0.0864 \text{ PSI}}$$

3. PRESSURE LOSS THRU TUBE-BUNDLE SUPPORTS.

BOILER #5 HAS 7 TUBE-BUNDLE SUPPORTS

K_{SP} (BOILER #4) = 1.1 (FROM BOILER #4 TEST DATA)

HOWEVER THE FREE FLOW AREA THRU THE SUPPORT SECTION OF BOILER #5 IS LARGER BY RATIO OF

$$\frac{.738}{.618} \cong 1.2$$

THEREFORE K_{SP} (BOILER #5) $= \frac{1.1}{1.2} = 0.915$

$$\Delta P_{SP} = 7 \times 0.915 \times 0.0568 = \underline{0.364 \text{ PSI}}$$

4. PRESSURE LOSS DUE TO FRICTION

$$\Delta P_f = K_f H_N \quad \text{BUT} \quad K_f = f \cdot \frac{L}{D_H}$$

$$f \text{ (TURBULENT FLOW)} = \frac{0.3164}{(Re)^{0.25}} = \frac{0.3164}{(110{,}000)^{.25}} = 0.017$$

$$\Delta P_f = f \times \frac{L}{D_H} \times H_N = 0.017 \times \frac{252}{0.905} \times 0.0568 = \underline{0.269 \text{ PSI}}$$

5. PRESSURE DROP DUE TO NAK TURBULATORS

THERE ARE TWO (2) TURBULATORS IN THE BOILER #5.
THE INNER TURBULATOR IS 0.125 DIA WIRE, THE OUTER TURBULATOR IS 0.125 DIA WIRE.
THE PITCH AND LENGTH FOR BOTH TURBULATORS

IS 6" AND 10 FT RESPECTIVELY

BOILER #4 HAD ONLY ONE TURBULATOR, OF 0.125 DIA WIRE, 6" PITCH AND 9 FT LONG.

THE 'K' FACTOR FOR BOILER #4 FOR THE TURBULATOR

$K_{C_4} = 2.8$ (BASED ON BOILER #4 TEST DATA)

THEREFORE

$$K_{C5} = K_{C4} \times \left(\frac{L_5}{L_4}\right)(2) = 2.8 \times \frac{10}{9} \times 2 = 6.4$$

$$\Delta P_C = K_{C5} \cdot H_N = 6.4 \times 0.0568 = \underline{0.364 \text{ PSI}}$$

6. TOTAL PRESSURE DROP THRU NaK-SIDE OF BOILER #5

ΔP_{TOTAL} =	INLET & OUTLET	2 × 0.20 = 0.400
	2 - 180° BENDS	0.086
	TUBE SUPPORTS	0.364
	FRICTION	0.269
	TURBULATOR COILS	0.364
		1.483 PSI

$\underline{\Delta P_{TOTAL} \cong 1.50 \text{ PSID}}$ (CALCULATED)

REFERENCE:

1. F.D. YEAPLE. "HYDRAULIC & PNEUMATIC POWER & CONTROL," 1966 McGRAW-HILL, NEW YORK
2. J.K. VENNARD: "ELEMENTARY FLUID MECHANICS" 3rd ED., 1954, JOHN WILEY & SONS NEW YORK.

ENCLOSURE (1)

01-071-002

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QUADRILLE WORK SHEET

DATE July 29 1970

SUBJECT BRDC BOILER No. 5 BY R. ALENA WORK ORDER 1475-44-0117

DETERMINATION OF FLOW GEOMETRY OF NaK-SIDE OF BOILER No 5

I. FREE FLOW AREA AT TUBE-BUNDLE SUPPORTS

REF. FIG. 1 QUADRANT OF NaK SIDE FLOW PATH OF BOILER No. 5

1. AREA OF ANNULUS QUADRANT = $\frac{\theta}{2}(r_o + r_i)(r_o - r_i)$

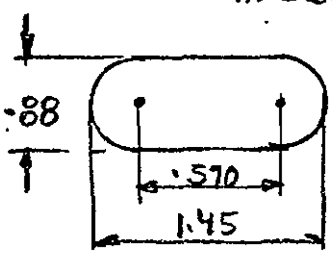
where $\theta = 90°$ or $\frac{\pi}{2}$ RADIANS = 1.5708 RADIANS

$$A_{AN} = \frac{1.5708}{2}(3.54 + 1.875)(3.54 - 1.875) =$$

$$\underline{A_{AN}} = 0.785(5.415)(1.665) = \underline{7.08\ in^2}$$

2. OUTSIDE AREA OF OVAL TUBES

THERE ARE 3 COMPLETE OVAL TUBES IN A QUADRANT



$$A_{OV} = 3\left[\left(\frac{\pi}{4}(.88)^2\right) + (.570 \times .88)\right] = 3(.61 + .501)$$

$$\underline{A_{OV}} = \underline{3.33\ in^2}$$

3. AREA OF CRADLE SUPPORT

THERE ARE 4 SUPPORTS IN A QUADRANT - ABOUT 20% FROM THE CRADLE SUPPORTS IS CUT AWAY.

$$A_{CR} = 4\left\{\left[\frac{\pi}{2}(.50 + .44)(.50 - .44)\right] - (0.20\ A_c)\right\}$$

$$4\left[1.5708(.94)(.06) - (0.20 A_c\right] = 4(0.0885 - 0.0177)$$

$$\underline{A_{CR}}\ 4 \times 0.0868 = \underline{0.347\ in^2}$$

STK. NO. D.1-103

4. AREA OF RADIAL SUPPORTS — 3 SUPPORTS / QUADRANT

$$A_{RS} = 3 \times 0.125 \times 1.665 = \underline{0.625 \text{ in}^2}$$

5. NET FREE FLOW AREA OF NaK-SIDE OF BOILER #5 AT TUBE-BUNDLE SUPPORTS IS

$$A_{FREE-AT\ SUPPORTS} = 4\left[(A_{AN}) - (A_{OV} + A_{CR} + A_{RS})\right]$$
$$= 4\left[(7.08) - (3.33 + 0.347 + 0.625)\right]$$
$$= 4(7.08 - 4.302) = \underline{11.11 \text{ in}^2}$$

6. NET FREE FLOW AREA OF NaK-SIDE OF BOILER #5

$$A_{FREE} = 11.11 + 4(A_{CR} + A_{RS})$$
$$= 11.11 + 4(0.347 + 0.625) = 11.11 + 4 \times 0.972$$
$$= 11.11 + 3.90 = \underline{15.01 \text{ in}^2}$$

II WETTED AREA

A_W = A_{FREE} + AREA TAKEN BY INNER (.125 DIA) AND OUTER (.125 DIA) TURBULATOR WIRES.

$$A_{AN\ (\text{WITHOUT TURBULATOR COILS})} = 0.785(3.63 + 1.750)(3.63 - 1.750)$$
$$= 0.785 \times 5.38 \times 1.88 = 7.95 \text{ in}^2$$

$$A_W = 4(7.95 - 3.33) = \underline{18.48 \text{ in}^2}$$

III WETTED PERIMETER

$$P_W = (6.28 \times 1.750) + (6.28 \times 3.63) + 12\left[(3.14 \times .88) + 2 \times .570\right]$$
$$= 11 + 22.8 + 12 \times (3.90)$$
$$= 11 + 22.8 + 46.8 = \underline{80.6 \text{ in}}$$

AEROJET GENERAL TIRE GENERAL

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

QUADRILLE WORK SHEET

DATE July 29, 70

SUBJECT BRDC BOILER #5 , BY R. ALENA WORK ORDER 1475-44-0117

IV HYDRAULIC DIAMETER

BY DEFINITION HYDRAULIC RADIUS $(R_H) = \frac{A_W}{P_W}$

or $R_H = \frac{\pi D^2}{4\pi D}$ or $D_H = 4R_H$

or $D_H = \frac{4A_W}{P_W} = \frac{4 \times 18.48}{80.6} = \underline{0.915 \text{ in.}}$

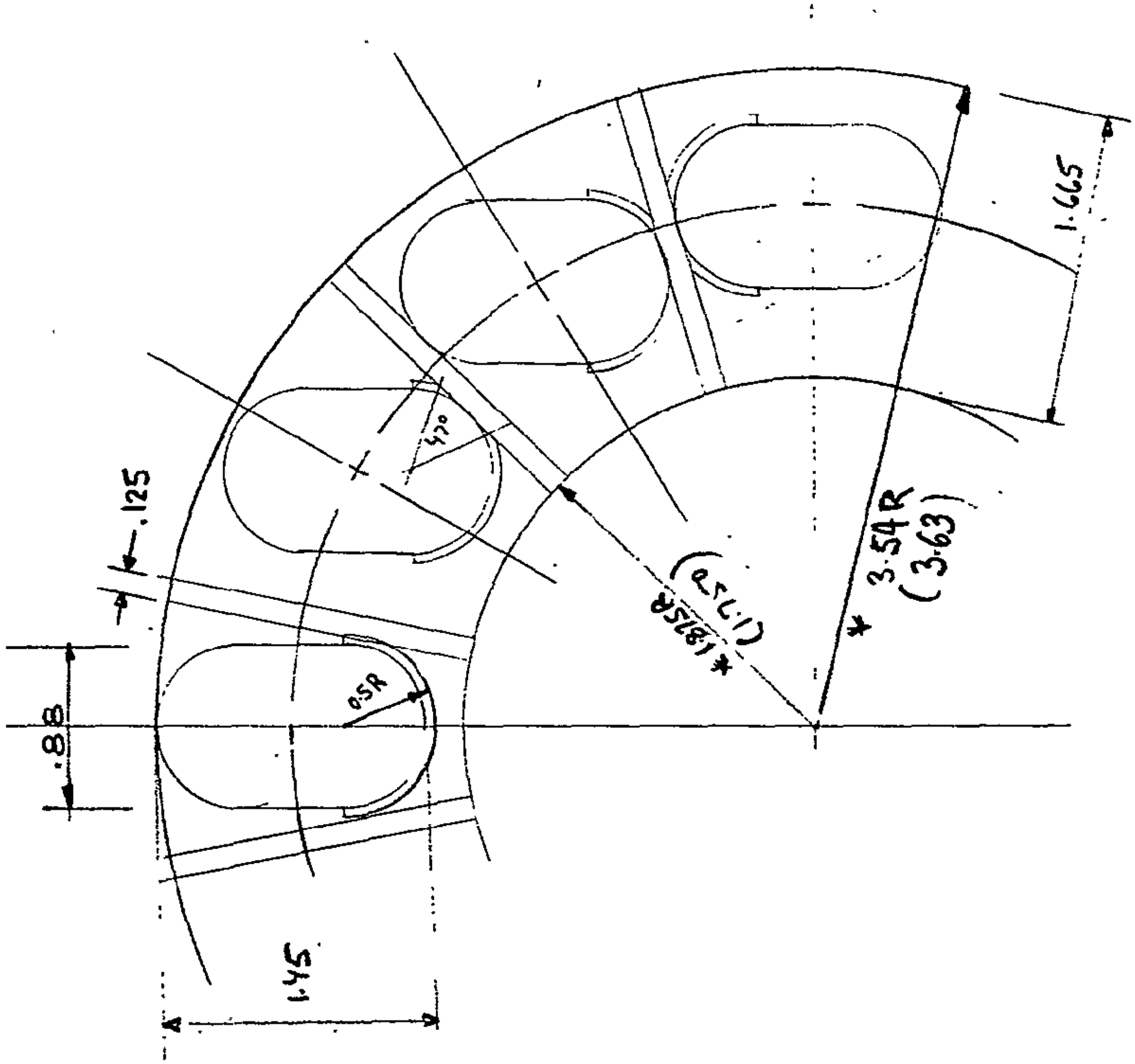


FIG 1. QUADRANT OF NaK-SIDE FLOW PATH OF BOILER No. 5 - TUBE-BUNDLE SUPPORT SECTION

* WITH TURBULATOR COILS.

APPENDIX E

BOILER WEIGHT ANALYSIS

AEROJET GENERAL

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

QUADRILLE WORK SHEET

PAGE 11 OF ____ PAGES
DATE Aug. 12, 1970
SUBJECT BRDC BOILER NO. 5 BY G. LOMBARD WORK ORDER ____

DRY BOILER WEIGHT - SUMMARY

TANTALUM VOLUME & WEIGHT

TRANS'N JOINTS :	v = 7.3 cu. in.	W = 4.4 lb
PLUG INSERTS :	v = 96.0 cu. in.	= 57.6 "
TUBING :	= 342.0	= 205.2
SWIRL WIRE :	= 10.7	= 6.4
HEADERS :	= 53.3	= 32.0
ORIFICES :	= 4.4	= 2.7
INLET REDUCER :	= 12.0	= 7.2
OUTLET REDUCER :	= 11.9	= 7.1
TOTAL	537.6 cu. in	322.6 lb

TRANS'N JOINTS :	v = 16.6 cu. in.	W = 4.8 lb
NAK TURB. COIL :	v = 18.9 cu. in.	= 5.4
7.5" O.D. SHELL :	= 726.0 cu. in.	= 209.0
3.5" O.D. SHELL :	= 251.0	= 72.4
HEADERS :	= 41.6	= 12.0
TUBE SUPPORTS :	= 31.8	= 9.2
TEES :	= 79.4	= 22.9
RINGS - TEE :	= 5.6	= 1.6
ADAPTERS - SHELL :	= 12.5	= 3.6
REDUCER - OUTLET :	= 9.8	= 2.8
REDUCER - INLET :	= 29.6	= 8.5
TUBE - ENDS :	= 35.3	= 10.2 } 321 SS
STATIC-NAK TUBES :	= 511.0	= 147.0 }
DRAIN LINES :	= 3.5	= 1.0
TOTAL	1772.6 cu. in.	510.4 lb

DRY BOILER WEIGHT = 833. lb
WET BOILER WEIGHT = 1030. lb

STK. NO. D-1-103

PART A. - BOILER DRY WEIGHT CALCULATIONS

1. WEIGHT OF TANTALUM PARTS: ($\rho_{TA} = 0.6$ lb/cu. in.)

a. PLUG INSERTS (P/N 1268612)

$$v = \left[\pi/4\,(.640)^2 - 16(5.34\times10^{-3})\right](12.)(33.9) = 96.0 \text{ cu. in.}$$

$$w = v\rho_{TA} = (96.0)(0.6) = 57.6 \text{ lb.}$$

b. TA TUBING

$$v = \pi/4\,(.750^2 - .652^2)(12.)(263.08) = 342. \text{ cu. in.}$$

$$w = (342.)(0.6) = 205.2 \text{ lb}$$

c. 90TA-10W SWIRL WIRE

$$v = \pi/4\,(.062)^2(12.)(216.)\left(\sqrt{1 + (\pi \cdot .590/2.0)^2}\right) = 10.69 \text{ cu. in.}$$

$$w = (10.69)(0.6) = 6.41 \text{ lb}$$

d. TA HEADERS

$$v = \pi/4\left[7.062^2 - (12.)(.755^2)\right](2)(.75) + \pi/4\left[7.062^2 - 6.765^2\right]\ldots$$
$$\ldots(2)(.25) + \pi/4\left[.840^2 - .780^2\right](2.)(12.)(.25)$$

$$v = 50.8 + 2.05 + .46 = 53.3 \text{ cu. in.}$$

$$w = (53.3)(0.6) = 32.0 \text{ lb}$$

PART A. - BOILER DRY WEIGHT (CONT'D)

e. TA Hg INLET ORIFICES

$$v = \pi/4\,(.652^2 - .050^2)(12)(1.06) + \pi/4\,(.652^2 - .572^2)(12)\ldots$$
$$\ldots(.25)$$

$$v = 4.21 + .23 = 4.44 \text{ cu. in.}$$

$$w = (4.44)(0.6) = 2.66 \text{ lb.}$$

f. TA Hg INLET REDUCER

$$v = \left(\frac{77^\circ}{360^\circ}\right)(\pi)(.64^2 - .40^2)(2\pi)(3.260) + \ldots$$
$$\ldots + \pi/4\,(3.05^2 - 1.1^2)(.24) + \pi/4\,(1.0^2 - .75^2)(.4) + \ldots$$
$$\ldots + (.505)(2\pi)(.75)$$

$$v = 3.40 + 6.1 + .140 + 2.38 = 12.02 \text{ cu. in.}$$

$$w = (12.02)(0.6) = 7.21 \text{ lb}$$

g. TA Hg OUTLET REDUCER

$$v = \left(\frac{78^\circ}{360^\circ}\right)(\pi)(2.10^2 - 1.95^2)(2\pi)(2.855) + \pi/4\,(7.06^2 - 6.76^2)(.5)$$
$$\ldots + \left(\frac{68^\circ}{360^\circ}\right)(\pi)(1.89^2 - 1.74^2)(2\pi)(1.5) + \pi/4\,(1.0^2 - .88^2)(.3)$$

$$v = 7.3 + 1.61 + 2.96 + .05 = 11.92 \text{ cu. in}$$

$$w = (11.92)(0.6) = 7.15 \text{ lb}$$

h. TA IN TRANSITION JOINTS

$$v = \pi/4\,(.95^2 - .75^2)(8.5) + \pi/4\,(1.95^2 - 1.75^2)(8.5) = 7.27 \text{ cu. in.}$$

$$w = (7.27)(0.6) = \underline{4.4 \text{ lb}}$$

2. WEIGHT OF STEEL PARTS (ρ_{ss} = 0.288 lb/cu.in.)

a. 7.50" O.D. SHELL (BETWEEN HEADERS)

$v = \pi/4\,(7.5^2 - 7.26^2)(256.) = 726.$ cu.in.

$w = (726.)(0.288) = 209.$ lb

b. 3.5" O.D. INNER SHELL

$v = \pi/4\,(3.50^2 - 3.31^2)(256.) = 251.$ cu.in.

$w = (251.)(0.288) = 72.4$ lb

c. 316SS HEADERS

$v = \pi/4\left[7.5^2 - 12.(1.2)^2\right](.625) + \pi/4\left[1.20^2 - 1.075^2\right](12.)(.093)$

$\ldots\ \pi/4\,(7.50^2 - 7.25^2)(.5)$

$v = 19.15 + .24 + 1.43 = 20.82 \times 2 = 41.64$ cu.in.

$w = (41.64)(0.288) = 12.0$ lb

d. TUBE BUNDLE SUPPORTS

$v = \left[\pi(3.62)(.090)(.75)(4) + \pi(7.148)(.090)(.37)\right](7) + \ldots$

$\ldots + (1.674)(.75)(.090)(12.)(7.) + \pi(7.)(.06)(.960)(7.)$

$v = 13.44 + 9.5 + 8.86 = 31.8$ cu.in.

$w = (31.8)(0.288) = 9.15$ lb

e. NaK INLET & OUTLET TEES

$$v = 2\pi(4.235)(.140)(10.5) + 2\pi(1.38)(.120)(.562)$$

$$v = 39.1 + .59 = 39.69 \text{ /tee}$$

$$v = 79.38 \text{ cu. in for 2 tees}$$

$$w = (79.38)(0.288) = 22.9 \text{ lb}$$

f. TEE ADAPTER RINGS

$$v = \left[\pi(.32^2 - .18^2)(.25)(\pi)(8.166)\right](4) = 5.61 \text{ cu. in}$$

$$w = (5.61)(0.288) = 1.62 \text{ lb}$$

g. SHELL-TO-TEE ADAPTERS

$$v = \left[\pi(7.375)(.135)\right](4) = 12.5 \text{ cu. in.}$$

$$w = (12.5)(0.288) = 3.6 \text{ lb}$$

h. BOILER-END REDUCER — Hg INLET

$$v = \pi/4\,(2.5^2 - 2.25^2)(.75) + \pi/4(7.95^2 - 7.70^2)(1.60) + \ldots$$
$$\ldots + (2.0/3.)\Big[\pi/4\,(7.95)^2 + \pi/4(2.50)^2 + \pi/4\,(7.95)(2.50) - \ldots$$
$$\ldots - \pi/4(7.70)^2 - \pi/4(2.25)^2 - \pi/4\,(7.70)(2.25)\Big]$$

$$v = 0.71 + 5.03 + 4.06 = 9.80 \text{ cu. in.}$$

$$w = (9.80)(0.288) = 2.8 \text{ lb}$$

i. BOILER-END REDUCER – Hg OUTLET

$$v = \pi/4(7.95^2 - 7.70^2)(2.4) + \pi/4(4.25^2 - 4.00^2)(1.75) + \ldots$$
$$\ldots + \pi(2.5^2 - 2.25^2)(55°/360°)(\pi)(6.95) + \ldots$$
$$\ldots + \pi(1.95^2 - 1.70^2)(55°/360°)(\pi)(4.95)$$

$$v = 7.54 + 2.75 + 12.55 + 6.71 = 29.55 \text{ cu.in.}$$

$$w = (29.55)(0.288) = 8.5 \text{ lb}$$

j. 321 ss STATIC NaK TUBE ENDS

$$v = \left[\pi/4(1.075^2 - .875^2)(4.35) + \pi/4(1.187^2 - 1.089^2)(.75)\right](24)$$

$$v = 35.3 \text{ cu.in.}$$

$$w = (35.3)(0.288) = 10.17 \text{ lb.}$$

k. 321 ss STATIC NaK TUBES

$$v = \pi/4(1.187^2 - 1.089^2)(12)(246.4) = 511. \text{ cu.in.}$$

$$w = (511.)(0.288) = 147. \text{ lb}$$

l. NaK DRAIN & FILL LINES

$$v = \pi/4(.75^2 - .560^2)(18.0) = 3.53 \text{ cu.in.}$$

$$w = (3.53)(0.288) = 1.02 \text{ lb}$$

m. NaK TURBULATOR COIL

$$v = \pi/4(.125)^2(256.)\left(\sqrt{1+\left(\tfrac{7.12\pi}{6}\right)^2} + \sqrt{1+\left(\tfrac{3.62\pi}{6}\right)^2}\right) = 18.9 \text{ cu.in}$$

$$w = (18.9)(0.288) = 5.4 \text{ lb}$$

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SUBJECT BRDC BOILER NO. 5 BY

WORK ORDER

A. 316 SS IN THE TRANSITION JOINTS

$$v = \pi/4(2.25^2 - 1.400^2)(.5) - \pi/4(2.25^2 - 1.75^2)(.3) + \ldots$$
$$\ldots + \pi/4(1.250^2 - 0.95^2)(9.41) + \pi/4(4.0^2 - 2.40^2)(.50) - \ldots$$
$$\ldots - \pi/4(4.0^2 - 3.25^2)(.30) + \pi/4(2.254^2 - 1.96^2)(9.41)$$

$$v = 1.21 - 0.47 + 4.88 + 3.22 - 1.27 + 9.02$$
$$v = 16.6 \text{ cu. in.}$$

$$w = (16.6)(0.288) = 4.78 \text{ lb}$$

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QUADRILLE WORK SHEET

DATE

SUBJECT BRDC BOILER NO. 5 BY

WORK ORDER

PART B. - BOILER FLUID VOLUME & WEIGHT

1. PRIMARY NAK:

$$v_{PN} = \left[\pi/4\,(7.25^2 - 3.50^2) - 12(1.11)\right](257.) - 31.8 - 18.9$$

$$v_{PN} = 4649.\ \text{cu.in.}$$

$$w_{PN} = \left[(4649.)/(1728)\right](45.0) = 121.\ \text{lb}$$

2. STATIC NAK:

$$v_{SN} = \left[1.93 - \pi/4(.75)^2\right](257.)(12) = 1510.\ \text{cu.in.}$$

$$w_{SN} = \left[(1510.)/(1728)\right](45.0) = 39.3\ \text{lb}$$

SUBJECT BRDC BOILER NO. 5 BY G. LOMBARD WORK ORDER

LIQUID MERCURY INVENTORY

MERCURY TEMP. (LIQ.) = 353°F
MERCURY DENSITY (LIQ.) = 822. lb/cu. ft.

A. INLET TRANSITION TUBE:

$$v = \pi/4(.755)^2(8.5) + \pi/4(.955)^2(1.5) = 3.8 + 1.08$$

$$v = 4.88 \text{ cu. in.}$$

$$w = (4.88)(822.)/(1728.) = 2.32 \text{ lb}$$

B. INLET CONCENTRIC REDUCER-DOME:

$$v = (\pi/4)(.10)\sum_{i=1}^{i=24} d_i^2 + (\pi/4)(.755^2)(1.05)$$

$$= (\pi/4)(.10)(714.3) + .51 = 56.5 \text{ cu. in.}$$

$$w = (56.5)(822.)/(1728.) = 26.9 \text{ lb}$$

C. ORIFICES:

$$v = \pi/4(.050)^2(1.06)(12.0) + \pi/4(.572)^2(.25)(12.0)$$

$$= .0025 + .7725 = .775 \text{ cu. in.}$$

$$w = (.775)(822.)/(1728.) = .37 \text{ lb}$$

d. OPEN TUBE BETWEEN ORIFICES & PLUG INSERTS

$$v = \pi/4(.652^2)(12.)(1.3) = 5.21 \text{ cu. in.}$$

$$w = (5.21)(822.)/(1728.) = 2.5 \text{ lb}$$

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

DATE Aug. 28, 1970

SUBJECT BRDC BOILER NO. 5 BY G. LOMBARD WORK ORDER

LIQUID MERCURY INVENTORY (CONT'D)

e. PLUG INSERTS:

1. LOW NaK TEMP. = 1185°F

PRE-HEAT LENGTH = 0.7 ft

$\dot{w}_{Hg}$ = 13565. lb/hr

$v = (12.0)(0.7)(12.0)(85.4\times10^{-3}) = 8.61$ cu.in.

$w = (8.61)(822.)/(1728.) = 4.1$ lb

2. HIGH NaK TEMP. = 1210°F

PRE-HEAT LENGTH = 0.6 ft

$\dot{w}_{Hg}$ = 13555. lb/hr

$v = (12.)(0.6)(12.0)(85.4\times10^{-3}) = 7.37$ cu.in.

$w = (7.37)(822.)/(1728.) = 3.51$ lb

TOTAL LIQUID Hg INVENTORY IN THE BOILER IS:

36.2 lb @ TNBI = 1185°F
35.6 lb @ TNBI = 1210°F

APPENDIX F

TANTALUM-to-STAINLESS STEEL TRANSITION JOINT TEST AND INSPECTION PROGRAM

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS

M E M O R A N D U M

FILE: ME 11:110

DATE: 2 September 1970
7972:70:0097:CGN:eh
Bldg. 160, X6730

TO: Distribution

FROM: C. G. Neitsch

SUBJECT: Low Cycle Fatigue Evaluation of Coextruded 316SS/Ta Tubing

DISTRIBUTION: B.L. Amstadter, H.E. Bleil, E.S. Chalpin, H. Derow, A.H. Kreeger, G.L. Lombard, L.P. Lopez, R.W. Marshall, U.A. Pineda, file
Cleveland: W.L. Snapp

NASA LeRC: E.R. Furman, P.L. Stone

REFERENCE:
(a) J.N. Kass and D.R. Stoner, "Evaluation of Ta/316SS Bimetallic Tubing," WANL-PR-PPP-001, 1968
(b) U.A. Pineda, "Stress Relaxation of Coextruded Bimetallic Tubes", Stress Analysis 4927:SA-B-105, August 1967

ENCLOSURE:
Figure 1 - 316SS/Ta Coextruded Tube Thermal Exposure Specimen
Figure 2 - Ultrasonic Inspection of 316SS/Ta Coextruded Tubing
Figure 3 - Std. for Ultrasonic Bond Inspection of 316SS Ta Coextruded Tubing
Figure 4 - Std. for Ultrasonic Inspection of Ta Liner in 316SS/Ta Coextruded Tubing
Figure 5 - Dimensional Changes in 316SS/Ta Coextruded Tubing Resulting from Thermal Exposure at 1350°F
Figure 6 - Appearance of Coextruded 316SSTa Tube Specimens After Approximately 4800 hrs. at 1350°F
Figure 7 - Coextruded 316SS/Ta Ring Specimens After Flattening Test
Figure 8 - Hardnesses of Coextruded 316SS/Ta Tubing After 1350°F Exposure
Figure 9 - Bond Interface of 316SS/Ta Coextruded Tube Specimens After 1350°F Thermal Exposure
Figure 10- Microstructure of 316SS in Coextruded 316SS/Ta Tubing After 4,364 hrs. at 1350°F
Table 1 - Summary of Thermal Exposure and Evaluation of Coextruded 316SS/Ta Tubing

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Evaluation of 316SS/Ta coextruded tube specimens was conducted after a maximum of 5,353 hours exposure at 1350°F including 275 thermal cycles between 250 and 1350°F. It is concluded that:

1. Coextruded 316SS/Ta tubing of 100% initial bond exhibits no tendency of debonding under simulated SNAP-8 boiler low thermal fatigue cycling.

2. The sleeve bushing design is adequate to prevent 316SS/Ta debonding at the tube ends during thermal exposure.

3. Changes in Ta hardness resulting from thermal exposure were attributed to interstitial element diffusion from the 316SS into the Ta.

4. Additional data is required to predict the effect of sigma phase on 316SS ductility reduction resulting from 40,000 hour SNAP-8 boiler exposure.

5. It is unknown whether the dimensional changes of the bimetal tube specimens which occurred after approximately 3,000 hr. thermal exposure are representative of dimensional changes expected during boiler operation due to a 65°F axial gradient along the specimens' lengths.

6. The evaluation indicated that 316SS/Ta tubing manufactured by the coextrusion process is capable of maintaining adequate bonding during 40,000 hr. BRDC boiler exposure.

The following recommendations result from this study:

1. Continue thermal exposure of the two remaining coextruded tube specimens to accumulate additional data on the effect of sigma phase formation.

2. Review the 316SS/Ta coextruded fabrication procedure for possible modifications to reduce sigma phase formation potential.

3. Perform a stress analysis to determine the effect of a 65°F axial temperature gradient upon the 1350°F dimensional stability of 316SS/Ta coextruded tubing.

4. Perform a stress analysis to determine the effect of BRDC boiler operation upon the dimensional stability of 316SS/Ta coextruded sleeving.

INTRODUCTION

One conceptual design of a SNAP-8 boiler uses a bonded 316SS/Ta bimetal tube as the Hg containment material. The tantalum (Ta) serves as the Hg exposed liner. Bare refractory-double containment boilers No. 4 and 5 employ coextruded Ta/316SS sleeves at the Hg inlet and outlet to provide the transition from the 316SS Hg liquid and vapor lines to the Ta boiler material. Evaluation of the metallurgical stability and debonding potential of the bimetal tubing during boiler operation is necessary to establish reliability for forty thousand hour service. This investigation evaluated the metallurgical stability and debonding tendency of 316SS/Ta coextruded tube specimens under a simulated boiler operating environment of thermal exposure at 1350°F in combination with both low thermal fatigue cycling and fast thermal cycling between 250 and 1350°F.

TEST PROCEDURE

Four 15 inch long 316SS/Ta coextruded specimens were prepared. The specimens were cut from 17 foot long tubes fabricated by Nuclear Metals, Concord, Mass. The tube specimens contained 316SS I.D. support bushings at the tube ends, Figure 1.

Bushings are an integral part of the bimetal boiler design to support the Ta thus minimizing potential tube end debonding stresses due to differential thermal expansion between the Ta liner and the 316SS clad during thermal cycling(1). One bushing in each test specimen was solid, forming an end cap. The other tube end was sealed by electron-beam welding a flat 316SS disc to the bimetal tube 316SS clad. Electron beam closure welding results in a vacuum of approximately 10^{-4} Torr inside the tube serving two purposes. First, the Ta liner was protected against oxidation during elevated temperature exposure. Second, a simulation is produced of the vacuum conditions imposed on the Hg containment tube during boiler hot outgassing in preparation for system start-up.

The four sealed specimens were thermally exposed in a stainless steel susceptor in a vacuum induction furnace at 10^{-5} Torr for redundant protection of the tantalum liner against oxidation. The furnace controls provided automatic shutdown in case of loss of vacuum and/or excessive temperature (1375°F along centerline of susceptor). Both fast and slow cycling rates were used during thermal exposure. The thermal cycle was defined as fast if the exposure temperature was increased and/or decreased at a rate greater than 250°F/hr. A slow cycle was defined as the cycle resulting when both the heating and cooling rates were less than 250°F/hr., and is equivalent to the presumed severest SNAP-8 boiler thermal operating conditions. The slow thermal cycle is considered to be a low fatigue cycle because differential thermal expansion stresses plastically strain the tantalum during each heating phase and cooling phase of the cycle.

EVALUATION PROCEDURE

The thermal exposure was interrupted occasionally for ultrasonic bond inspection, ultrasonic Ta liner evaluation, metallography, and dimensional inspection, Table 1.

1. Ultrasonic Bond Inspection

Ultrasonic bond inspection employed the pulse-echo, immersion, C-scan, longitudinal wave technique, Figure 2. The test standard had simulated unbond for ultrasonic equipment calibration, Figure 3. Unbond was simulated by four eloxed, 1/8 inch diameter holes on the Ta I.D. with depths of .010, .020, .030, and .040 inch respectively. Ultrasonic equipment was calibrated to show all defects parallel to the 316SS/Ta interface between .010 and .040 inch from the Ta surface as unbond. The 316SS/Ta interface is a nominal .025 inch distance from the Ta I.D. surface.

2. Ultrasonic Ta Liner Inspection

Ultrasonic inspection for Ta liner integrity employed the pulse-echo, C-scan, immersion, shear wave technique, Figure 2. For ultrasonic equipment calibration, the test standard, Figure 4, had two 1/4 inch long .005 inch deep notches eloxed on the Ta I.D. surface. One notch was parallel and the other notch

---

(1) Thermal expansion coefficients, 75 to 1350°F are 4.1×10^{-6} and 10.7×10^{-6} in./in.-°F for Ta and 316SS, respectively.

was transverse to the bimetal tube axis. Ultrasonic equipment was calibrated to show all Ta I.D. defects with depths equal to or greater than .005 inches. Axial and radial shear scans were used to inspect for both longitudinal and transverse type defects.

3. Dimensional Inspection

During the periodic interruptions of the thermal exposure, the bimetal tube specimens were measured for possible changes in diameters resulting from the thermal exposure.

4. Flattening Test

Flattening tests were performed on a pre-exposure specimen and on thermally exposed specimens to determine whether the ductility of 316SS was affected by thermal exposure. Ring specimens were flattened between parallel plates until either cracking occurred or opposite I.D. surfaces came into contact.

5. Metallography

One end was removed from specimens after exposure at 1350°F for times of 1,000 hr., 4,095 hr., and 4,864 hr. Two longitudinal cross-sections at 180 and one full transverse section were examined microscopically to determine the effect of thermal exposure upon 316SS/Ta bond integrity and microstructure. Microhardnesses were measured across the Ta and 316SS to compare with before exposure hardnesses.

EVALUATION RESULTS

1. Ultrasonic Bond Inspection

No debonding was revealed by ultrasonic inspection. The last bond inspection was performed after a maximum of 3,043 hours at 1350°F.

2. Ultrasonic Ta Liner Inspection

No Ta liner defects were detected by ultrasonic inspection. The last inspection was performed after a maximum of 3,043 hours at 1350°F.

3. Dimensional Inspection

No changes in the tube specimens' outside diameters were apparent after approximately 3000 hours at 1350°F, but all four specimens showed significant changes in diameters resulting from 1350°F exposure to times greater than 3,043 hours, Figures 5 and 6. After exposure period No. 8 was complete, Table 1, it appeared that the dimensional changes were a function of axial position, and that non-uniform specimen temperature may have contributed to the unequal dimensional changes along the specimens' lengths. Therefore, specimens AA and PP were repositioned in the furnace susceptor to ensure a 1350°F ±20°F along the specimens' lengths. During the ensuing exposure of 489 hr. at 1350°F, both specimens AA and PP showed additional changes in dimensions, Figure 5.

4. Flattening Test

No cracking occured in either the 316SS or Ta in the pre-exposure specimen which was flattened until opposite I.D. surfaces came into contact. Specimens which had been exposed to 4,095 and 4,864 hours at 1350°F cracked in the 316SS when flattened to 0.10 inch separation distance between I.D. surfaces, Figure 7.

5. Hardness Measurements

The hardness of the Ta increased adjacent to the 316SS/Ta interface, Figure 8. The hardness of the 316SS was unchanged.

6. Microscopic Examination

At magnifications up to 1000X, no debonding was observed either at the end of the tapered Ta liner, or along the 316SS/Ta bond length. At 2000X magnification, very localized areas of microcracking were observed in approximately 0.2% of the bond length examined, Figure 9.

No apparent change in the width of the diffusion zone between the 316SS and the Ta resulted from 1350°F exposure, Figure 9.

Thermal exposure caused sigma phase precipitation across the 316SS cross-section, Figure 10. After 4,864 hrs. thermal exposure, specimen LL had 5.1% sigma at one end (end location corresponding to tube end of greatest dimensional change, Figure 5) and 3.8% sigma at the opposite end. Carbide precipitation in the 316SS microstructure occurred prior to thermal exposure during coextruded bimetal tube fabrication.

DISCUSSION

The intact bond line at the tube end indicates that the support bushing design is adequate to prevent end debonding. It is unknown whether the microcracks in the 316SS/Ta bond in specimen LL away from the support bushing area after 4,864 hr. thermal exposure are fabrication defects or a result of thermal exposure. The extremely short crack lengths, approximately 2×10^{-4} in., are not detectable by ultrasonic inspection. Also, the linear distribution of the microcracks, along approximately 0.2% of the bond line, makes metallographic determination of the presence or absence of microcracks in pre-exposure specimens difficult.

The unchanged Ta liner I.D. hardnesses indicate that the vacuum protection of the Ta liner during thermal exposure was adequate to prevent air contamination. The increased Ta hardness adjacent to the 316SS/Ta interface indicates that diffusion, probably of interstitial elements, from the 316SS into the Ta occurred as a result of thermal exposure. An earlier investigation by Westinghouse, Reference (a), reported similar results in that quantitatively determined interstitial changes were attributed to diffusion across the bimetal interface.

The length of time required for dimensional changes to begin occurring may be related to the relaxation of residual fabrication stresses. A stress analysis, Reference (b), indicated that approximately 3000 hrs. continuous soak at 1300°F is required for complete relaxation of the pre-stress induced in the coextrusion of the 316SS/Ta tubing. The coextrusion process imposes a tensile stress in the 316SS and a compressive stress in the Ta. With relaxation of pre-stress, the stress pattern in the bimetal tubing is reversed due to differential thermal expansion stresses. The stress pattern reversal apparently results in significant reductions in bimetal tube diameter with low thermal fatigue cycling.

It appears that the greater dimensional changes that occurred at one end of each tube specimen is related to a 65°F maximum axial temperature gradient. The temperature of one end of each specimen may have approached 1400°F, the temperature of the stainless steel susceptor I.D. The temperature of the other end of each specimen may have been as low as 1335°F, the temperature along the susceptor centerline. Cross-sections through the tube revealed that although the wall thickness remained constant, a marked variation in the Ta:316 thickness ratio occurred around the circumference of the tube at the end which exhibited the maximum dimensional change. This condition did not exist at the other end of the tube. Therefore, a stress analysis is required to determine if the dimensional changes which resulted are comparable to or greater than the effects expected as a result of boiler operation. The existence of an axial temperature gradient is also indicated by the greater amount of sigma precipitation at one tube end (5.1%) than at the other tube end (3.8%), as the amount of sigma formation is temperature independent. The unchanged width of the diffusion zone between the 316SS and the Ta after 4,864 hrs. of test indicates qualitatively that the 1350°F exposure was not greatly exceeded, as it is reported that 1600 hours exposure at 1500°F caused 2.5×10^{-4} inch growth in diffusion zone width of Ta/stainless steel composites, Reference (c).

Sigma phase, FeCr, is a hard, brittle constituent that forms on heating stainless steel alloys between 1000 and 1700°F. The amount of sigma formation depends upon the specific composition and structure of the stainless steel, the length of thermal exposure, and as mentioned previously, the temperature of exposure. Sigma formation is important becuase of the effect on the ductility of 316SS. The flattening test results indicated qualitatively reduced 316SS ductility with sigma formation. Tensile tests are required to quantitatively determine the change in ductility, but the remaining ductility appears to be acceptable as the flattening characteristics of the bimetal tubing after 4,864 hrs. at 1350°F meet the requirements of both the ASTM and ASME specifications for high quality, seamless 316SS tubing (ASTM A213 and ASME SA 213).

The current boiler design (BRDC) utilizes 10-inch long coextruded bimetal sleeves (of which 8 inches is effective) for transition sections between the Ta boiler tubing and the 316SS loop piping at the boiler inlet and outlet. 316SS to Ta bonding in the bimetal sleeving is required to maintain separation of the static NaK from the Hg loop. Test data indicates that 316SS/Ta tubing manufactured by the coextrusion process is capable of maintaining adequate bonding during the required 40,000 hr. BRDC boiler exposure. The significant effects of diameter reductions in the bimetal sleeves are changes to the Hg pressure drop across the boiler. However, if the sleeve diameter were to decrease in the same ratio as the bimetal tubing maximum diameter reduction (7%), no noticeable effect on boiler performance would occur. The effect of thermal exposure upon bimetal tube specimens diameters of this investigation cannot be extrapolated to the bimetal sleeve design because of differences in wall thickness relationships. The ratio of 316SS thickness to Ta thickness is 2.4:1 for the thermal exposure specimens and 1.5:1 for the bimetal sleeves. A stress analysis is required to predict potential changes to bimetal sleeve diameters resulting from boiler operation.

Information on sigma effects due to long time elevated temperature exposure is insufficient to make a quantitative prediction on either the total amount of precipitate formed or the extent of ductility reduction which would occur in 40,000 hr., 1350°F exposure. Cyclic thermal exposure of the two remaining coextruded tube specimens should be continued to accumulate additional data on sigma effects. The 316SS/Ta coextruded fabrication procedure should be reviewed and modified if possible to reduce sigma phase formation potential.

HEBleil for
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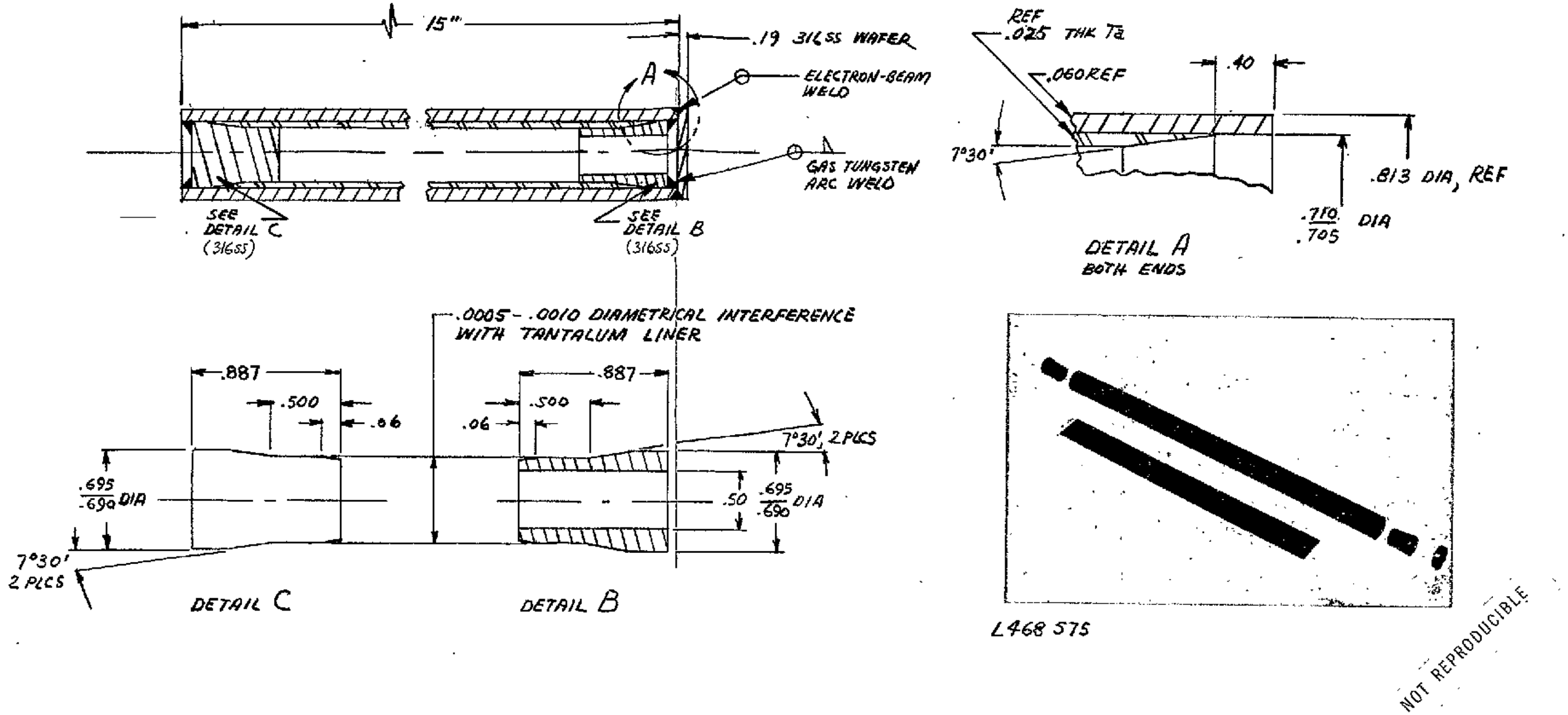


316SS/Ta COEXTRUDED TUBE THERMAL EXPOSURE SPECIMEN

FIGURE 1

LEGEND

A· ULTRASONIC SEARCH UNIT (MOVEMENT PARALLEL TO TUBE AXIS) SENDS AND RECEIVES SOUND ENERGY.

B PULSE-ECHO SOUND ENERGY IN WATER MEDIUM

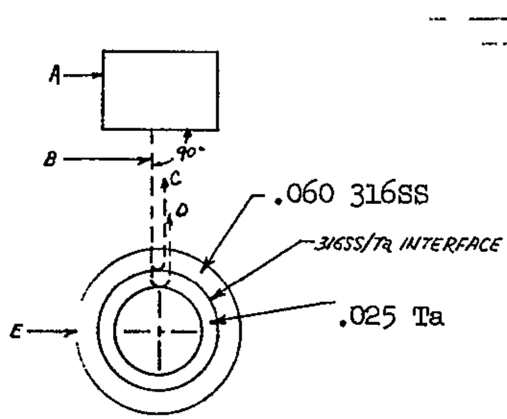
C· PATH OF REFLECTED SOUND BEAM WHEN 316SS/Ta UNBOND EXISTS, INDICATED AS UNBOND ON C-SCAN RECORDING.

D PATH OF REFLECTED SOUND BEAM WHEN 316SS/Ta BONDING EXISTS.

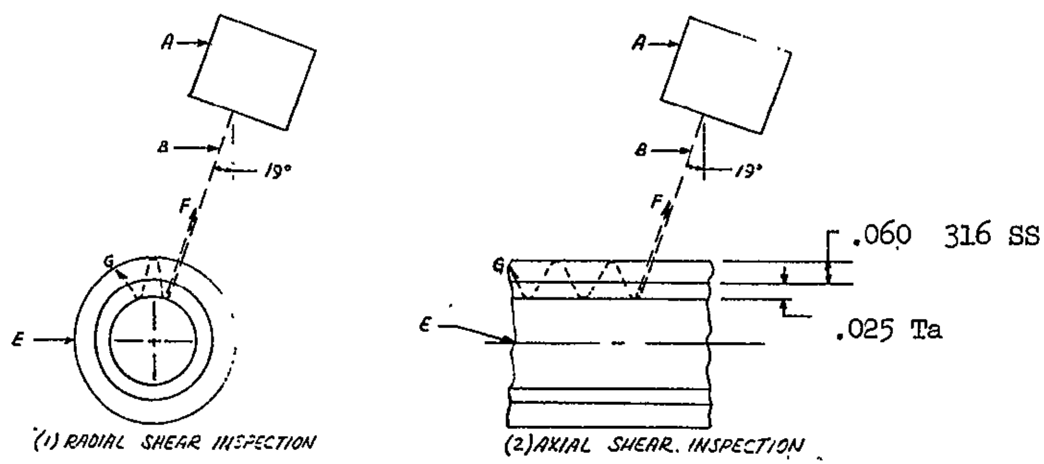
E. 316SS/Ta TUBE ROTATED 4 DEGREES AFTER EACH SCAN OF THE SEARCH UNIT

F PATH OF REFLECTED SOUND BEAM IF CRACK DEFECT EXISTS, INDICATED AS DEFECT AREA ON C-SCAN RECORDING.

G PATH OF REFLECTED SOUND BEAM IF I.D. IS DEFECT FREE, SOUND CONTINUES IN SHEAR THROUGH TUBE WALL.



a. Ultrasonic Technique Used for Bond Inspection



b. Ultrasonic Technique Used for Ta Liner Inspection

Fig. 2. ULTRASONIC INSPECTION OF 316SS/Ta Coextruded Tubing

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

PAGE ____ OF ____ PAGES
DATE 7/7/70
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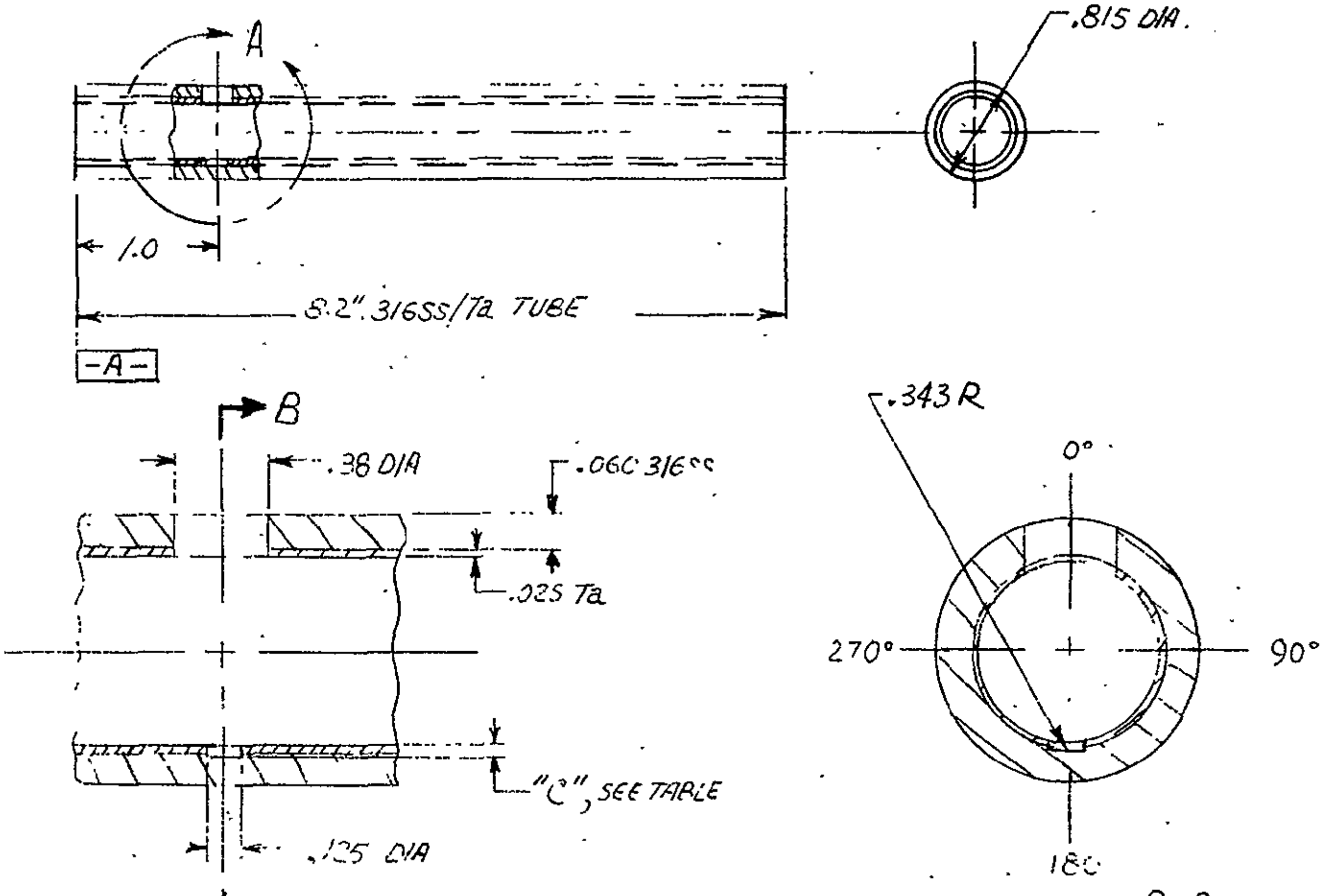
SUBJECT STD FOR ULTRASONIC BOND INSPECTION OF 316SS/Ta COEXTRUDED TUBING
BY C Kectuh



SECTION B-B
TYPICAL

DETAIL A
4 PLCS

DETAIL A		"C",
LOCATION -A-	ORIENTATION	ELOXED HOLE
1.0	0°	.030
3.0	180°	.040
5.0	270°	.010
7.0	90°	.020

FIGURE 3

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
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PAGE ____ OF ____ PAGES
DATE 7/7/70
WORK ORDER ____

SUBJECT STD FOR ULTRASONIC INSPECTION OF Ta LINER IN 316SS/Ta COEXTRUDED TUBING

BY C. Deitch

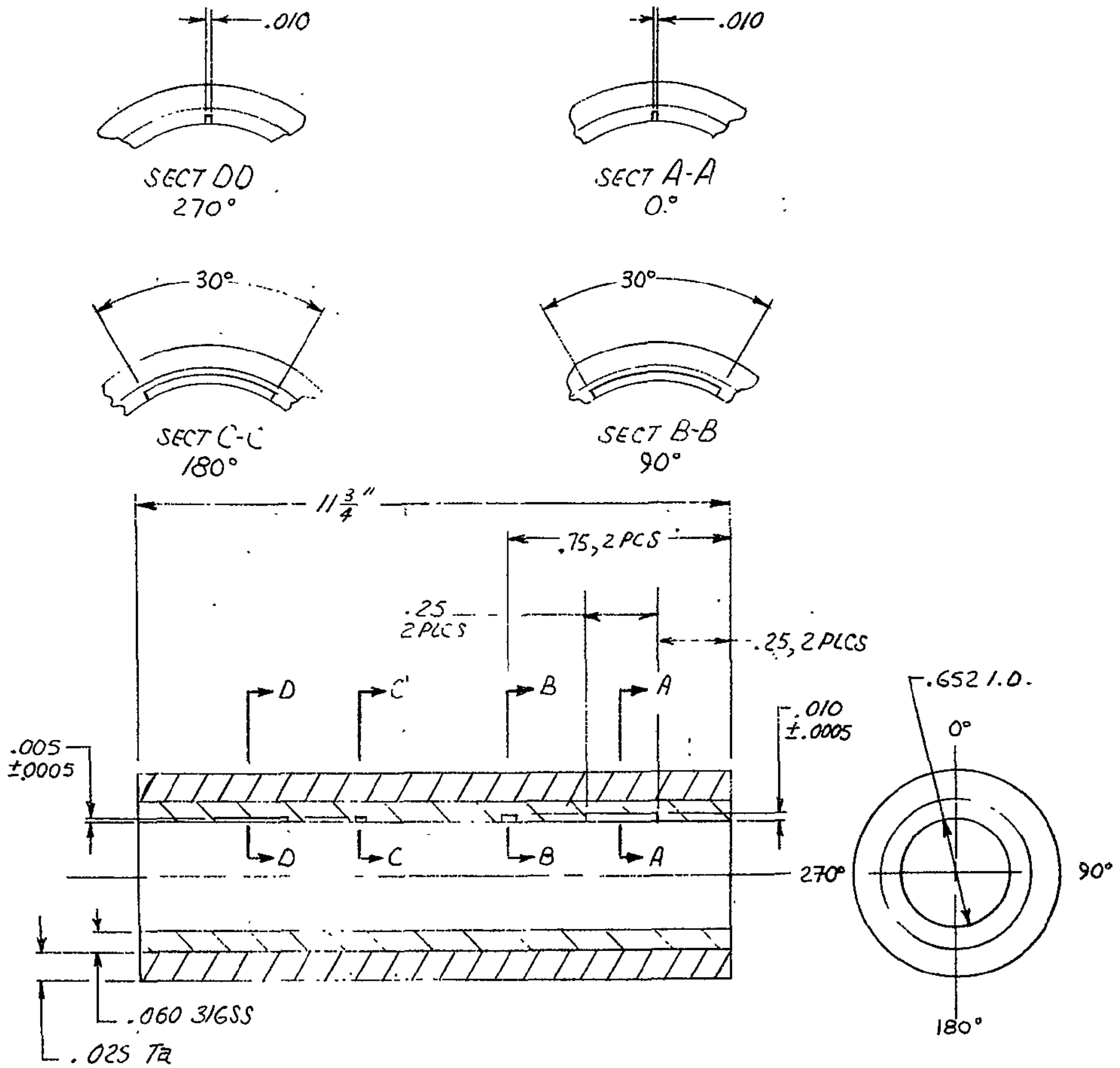
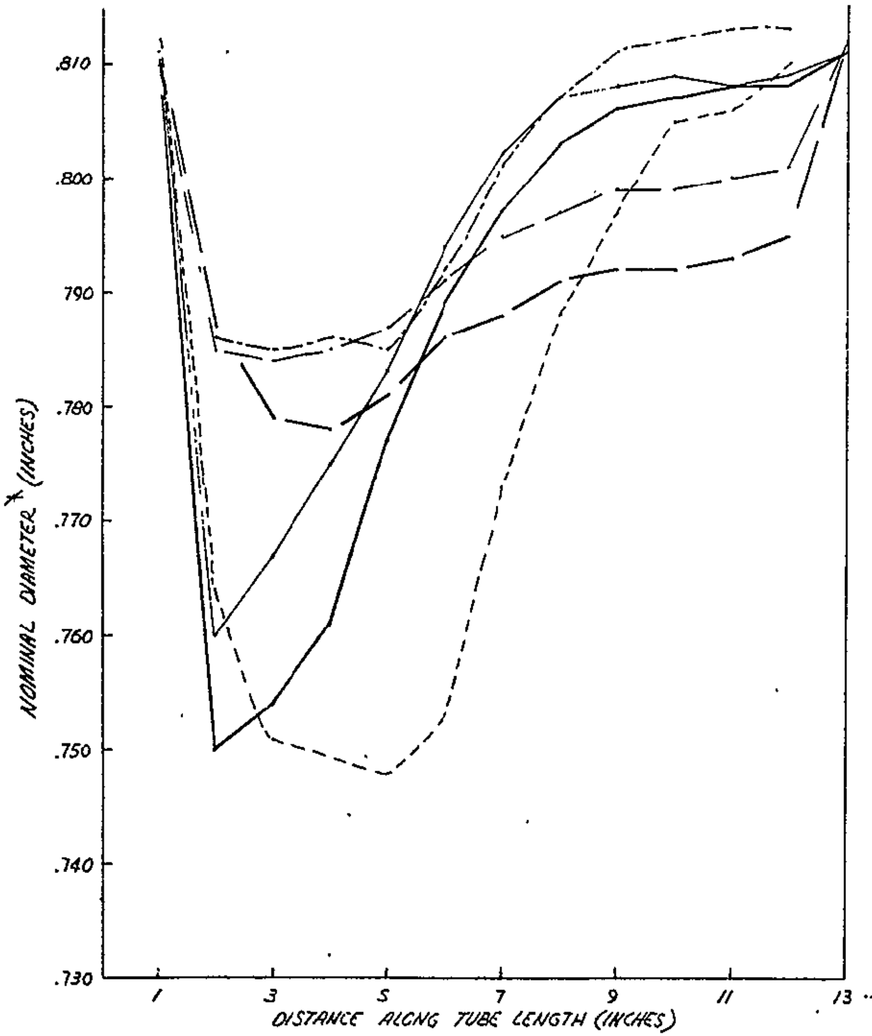


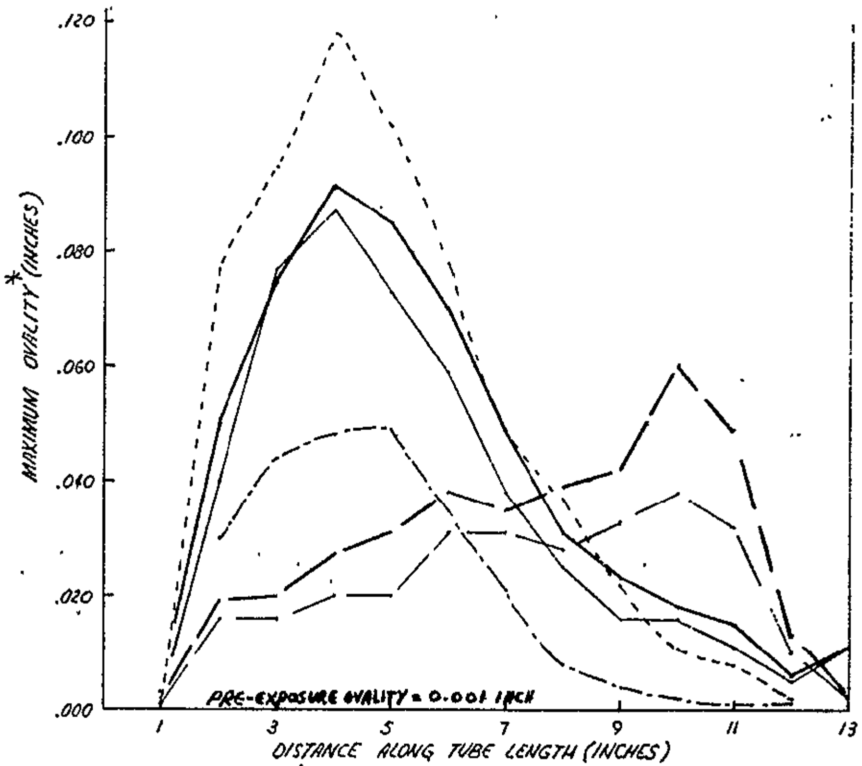
FIGURE 4

STK. NO. D-1-103



LEGEND	SPECIMEN	THERMAL HISTORY	
		CYCLES (250 TO 1350°F)	1350°F DWELL (HRS)
	KK	164	4,095
	LL	240	4,864
	PP	216	4,839
	PP	251	5,328
	AA	240	4,864
	AA	275	5,[illegible]

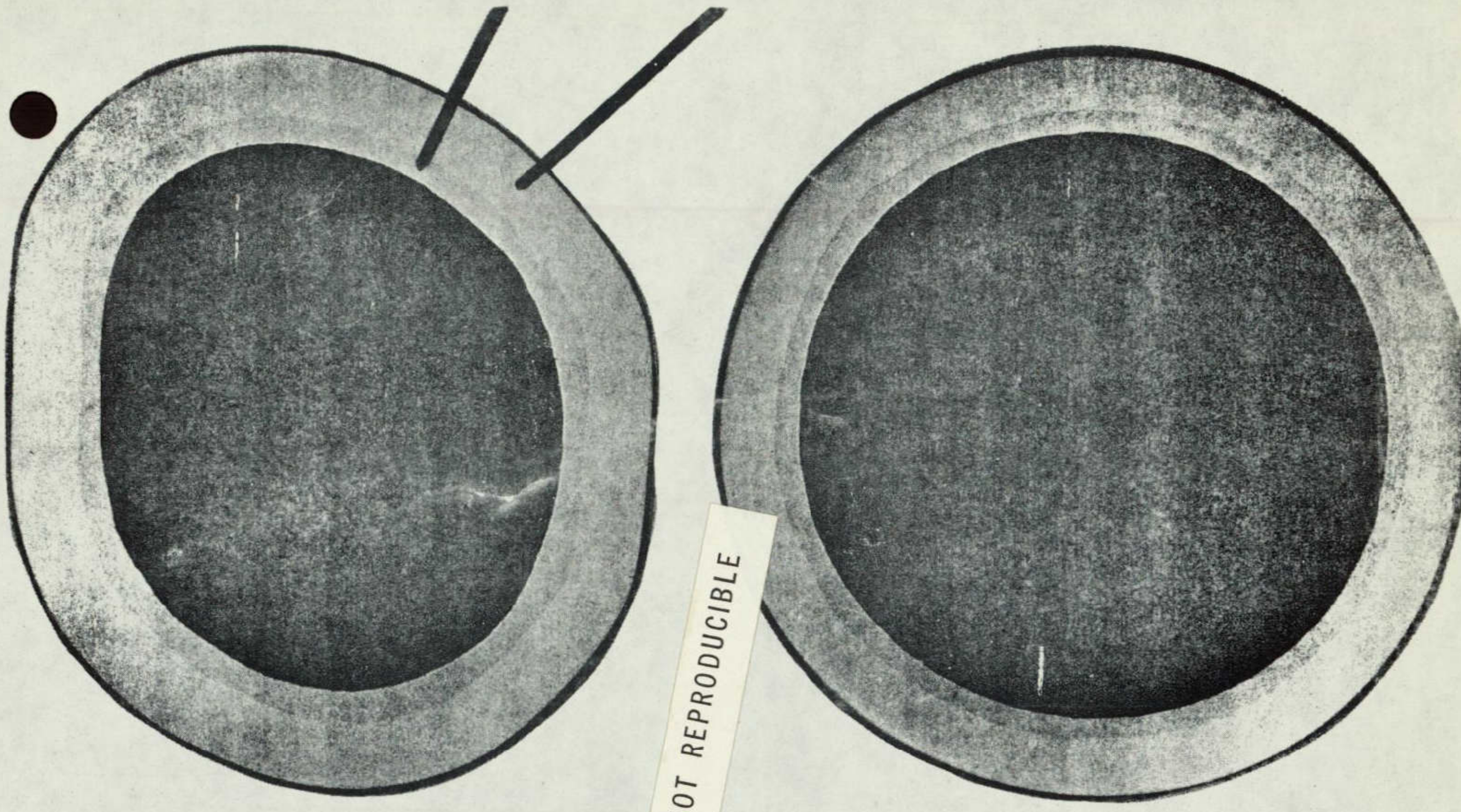
*DETERMINED FROM MEASURED DIAMETERS AT CIRCUMFERENTIAL POSITIONS OF 0°, 45°, 90° & 135°.



DIMENSIONAL CHANGES IN 316SS/Ta COEXTRUDED TUBING RESULTING FROM THERMAL EXPOSURE AT 1350°F

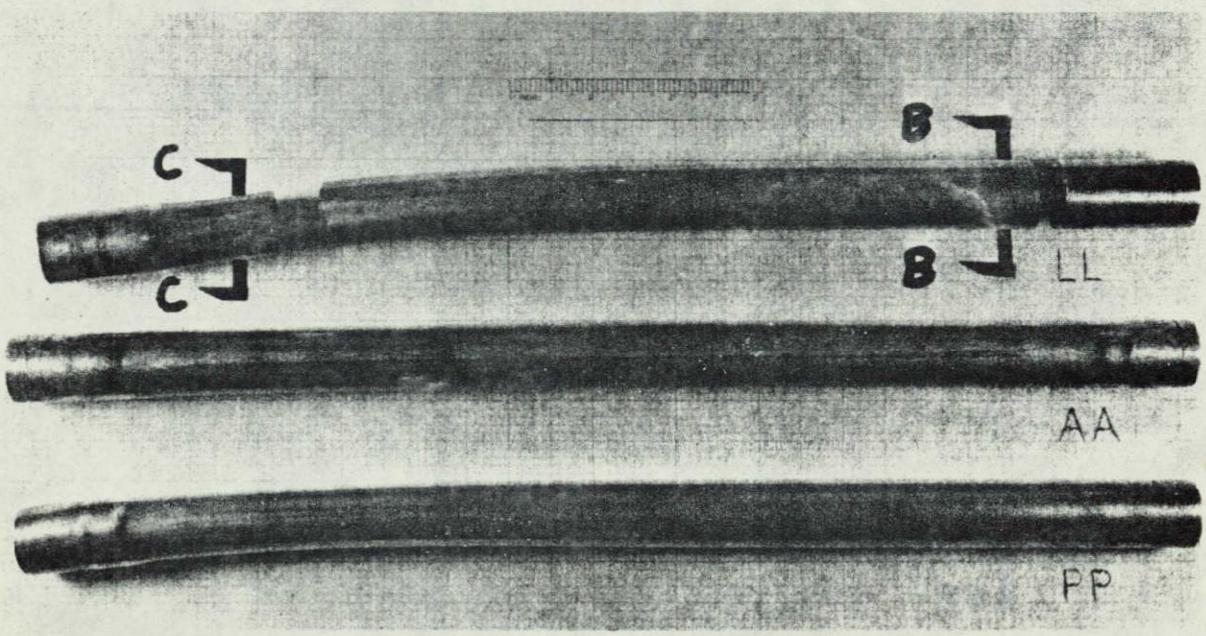
FIGURE 5

Ta 316SS



5X 0492
Sect. C-C

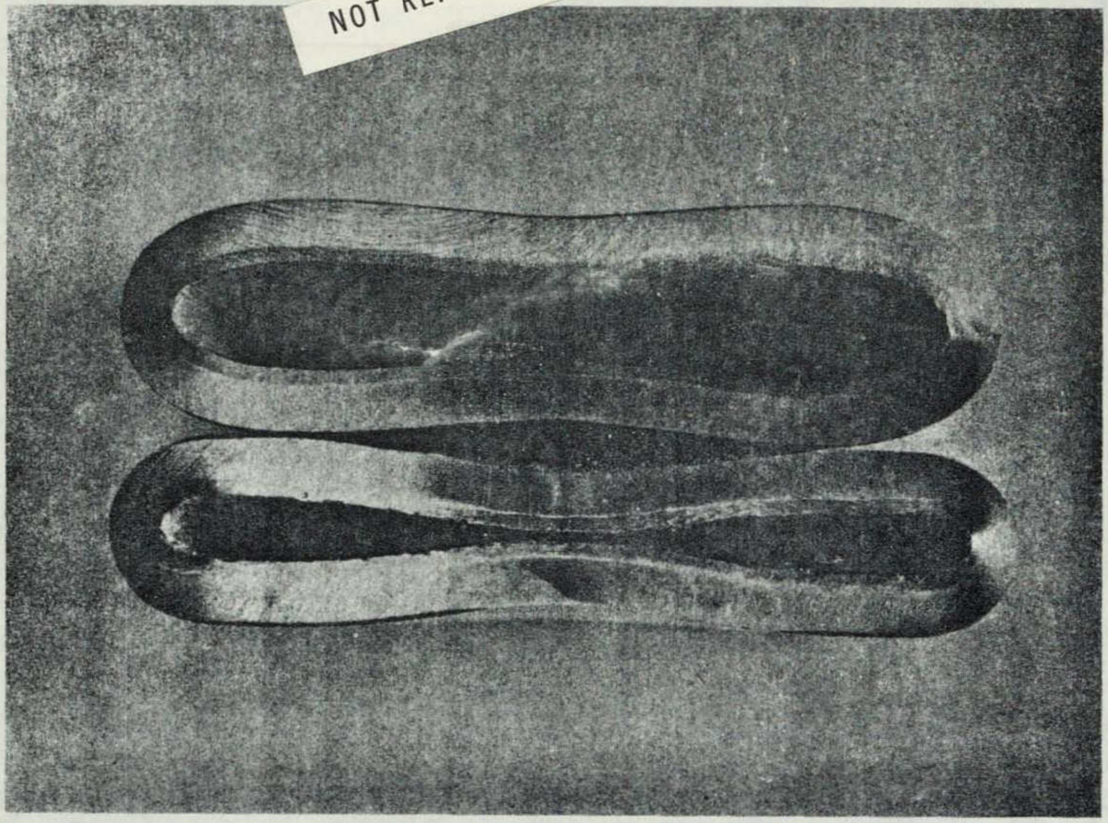
5X 0491
Sect. B-B



Hours at 1350°F
4,864
4,864
4,839

Approx. 1/2 X 0469

Fig. 6. Coextruded Ta/316SS tube specimens after exposure at 1350°F.

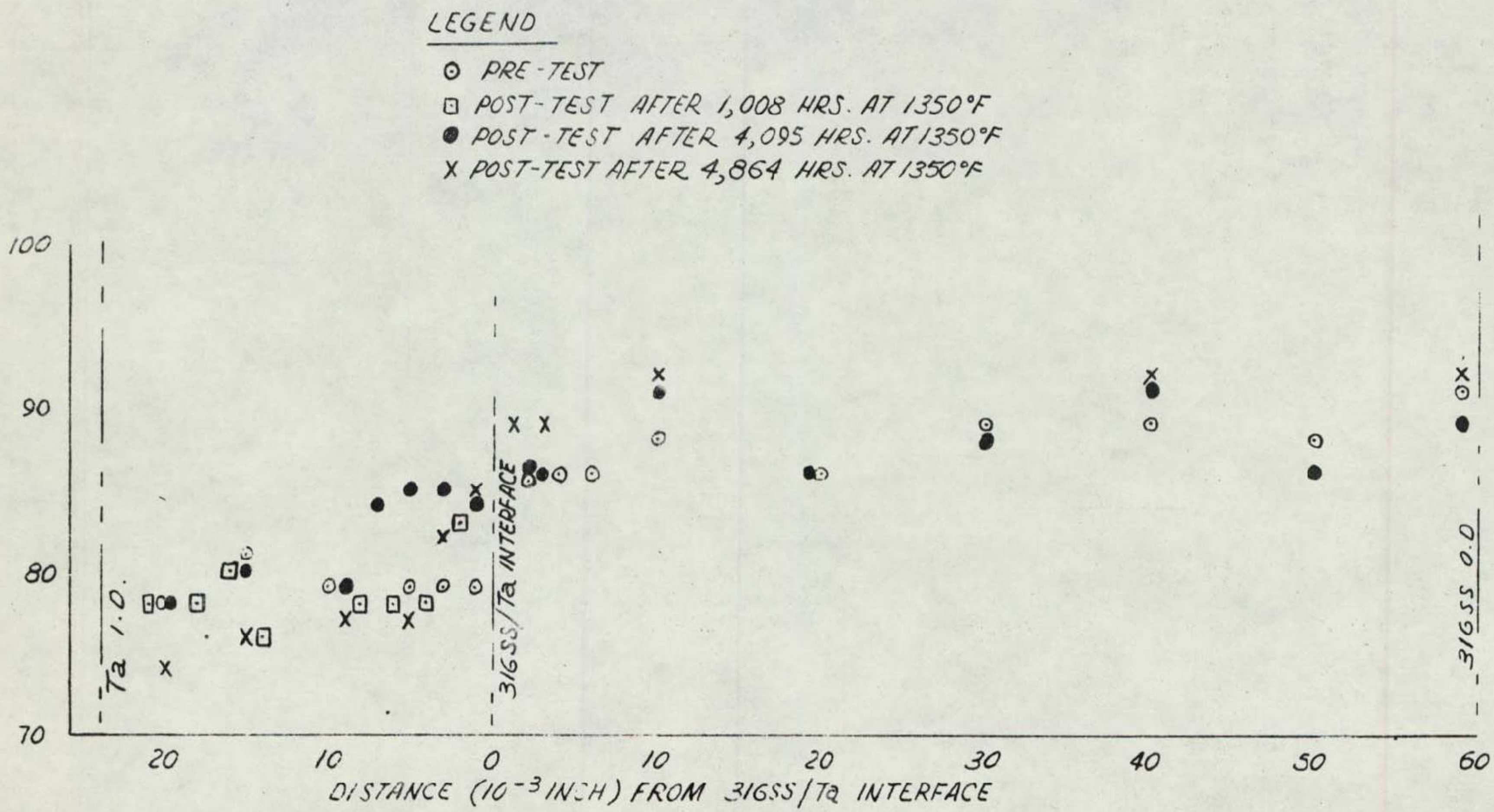


Specimen KK after 4,095 hrs. at 1350°F

As coextruded specimen

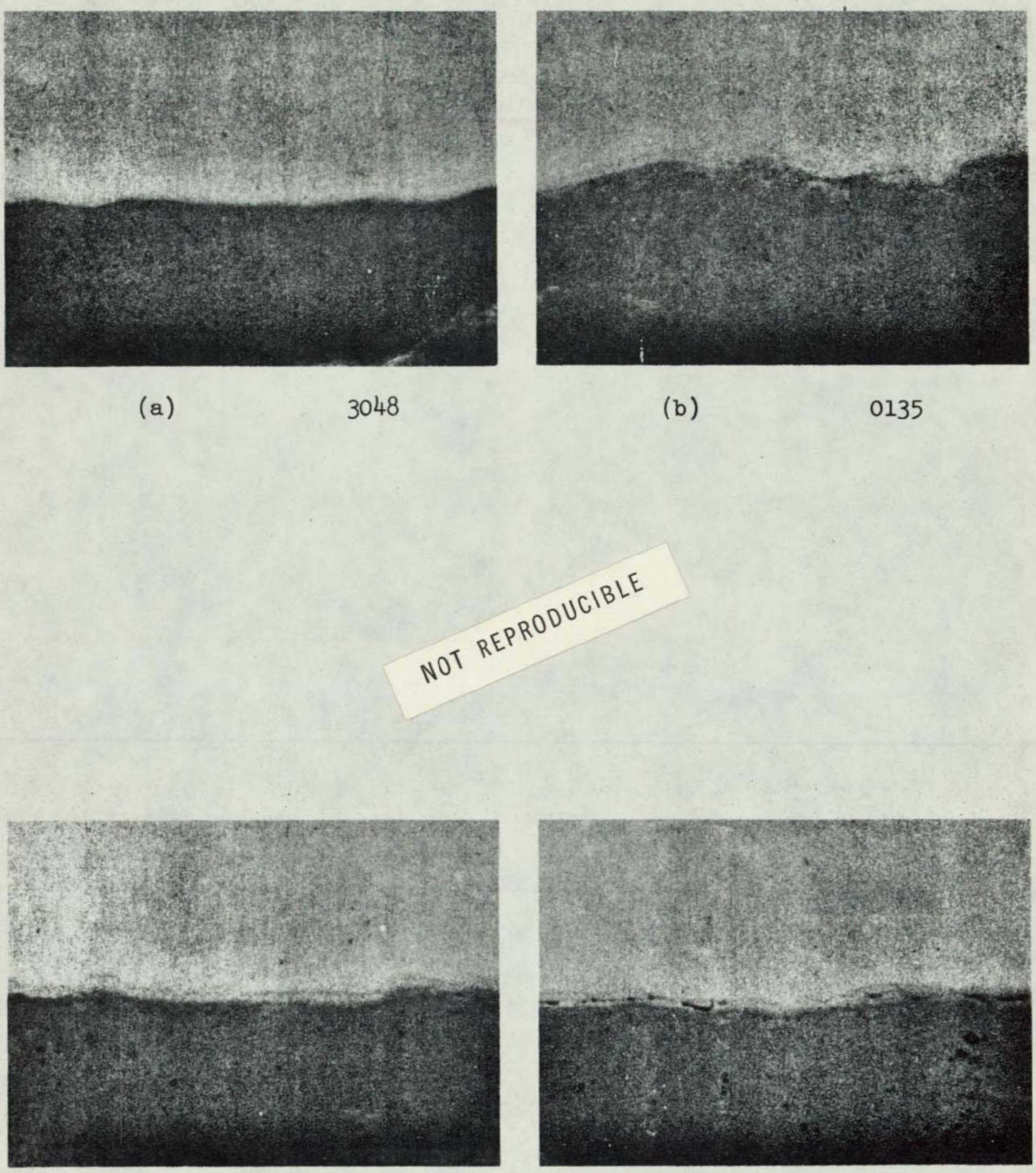
4X 0149

Fig. 7. Coextruded Ta/316ss tube specimens after flattening test, showing end cracking in thermally exposed specimen and absence of cracking in as coextruded specimen.



HARDNESSES OF COEXTRUDED 316SS/Ta TUBING AFTER 1350°F EXPOSURE

FIGURE 8



316SS

Ta

(a) 3048 (b) 0135

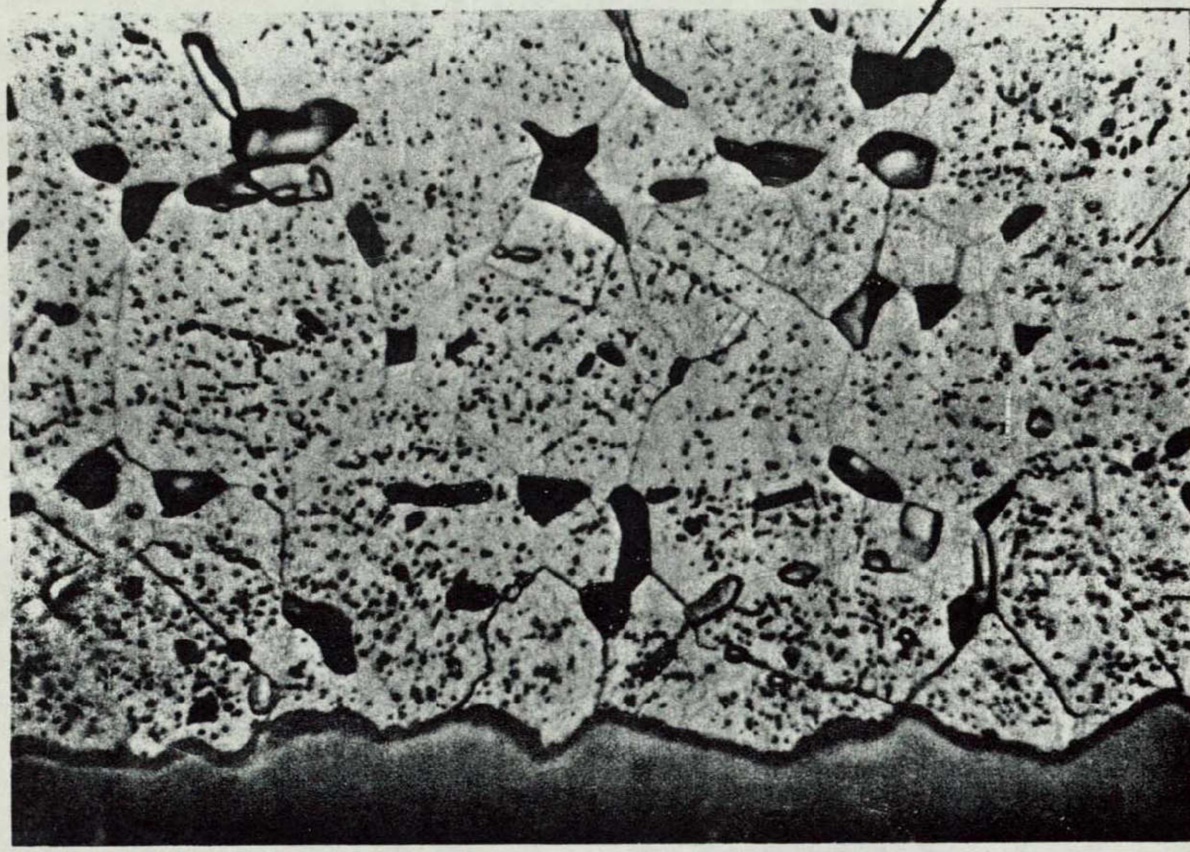
316SS

Ta

(c) 0519 (d) 0520

Figure 9. Ta-316SS interface of coextruded tubing, 2000X
All interfacial diffusion zones are 10^{-5} inches thick.

(a) As coextruded specimen, (b) specimen KK after 4,095 hours at 1350°F, (c) specimen LL after 4,864 hours at 1350°F), (d) specimen LL after 4,864 hours at 1350°F showing microcracking which was present in approximately 0.2% of the interface.



2000X, 10% $(NH_4)_2S_2O_8$ etch.   0525

Fig. 10. Microstructure of 316SS in coextruded Ta/316 SS tubing after 4,864 hours at 1350°F

TABLE I - SUMMARY OF THERMAL EXPOSURE AND EVALUATION OF COEXTRUDED 316SS/Ta TUBING

SPECIMEN, 15" LENGTH(a)	EXPOSURE PERIOD	NO. OF CYCLES		CYCLE DESCRIPTION (HRS.)					CYCLE TYPE	SPECIMEN EVALUATION(b)			
		PER EXPOSURE PERIOD	ACCUMULATED	HEATING TIME 250 TO 1350°F.	1350°F DWELL TIME			COOLING TIME 1350 TO 250°F		316SS/Ta BOND ULTRASONIC INSPECTION	Ta LINER ULTRASONIC INSPECTION	METALLOGRAPHY	DIMENSIONAL INSPECTION
					PER CYCLE	PER EXPOSURE PERIOD	ACCUMULATED						
	1	1	1	1/2	95	95	95	2-1/2	Fast	KK PP	-	-	-
	2	25	26	1/2	5	125	220	2-1/2	Fast	KK, PP	-	-	-
	3	1	27	1/2	100	100	320	2-1/2	Fast	KK, PP	-	-	-
	4	51	78	4-1/2	13	663	983	6-1/2	Slow	KK, PP	-	PP(c)	KK PP
	5a	1	79	7	53-1/2			13	Slow	-	-	-	-
	b	1	80	1-1/2	8				Fast	-	-	-	-
KK (N24)	c	1	81	7	164	1,034			Slow	-	-	-	-
PP (N26)	d	1	82	7	58-1/2				Slow	-	-	-	-
	e	1	83	3-1/2	314				Fast	-	-	-	-
	f	1	84	4	436		2,017	13	Fast	KK. PP	KK. PP	-	KK PP
	6a	1	85	7	380-1/2			12	Slow	-	-	-	-
	b	1	86	7	645-1/2	1,026	3,043	12	Slow	KK. PP	KK PP	-	KK. PP
	7	78	164	8-1/4	14-1/4	1,052	4,095	9-1/2	Slow	-	-	KK(d)	KK
PP (N26)	8	52	216	8-1/4	14-1/4	744	4,839	9-1/2	Slow	-	-	-	PP
PP (N26)	9	35	251	8-1/4	14-1/4	489	5,328	9-1/2	Slow	-	-	-	PP
	1	25	25	1/2	5	125	125	2-1/2	Fast	AA, LL	-	-	-
	2	1	26	1/2	95	95	220	2-1/2	Fast	AA. LL	-	-	-
	3	25	51	1/2	5	125	345	2-1/2	Fast	AA LL	-	-	-
AA (N24)	4	51	102	4-1/2	13	663	1,008	6-1/2	Slow	AA LL	-	LL(c)	AA LL
LL (N26)	5a	1	103	7	53-1/2			13	Slow	-	-	-	-
	b	1	104	1-1/2	8			13	Fast	-	-	-	-
	c	1	105	7	164	1,034		13	Slow	-	-	-	-
	d	1	106	7	58-1/2			13	Slow	-	-	-	-
	e	1	107	3-1/2	314			13	Fast	-	-	-	-
	f	1	108	4	436		2,042	13	Fast	AA, LL	AA LL	-	AA LL
	6a	1	109	7	380-1/2			12	Slow	-	-	-	-
	b	1	110	7	645-1/2	1,026	3,068	12	Slow	AA. LL	AA, LL	-	AA LL
	7	78	188	8-1/4	14-1/4	1,052	4,120	9-1/2	Slow	-	-	-	-
	8	52	240	8-1/4	14-1/4	744	4,864	9-1/2	Slow	-	-	LL(d)	AA LL
AA (N24)	9	35	275	8-1/4	14-1/4	489	5,353	9-1/2	Slow	-	-	-	AA

(a) Specimens were cut from either N24 or N26. N24 and N26 were 2 tubes of a 10-tube order (17 ft. lengths) received from Nuclear Metals

(b) Evaluation followed exposure period indicated.

(c) One-inch length cut from tube end for hardness and interface examination. Specimen was then resealed and thermal exposure continued

(d) Thermal exposure discontinued

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS

M E M O R A N D U M

FILE: ME 11:110

DATE: 8 October 1970
7972:70:0111:CGN:eh
Bldg. 160, X6730

TO: E. S. Chalpin

FROM: C. G. Neitsch

SUBJECT: Re-evaluation of Ultrasonic Bond Inspection of Ta/316SS Bimetal Sleeve No. 7

COPIES TO: H. Derow, A. H. Kreeger, G. L. Lombard, J. R. Pope, U. A. Pineda

Cleveland: W. L. Snapp

NASA, LeRC: E. R. Furman, P. L. Stone

NAVPLANTREP/NASA-COR: D. E. Blasco

REFERENCE: (a) J. R. Pope to P. L. Stone, Letter 7972:70:0077, "Ultrasonic Bond Inspection of Sleeve Joints No. 6 and No. 7", 15 July 1970
(b) D. R. Stoner to H.E. Bleil, Westinghouse Letter 70:132:DRS, 26 August 1970
(c) C. G. Neitsch to E. S. Chalpin, Memo 7972:70:0067, "Ultrasonic Bond Inspection of Boiler No. 4 Hg. Inlet and Outlet Bimetal Sleeves", 17 June 1970

SUMMARY & CONCLUSIONS

A re-evaluation of the ANSC/CONAM bond inspection of Ta/316SS Bimetal Sleeve No. 7 was made after Westinghouse proved the original inspection results unreliable. It was concluded that:

1. The original ultrasonic inspection of Sleeve No. 7 was interpreted incorrectly as indicating unbond due to failure to follow the previously developed inspection procedure. The present inspection revealed no debonding of Sleeve No. 7.

2. The reported results of the ultrasonic inspection of BRDC Boiler No. 4 Hg Inlet and Outlet Bimetal Sleeves are reliable.

3. The ultrasonic procedure developed by ANSC to inspect the bond of bimetal sleeves is adequate.

INTRODUCTION

In July 1970 Ultrasonic Inspection of Ta/316SS bimetal sleeves No. 6 and No. 7 was performed at Conan for ANSC. This inspection resulted in reporting that sleeve No. 7 exhibited debonding at the Ta/316 interface and that sleeve No. 6 was bonded, Reference (a). Subsequent ultrasonic and metallographic examination of the sleeve by Westinghouse indicated that joint No. 7 was not debonded, Reference (b). Re-inspection of the remnant section of sleeve No. 7 was conducted by Conan under ANSC surveillance on 5 October 1970 to determine the cause of the original erroneous report of the presence of debond.

ULTRASONIC RECHECK OF JOINT NO. 7 REMNANT

The remnant of joint No. 7 remaining after Westinghouse metallography was ultrasonically inspected using the C-scan technique reported previously in Reference (a). A variable reflection was received from the 316SS/Ta bond interfaces of both the inspection standard, T1286791, and joint No. 7 without a corresponding loss of reflection from the I.D. surfaces, but the amplitude of the bond interface reflection was greater from joint No. 7 than from the inspection standard. During the original inspection of joint No. 7, the greater amplitude of the interface reflection was interpreted incorrectly as indicating unbond. The greater amplitude results from a combination of two effects: (1) The 316SS thickness in joint No. 7 (.16 in.) is greater than the inspection standard thickness (.12 inch) which results in the bond interface distance from the joint O.D. being greater in joint No. 7 than in the inspection standard, and (2) The amplitude of the signal reflection is greater at .16 in. than at .12 in. distance from the O.D. due to variation in signal strength with specimen position. The originally developed inspection procedure determined that unbond is indicated by a loss of reflection from the I.D. surface, Reference (c). Therefore, no unbond of joint No. 7 is indicated as no loss of I.D. surface reflection occurred during inspection. The originally reported results of unbond in joint No. 7 resulted from the unacceptable deviation in the developed ultrasonic inspection procedure of not monitoring the I.D. surface reflection when reflections from the 316SS/Ta interface were received.

The previously reported results of ultrasonic bond inspection of Boiler No. 4 bimetal sleeves are reliable as unbonding was reported only at locations where loss of I.D. reflection accompanied bond line reflections, Reference (c).

HBleil for
C. G. Neftsch
Materials Engineering Group

APPROVED:

HBleil

H. E. Bleil, Supervisor
Materials Engineering Group
Technical Resources Section
Engineering Department
Power Systems Operations

APPENDIX G

OVERALL BOILER STRESS ANALYSES

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS
ENGINEERING DESIGN FILE

ENGINEERING FILE NO.
EDF SERIAL NO. DE 0016
DATE 6 July 1970
W. O. NO. 1475-44-0114

PROJECT SNAP-8

SUBJECT

BRDC BOILER #5 OPERATING CRITERIA FOR STRESS ANALYSES

ABSTRACT

MEMO 7978:70:0003, same subject, dated 6 July 1970 itemizes the operating criteria to consider when performing stress analyses for the BRDC #5 boiler.

With this memo and the work done previously by the Stress Analysis Group for BRDC #4, the parameters to work to in evaluating the stress levels for BRDC #5 are well defined.

DISTRIBUTION

Distribution made under Memo No. 7978:70:0003

COVER SHEET ONLY

E. S. Chalpin, U. A. Pineda, R. W. Marshall, H. Derow, Dr. W. Weleff, A. J. Sellers

KEY WORDS

BRDC #5 Boiler, Operating Criteria, Stress Analyses

AUTHOR	DEPT	REVIEWED	DATE	REVIEWED	DATE
E. S. Chalpin ESC	7978			RWM	8/5/70

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS

DATE: 6 July 1970
7978:70:0003:mrs
Bldg. 160/X5522

MEMORANDUM

TO: Dr. W. Weleff/H.Derow

FROM: E. S. Chalpin

SUBJECT: BRDC Boiler #5 Operating Criteria for Stress Analyses

COPIES TO: B. Breindel, R. G. Geimer, C. Hawk, J. Hodgson, S. Krikopulo, G. L. Lombard, L. Lopez, R. W. Marshall, U. A. Pineda, File

ENCLOSURE: (1) Table I - "BRDC Boiler #5 Operating Criteria"

When analyzing the stresses for the BRDC Boiler #5, please use the values tabulated in Enclosure (1) and the materials properties used when you analyzed the BRDC Boiler #4 design in April through June 1969.

The following operational modes must also be considered in your analyses:

Heatup - Boiler heats up from ambient to 1211°F. Mercury pressure is at zero psia during this time. Static NaK pressure rises from ambient to 30 psia at 1211°F.

Flowing primary NaK inlet and outlet temperature rises from ambient to 1211°F and the pressure rises from ambient to 60 psia.

Startup - See A. J. Sellers' thermal map for the maximum temperature gradients during the transient state. Mercury inlet pressure rises from zero psia to 333 psia during this time. Static NaK pressure remains at 30 psia. Flowing primary NaK are at 60 psia and 57 psia respectively. NaK outlet temperature drops to 1044°F. This can occur 100 times during the 5 year life of the boiler.

Steady-state - Mercury inlet temperature will remain 420°F and the pressure will remain at 333 psia. The mercury outlet temperature will remain at 1190°F and the pressure will be 148 psia.

The static NaK pressure will be at 30 psia and a temperature of 1190°F. The flowing primary NaK inlet will be at 60 psia and 1211°F while the outlet will be at 57 psia and 1044°F.

Emergency Conditions - Consider that for 20 cycles of 40 seconds duration each, the following conditions will exist:

Mercury inlet - 500 psia and 600°F

Mercury outlet - 222 psia and 1375°F

Flowing primary NaK inlet and outlet - 90 psia and 1485°F

Static NaK - 90 psia and 1485°F

Calculate the low cycle fatigue life of the tantalum for the 5 years of operation.

There are two (2) boilers in series for PCS-G as far as the flowing primary NaK is concerned and the mercury loops are in parallel along with the static NaK loops. Therefore, consider thatt one boiler will be at the "heat up" state (zero mercury pressure, static KNaK at 30 psia and 1211°F with the flowing primary NaK at 60 psia and 1211°F). This results in having one boiler at this condition while the other is at the "steady-state" condition for the 5 years of operational life.

Please see Barry Breindel for the piping and bracketry loads imposed on the boiler.

ES Chalpin

E. S. Chalpin, Supervisor
Mechanical Design Group
Design Engineering Section
Engineering Department

Enclosure (1)

TABLE I - BRDC BOILER #5 OPERATING CRITERIA

Hg Inlet	Hg Outlet	NaK Inlet	NaK Outlet	Static NaK
Low Schedule Inlet Press.=Zero to 323 PSIA Inlet Temp.=70°F. to 420°F Flow = 7,740 #/hr. in 75 sec. =13,775 #/hr. @ steady state.	Outlet Press. = Zero to 148 PSIA. Outlet Temp.=70 to 1185 to 1165°F.	Inlet Press.=Zero to 60 PSIA. Inlet Temp.=70°F to 1185°F Flow=57,148 #/hr.	Outlet Press.=Zero to 57 PSIA. Outlet Temp.=70°F to 1015°F.	Press.=30 PSIA Temp. =70°F to 1185°F
High Schedule Inlet Press.= Zero to 333 PSIA. Inlet Temp. = 70°F. to 420°F. Flow = 7,740 #/hr in 75 sec. = 13,600 #/hr @ steady state	Outlet Press. = Zero to 147 PSIA. Outlet Temp.=70 to 1211 to 1190°F.	Inlet Press.=Zero to 60 PSIA Inlet Temp. = 70 to 1211°F. Flow =57,148 #/hr.	Outlet Press.=Zero to 57 PSIA Outlet Temp.=70°F. to 1044°F.	Press. = 30 PSIA Temp. = 70°F to 1211°F.
Max. Conditions Press. = 500 PSIA Temp. = 600°F. +	Press.= 222 PSIA Temp. = 1375°F.	Press. = 90 PSIA Temp. = 1485°F	Press. = 90 PSIA Temp. = 1485°F.	Press. = 90 PSIA Temp. = 1485°F

AEROJET NUCLEAR SYSTEMS COMPANY
POWER SYSTEMS OPERATIONS

MEMORANDUM

FILE: SS 1020

DATE: 10 July 1970
7974:70:0047:gk
Bldg 160/X6255

TO: H. Derow

FROM: W. Weleff

SUBJECT: Boiler #5 Critical Areas

COPIES TO: E.S.Chalpin, A.H.Kreeger, L.P.Lopez, R.W.Marshall, U.A.Pineda, Dept 7974 File

ENCLOSURE: (1) BRDC Boiler #5 Operating Criteria - Table I
(2) Boiler #5 NaK and Hg Inlet and Outlet Interface Loads - Table II

This memo contains a brief description of the critical areas in the #5 boiler which require stress analyses, the input data needed for performing this analysis, and the approach to be undertaken.

A. CRITICAL AREAS

The Boiler #5 design requires evaluation of the stresses due to the transient and steady-state operational condition. The following areas will require analyses and evaluation.

1. Hg Inlet End

- Bi-metallic tube
- Tantalum Dome
- SS Headers
- SS Dome
- Static NaK Tube-to-Header
- Boiler Shell-to-Header
- NaK Outlet Tee-Section

2. Hg Outlet

- Bi-metallic Tube
- Tantalum Dome
- Tantalum Header
- SS Headers
- SS Dome
- Static NaK Tube-to-Header
- NaK Inlet Tee-Section
- Boiler Shell

3. Overall Boiler

- Spacers
- Shell Deformation
- Ta-Tube vs SS Housing Relative Movement

4. Boiler Mounting

- Design Details
- Integration

B. DATA REQUIRED FOR PERFORMING THE STRUCTURAL ANALYSIS

There are three types of information needed to conduct this analysis:

1. Operational Data

Proper consideration must be given to the pressure, gravity loads and temperature. Axial and radial temperature distribution of all critical locations, particularly where sharp gradients are expected is required to properly evaluate the thermal stresses. This is of considerable importance at the Hg inlet end. This information needs to be very specific for actual values (see Enclosure (1)).

2. Interface Loads

The interface requirements at the NaK and Hg inlet and outlet junctions are specified in Enclosure (2).

3. Material Properties

Mechanical and physical properties data at various temperature levels are required. This includes tensile yield and ultimate strength, elongation, area reduction modulus of elasticity, thermal expansion, creep and stress-rupture data.

C. APPROACH AND METHOD OF ANALYSIS

1. Finite elements Computer Program E-11401 will be used for the Hg inlet and outlet ends. These components have axisymmetrical geometry and loading directly suited for application of the finite elements computer program.

2. Hand calculation will be used for evaluation of the boiler body, based on the thermal expansion characteristics of the two structural materials (Ta and SS).

3. The analyses of the interface loads and supporting structure will be performed by hand.

4. Thermal fatigue analyses will be made, using the Manson's method and the computer output, where applicable.

D. STRESS CRITERIA

Minimum design safety factors for Boiler #5 for the most critical loading condition shall be 1.25 against allowable creep load or yield strength, 1.50 against ultimate strength and 1.50 against endurance (fatigue strength).

Analysis of the boiler evaluation of the most critical loading conditions, primary and secondary stress safety margin, etc., should be in accordance with AGC-10650

The primary stresses for all components should be kept below the yield strength of the material whenever possible. The thermal stresses should be maintained at a minimum level by providing free expansion of the various components and by reducing the axial and radial thermal gradients. Materials with compatible coefficients of thermal expansion are desired. Supporting the boiler in the frame structure should be in such a way to permit free expansion or contraction of the overall boiler, thus, reducing the effects of thermal stresses on the structure which in turn will result in longer service life.

W. Weleff

W. Weleff, Supervisor
Structural Analysis Group
Technical Resources Section
Engineering Department

TABLE I - BRDC BOILER #5 OPERATING CRITERIA

Hg Inlet	Hg Outlet	NaK Inlet	NaK Outlet	Static NaK
Low Schedule Inlet Press.=Zero to 323 PSIA Inlet Temp.=70°F. to 420°F Flow = 7,740 #/hr. in 75 sec. =13,775 #/hr. @ steady state.	Outlet Press. = Zero to 148 PSIA. Outlet Temp.=70 to 1185 to 1165°F.	Inlet Press.=Zero to 60 PSIA. Inlet Temp.=70°F to 1185°F Flow=57,148 #/hr.	Outlet Press.=Zero to 57 PSIA. Outlet Temp.=70°F to 1015°F.	Press.=30 PSIA Temp. =70°F to 1185°F
High Schedule Inlet Press.= Zero to 333 PSIA. Inlet Temp. = 70°F. to 420°F. Flow = 7,740 #/hr in 75 sec. = 13,600 #/hr @ steady state	Outlet Press. = Zero to 147 PSIA. Outlet Temp. =70 to 1211 to 1190°F.	Inlet Press.=Zero to 60 PSIA Inlet Temp. = 70 to 1211°F. Flow =57,148 #/hr.	Outlet Press.=Zero to 57 PSIA Outlet Temp.=70°F. to 1044°F.	Press. = 30 PSIA Temp. = 70°F to 1211°F.
Max. Conditions Press. = 500 PSIA Temp. = 600°F.	Press.= 222 PSIA Temp. = 1375°F.	Press. = 90 PSIA Temp. = 1485°F	Press. = 90 PSIA Temp. = 1485°F.	Press. = 90 PSIA Temp. = 1485°F

TABLE II - BOILER #5 NAK AND HG INLET AND OUTLET INTERFACE LOADS

INTERFACE DESCRIPTION	FORCE (lb)			MOMENT (in.-lb)			LOAD TYPE
	Fx	Fy	Fz	Mx	My	Mz	
Boiler Hg Outlet	-15.1	-10.1	39.4	433	414	-283	Thermal, T = 1190°F
	-12	-9	285	333	267	235.5	Weight
	-27	- 19.1	67.9	766	681	518	Combined
Boiler Hg Inlet	-2.1	0	0	0	19.1	-4.25	Thermal, T = 417°F
	2	-8	0	-49	-20	-250	Weight
	-.1	-8	0	-49	0.9	-254.5	Combined
Boiler #1 NaK Inlet	+17.7	-67	+26.6	-434	-276	-504	Thermal, 1185°F, ΔT = 1110°F
3 in. OD x .085 in. Wall, 316 SS	-1.4	+85	+4	-659	-259	+347	Weight
	3.7	18	30.6	-1093	-535	-157	Total
Boiler #1 NaK Outlet	-1	2	11	388	-234	102	Thermal, 1185°F, ΔT = 1110°F
3 in. OD x .083 in. Wall, 316 SS	-95	-29	-10	494	-2010	1545	Weight
	-96	-27	1	882	-2244	1647	Total
Boiler #2 Inlet	-1	2	11	-513	440	-183	Thermal, 1185°F, ΔT = 1110°F
3 in. OD x .083 in. Wall, 316 SS	-95	-123	-10	402	90	-1024	Weight
	-96	-121	1	-111	530	-1207	Total
Boiler #2 Outlet	49	11	3	331	-830	-94	Thermal, 1015°F, ΔT = 940°F
3 in. OD x .083 in. Wall, 316 SS	39	2	-31	132	-248	-134	Weight
	88	13	-28	463	-1078	-228	Total

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

QUADRILLE WORK SHEET

PAGE 1 OF 1 PAGES
DATE 1 SEPT. 1970
WORK ORDER 1475-44-0114

SUBJECT E-11401 COMPUTER STRESS ANALYSIS INPUTS

BY El Chalpin

I. MATERIALS PROPERTIES INPUTS —

E = MODULUS OF ELASTICITY FOR TANTALUM & 316 SS
FROM 70°F. TO 1485°F.

ν = POISSON'S RATIO FOR TANTALUM & 316 SS
0.35 FOR Ta, 0.30 FOR 316 SS.

S_y = YIELD STRESS FOR TANTALUM & 316 SS
VALUES AT 70, 500, 900 & 1485°F

$$\text{MODULUS RATIO} = \frac{\text{PLASTIC MODULUS}}{\text{ELASTIC MODULUS}}$$

α = COEFFICIENT OF THERMAL EXPANSION FOR Ta & 316 SS
FROM 70°F. TO 1485°F.

P = PRESSURES, INTERNAL & EXTERNAL

II. NODAL POINTS

DETERMINE LOCATION OF NODAL POINTS IN RZ PLANES

III. MANSON EQUATION FOR DETERMINATION OF CYCLE LIFE —

$$\Delta \varepsilon_{eff.} = \left[\frac{2(1+\nu)}{3}\right]\left[\frac{3.5\,F_{TU}}{E}\right](N_f)^{-0.12} + (D)^{0.6}(N_f)^{-0.6}$$

WHERE:

$\Delta \varepsilon_{eff.}$ = EFFECTIVE STRAIN

ν = POISSON'S RATIO

F_{TU} = ULTIMATE STRENGTH AT TEMPERATURE

E = MODULUS OF ELASTICITY AT TEMPERATURE

N_f = CYCLES OF LIFE

D = DUCTILITY $= \ln \frac{100}{100-RA}$

RA = REDUCTION OF AREA (%)

DETERMINE N_f, THEN TAKE 10% OF N_f FOR PREDICTED LIFE CYCLES.

LOW CYCLE FATIGUE - ELEVATED TEMPERATURE, LOW FREQUENCY, LONG TIME EXPOSURE

by: U. A. Pineda

In low cycle fatigue investigations, strain rather than stress levels and ranges become the guiding factors. Plastic strain is the dominant element and an extremely important variable in predicting low cycle fatigue behavior.

The total strain range experienced during cycling consists of plastic and elastic strain components, thus

$$\Delta\epsilon_T = \Delta\epsilon_p + \Delta\epsilon_e \quad \text{------------} \quad (1)$$

where $\Delta\epsilon_T$ = Total strain range, in/in
$\Delta\epsilon_p$ = Total plastic strain range, in/in
$\Delta\epsilon_e$ = Total elastic strain range, in/in.

A relationship exists between the plastic strain, the number of cycles to failure and the ductility of the material. Experimental investigations have shown that the relationship can be mathematically expressed by a linearization of the log-log plot of data as follows:

$$\Delta\epsilon_p = \frac{C_D D^n}{N^K} \quad \text{------------} \quad (2)$$

where C_D = coefficient to linearize the log-log plot
D = Ductility = $\ln\left[\frac{100}{100 - RA}\right]$
RA = Reduction of Area
N = Cycles to failure
n = Slope of the linearized log-log plot of cyclic life vs. ductility
k = Slope of the linearized log-log plot of plastic strain range vs. cyclic life.

The elastic strain range is a direct proportional relationship with the stress range in the Hooke's Law regime:

$$\Delta\epsilon_e = \frac{\Delta\sigma}{E} \quad \text{-----------------} \quad (3)$$

$\Delta\sigma$ = Stress range, psi

E = Young's Elastic Modulus, psi

Cyclic patterns in the elastic range are normally referred to as the endurance strength of the material,

$$\Delta\sigma = 2F_e \quad \text{-----------------} \quad (4)$$

F_e = Endurance strength, psi

However, in view of elevated temperature, long time exposures, creep/rupture behavior of the material predominates; therefore,

$$\Delta\sigma = 2F_R \quad \text{-----------------} \quad (5)$$

F_R = Rupture strength at exposure temperature and time, psi

The creep-rupture stress-time curve is linearized in the log-log plot to an extrapolated rupture stress level equivalent to x times the ultimate strength:

$$F_R = x F_u \left(\frac{t_R}{A}\right)^{-m} \quad \text{-----------------} \quad (6)$$

where: A = time intercept on the linearized log-log plot at an extrapolated rupture level equivalent to $X \cdot F_u$, hours

t_R = time to rupture at F_R level, hours

X = arbitrary multiple of the ultimate tensile strength for linearizing the curve

m = slope of the linearized log-log plot of rupture strength vs. time.

using X = 1.75, adequate multiple for linearization

$$F_R = 1.75\, F_u \left[\frac{t_R}{A}\right]^{-m} \qquad (6A)$$

However, $t_R = \dfrac{N}{\omega}$ $\qquad (7)$

where ω = strain cycling frequency, cycles per hour

Hence, $F_R = 1.75\, F_u \left[\dfrac{N}{A\omega}\right]^{-m}$ $\qquad (8)$

Using equations (8) and (5) in equation (3) results in:

$$\Delta\epsilon_e = \frac{3.5\, F_u}{E} \left[\frac{N}{A\omega}\right]^{-m} \qquad (9)$$

Equation (1) becomes:

$$\Delta\epsilon_T = \frac{C_D D^n}{N^K} + \frac{3.5\, F_u}{E}\left[\frac{N}{A\omega}\right]^{-m} \qquad (10)$$

which is the low cycle fatigue equation. Coefficients and exponents are to be formulated from test data and material property curves.

Dept. 4927

ANALYSIS NO. SA-245

DATE 3 September 1970

SUMMARY OF ANALYSIS

Project SNAP-8 Component BRDC #5	Distribution:
Part NaK & Hg Inlet/Outlet Drawing No. 1268605	E. S. Chalpin
Subject Interface Loads	H. Derow
Reference(s) Memo E. Chalpin to W. Weleff, 6 July 1970.	U. A. Pineda
Subject: Operating Criteria for Stress Analysis	G.L. Lombard
Engineer J. C. Shen Approved W. Weleff	File: SS 1020-03

OBJECTIVE: To evaluate the structural integrity of NaK and Hg inlet/outlet for the piping interface loads.

ASSUMPTIONS:

Critical loading condition assumed when axial and radial forces are combined with axial and radial moments torque and internal pressure.

REFERENCES (Analysis Methods):

1. AGC-10650 - Structural Design Criteria, SNAP-8.
2. Materials Manual H-100.

RESULTS AND CONCLUSIONS:

1. The stress levels due to each individual loading condition are below the corresponding allowables.
2. The results of the interaction equation indicate sufficient margins of safety for each component.
3. The stresses in the welds at the proposed location are acceptable.

RECOMMENDATIONS AND COMMENTS:

All parts are considered structurally safe for the given interface loads.

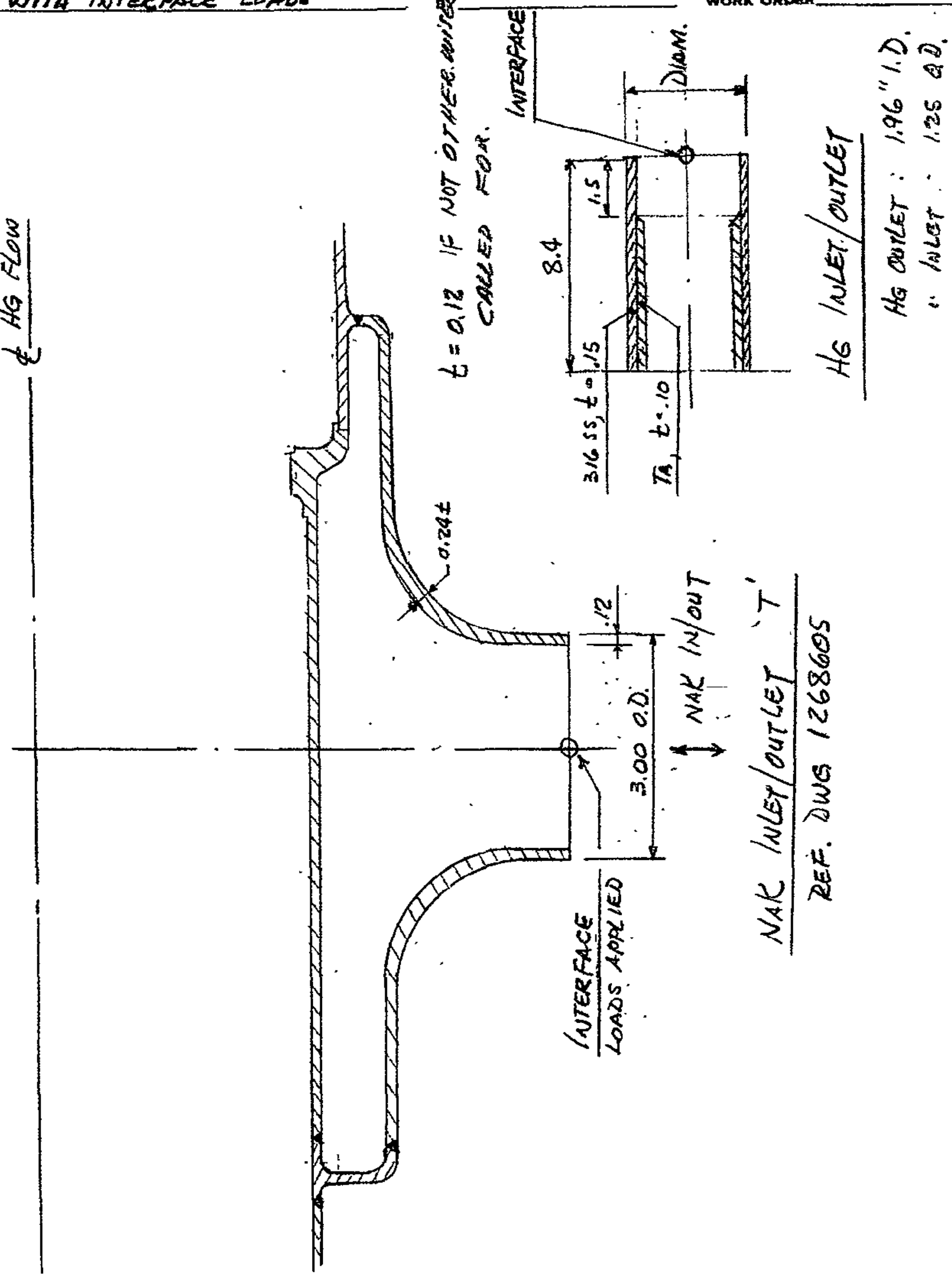
AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

QUADRILLE WORK SHEET

PAGE 1 OF 3 PAGES
DATE SEPT. 3, 1970
WORK ORDER

SUBJECT NAK & HG INLET/OUTLET STRESSES WITH INTERFACE LOADS

BY



NAK INLET/OUTLET & HG INLET/OUTLET STRESSES

REFERENCES:

1. CHALPIN'S MEMO - BRDC #5 OPERATING CRITERIA FOR STRESS ANALYSIS (JULY 6, 1970)
2. WELEFF'S MEMO - TABLE II - BRDC #5 NAK & HG INLET/OUTLET INTERFACE LOADS (JULY 10, 1970) SS 1020
3. AGC DESIGN HANDBOOK H-100
4. BRUHN: ANALYSIS & DESIGN OF FLIGHT VEHICLE STRUCTURE TABLE C.8.1 ON INTERACTION EQUATIONS
5. AGC SPECIFICATION 10650 - STRUCTURAL DESIGN CRITERIA

DESIGN CONDITIONS: REF. 1 TABLE I & REF. 2 TABLE II

1. HIGH SCHEDULE — MAX PRESSURE & TEMP. USED
2. EMERGENCY CONDITION — MAX PRESSURE & TEMPERATURE FOR 20 CYCLES OF 40 SEC DURATION
3. INTERFACE LOADS - COMBINED THERMAL & WT. LOADS ARE USED
4. INTERACTION EQUATION -

$$R_c + R_{sT}^2 + \sqrt[3]{R_b^3 + R_s^3} < 1.0$$

WHERE R'S ARE STRESS RATIO'S FOR BENDING, HOOP, TRANSVERSE SHEAR & DIRECT LOAD

+e

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

PAGE 3 OF 3 PAGES

DATE

SUBJECT

BY

WORK ORDER

RESULTS OF ANALYSIS

COMPONENT	DESIGN COND				INTERACTION EQU.		NOTES
	P psi	T °F	P psi	T °F	ALLOW F_{CREEP} CRITERIA (1% 40,000 HRS)	$F_{RUPTURE}$ * (EMERGENCY)	
NaK INLET:							
@ INTERFACE	p = 60 PSI	T = 1211 °F	p = 90 PSI	T = 1485 °F	ΣR	LOW	STRESSES ARE LOW
@ CURVATURE					0.202	0.058	
@ WELD					ΣR	LOW	STRESSES LOW
NaK OUTLET:							
@ INTERFACE	p = 57 PSI	T = 1044 °F	p = 96 PSI	T = 1485 °F	0.042	0.166	
@ CURVATURE					.121	.076	
@ WELD					.271	.226	
Hg INLET:							
@ 1.5"	p = 333 PSI	T = 420 °F	p = 500 PSI	T = 600 °F	ΣR	LOW	STRESSES LOW
@ 8.4"					ΣR	"	" "
Hg OUTLET:							
@ 1.5"	p = 147 PSI	T = 1190 °F	p = 222 PSI	T = 1375 °F	0.417	LOW	
@ 8.4"					LOW	LOW	

* FOR EMERGENCY CONDITION – REF. 1 SPECIFIES FOR 20 CYCLES OF 40 SECONDS DURATION EACH. FROM REF. 5 TABLE III FOR PRIMARY & SECONDARY STRESSES COMBINED, THE ALLOWABLE IS $2 \times F_{ty} = 2 \times 14{,}800 = 29{,}600$ PSI. HERE $F_{tu} = 29{,}000$ PSI IS USED.

Dept. 4927

ANALYSIS NO. SA- B-246

DATE 3 September 1970

SUMMARY OF ANALYSIS

Project SNAP-8	Component Boiler #5	Distribution:
Part 316SS Header	Drawing No.	E.S. Chalpin
Subject Structural Analysis - Interim Report		G.L. Lombard
Reference(s) Memo E. Chalpin to W. Weleff, 6 July 1970, Subject: Operating Criteria for Stress Analysis		U.A.Pineda/H. Derow
Engineer S. Krikopulo	Approved W. Weleff	File: SS 1020-03

OBJECTIVE: To evaluate the integrity of the 316SS header for the transient and steady state operational condition.

ASSUMPTIONS:

Most critical loading condition is assumed due to internal pressure differential (max.) and maximum thermal gradient -- high schedule.

REFERENCES (Analysis Methods):

AGC-10650 - Structural Design Criteria for SNAP-8
Materials Manual H-100.

RESULTS AND CONCLUSIONS:

1. The stresses in the stainless steel header (flat plate section) are found below the corresponding allowables.
2. At the juncture of the header to the exterior shell toward the inlet end a small yielding will take place.
3. The stress level at the juncture of the header toward the interior portion of the boiler unacceptable stress levels were obtained.

RECOMMENDATIONS AND COMMENTS:

Investigate a change in transition juncture of the header to the exterior NaK shell toward the inside section of boiler.

Finite element computer program analysis is recommended.

NOTE: The loading condition was found unrealistic. This analysis is cancelled.

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AZUSA, CALIFORNIA

QUADRILLE WORK SHEET

DATE 9-3-70
SUBJECT BRDC BOILER #5 BY SK WORK ORDER

Mercury Inlet End

316 SS Header

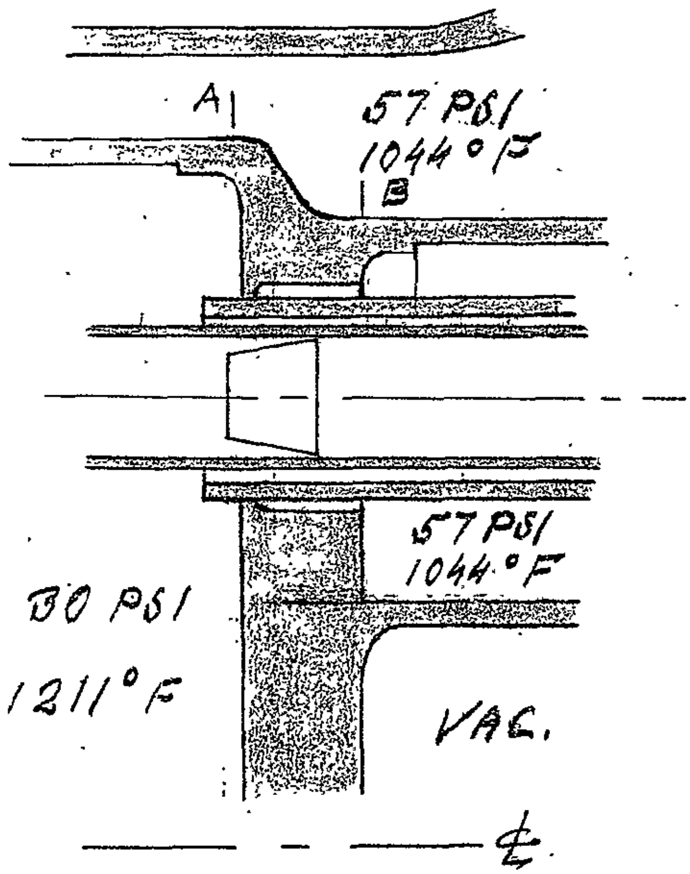


FIG. 1

Material: 316 SS
For temperature distribution see FIG. 1
Assumed critical case: high schedule
For pressures see FIG. 1

Header is assumed to be a solid contin. plate.

Stresses were checked at crossection A and B — see FIG. 1
Method of analysis:
Conventional calculations by hand.

Summary of stresses

CROSS-SECT.	MERID. OR HOOP	σ PSI STRESS	TYPE OF STRESS	T°F
A	M	18000	TENS.	1200
	H	5650	COMP.	
B	M	14400	TENS.	1100
	H	75800	COMP.	

Material allowables

T°F	F_{ty}	F_{tu}
1200	16000	53000
1100	16700	62000

Dept. 4927

ANALYSIS NO. SA-247

DATE 3 September 1970

SUMMARY OF ANALYSIS

Project SNAP-8	Component Boiler #5	Distribution:
Part Mercury Outlet	Drawing No.	W.S. Chalpin
Subject Structural Analysis		G.L. Lombard
Reference(s) Memo E.S. Chalpin to W.Weleff/H. Derow, dated 6 July 1970, Subject: Operating Criteria for Stress Analysis		U.A. Pineda
		H. Derow
Engineer S. Krikopulo	Approved W. Weleff	File: SS 1020-03

OBJECTIVE: Evaluate the structural integrity of the mercury outlet end for Boiler #5.

ASSUMPTIONS:

The most critical loading condition is assumed to be the maximum operational pressure and uniform steady state temperature at the emergency case: $p = 222$ psi
$T = 1375^{\circ}F$

REFERENCES (Analysis Methods):

AGC-10650 - Structural Design Criteria for SNAP-8.
Materials Manual H-100.
AGC Finite Element Computer Program E-11401

RESULTS AND CONCLUSIONS:

1. The stress levels obtained in most areas of the outlet are close to the stress levels obtained for Boiler #4
2. Comparison tables of the stresses for the bimetallic section and tantalum dome for Boilers No. 4 and No 5 are included.
3. Fatigue life is estimated to be close to the fatigue life of Boiler #4.

RECOMMENDATIONS AND COMMENTS:

The design for the mercury outlet end is acceptable.

MERCURY OUTLET

Geometry

Mercury outlet consists of three parts:

1 Header - circular plate - tantalum

2 Reducer - bell shell - tantalum

3 Bimetallic tube - inner tube tantalum outer tube 316 stainless steel

See the sketch #1 on pg. 2

Condition: Steady State

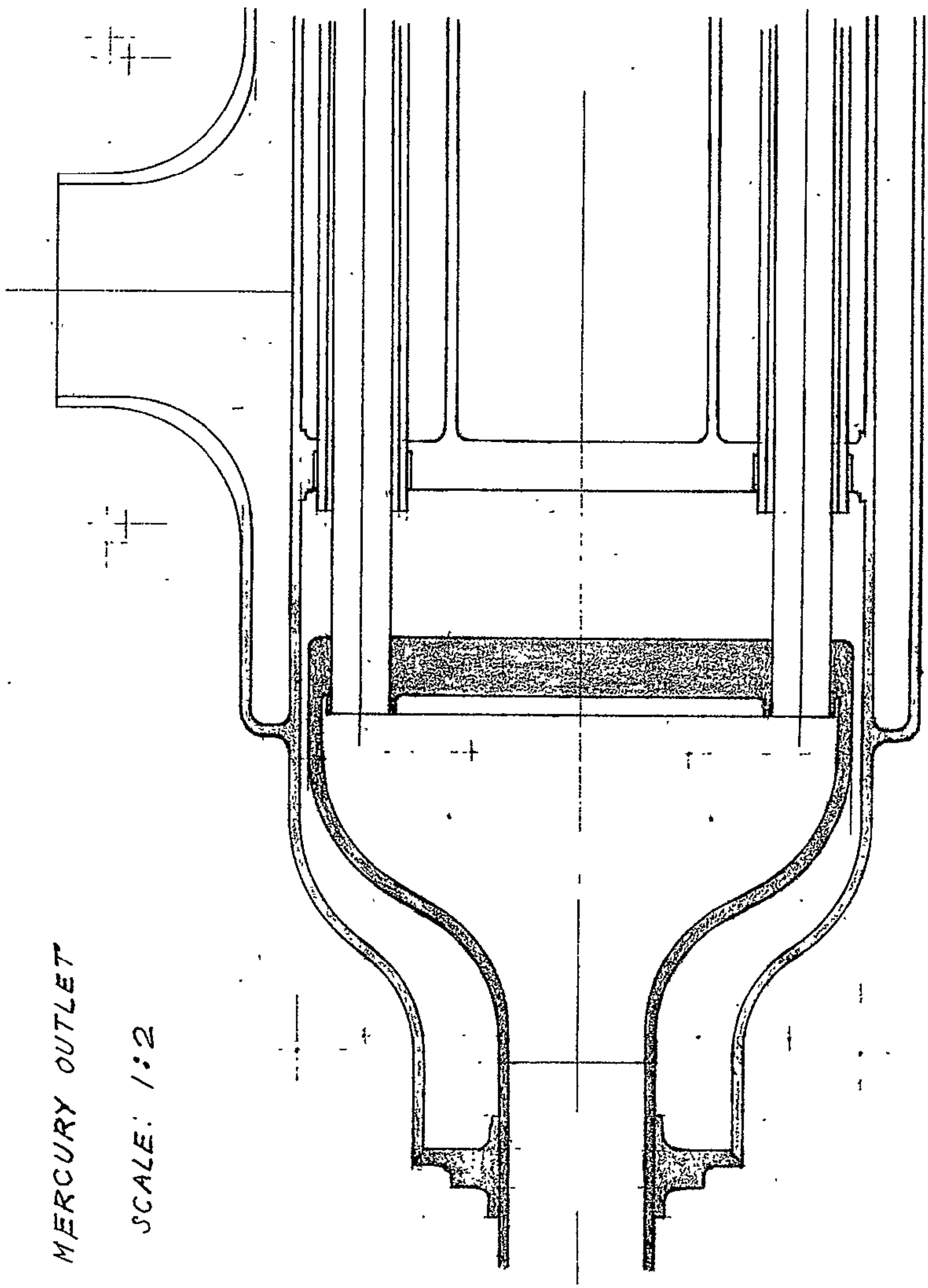
Temperature: uniform 1375 °F

Pressure:

NAK 30 PSI

Mercury 222 PSI

Dimensions of the bimetallic tube: see pg. 3



MERCURY OUTLET

SCALE: 1:2

FIG. 1

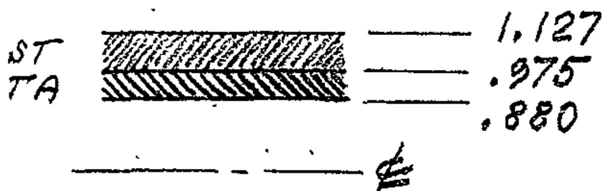


FIG. 2

Wall thickness:

$t_{ST} = .150''$ $t_{TA} = .095''$

Material properties at 1375 °F

	TA	316 SS
E	25.8×10^6	20.4×10^6
α	4.04×10^{-6}	10.9×10^{-6}
F_{tu}	13500	35000
F_{ty}	5000	15200

Method of attack

Finite element computer program for calculating stresses and strains.

Computer solution yields stresses and strains using six approximations.
Stresses and strains are tabulated on the following pages. The whole crossection is divided into four parts:

1 Header Tantalum
2 Bell shell "
3 Neck "
4 Bimetallic tube Tantalum & 316 SS

Effective stress is the total combined stress after six iterations.
Effective strain is the total combined strain corresponding to calculated effective stress.

In the "Range" column E stands for elastic and P for plastic stress.

Pages 16 and 17 show the crossection with the numbered elements as it was set up for the computer program.
The numbers of the tabulated elements correspond to those on the crossection.
In the unnumbered elements stresses are identical or close to the adjacent and therefore ommited.

Max stressed elements are those of Tantalum and are located in the bimetallic tube.

QUADRILLE WORK SHEET

AEROJET GENERAL
AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

DATE ______

SUBJECT ______ BY ______ WORK ORDER ______

MATER: TANTALUM F_{ty} = 5000 PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T° F	LOCATION
2	1098	4.2×10^{-5}	E	1375	
3	1206	4.7×10^{-5}			
4	1434	5.6×10^{-5}			
5	1751	6.8×10^{-5}			
6	2086	8.1×10^{-5}			
7	2389	9.3×10^{-5}			
8	2664	1.0×10^{-4}			
9	3081	1.2×10^{-4}			
19	754	2.9×10^{-5}			
20	1338	5.2×10^{-5}			
21	1795	7.0×10^{-5}			
22	1087	4.2×10^{-5}			
23	1343	5.2×10^{-5}			HEADER
25	1267	4.9×10^{-5}			
26	1570	6.1×10^{-5}			
27	1863	7.2×10^{-5}			
28	2134	8.3×10^{-5}			
29	2464	9.6×10^{-5}			
30	1622	6.3×10^{-5}			
31	2005	7.8×10^{-5}			
32	2229	8.6×10^{-5}			
33	3201	1.2×10^{-4}	E	1375	

01-071-002

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

PAGE 7 OF ____ PAGES

DATE ____

SUBJECT ____ BY ____ WORK ORDER ____

MATER.: TANTALUM $F_{ty} = 5000$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
34	1666	6.5×10^{-5}	E	1375	BELL SHELL
35	2037	7.9×10^{-5}	E		
36	5027	2.3×10^{-4}	P		
37	5032	3.5×10^{-4}	P		
38	1613	6.3×10^{-5}	E		
40	4293	1.7×10^{-4}			
41	2274	8.8×10^{-5}			
42	2649	1.0×10^{-4}			
45	2302	8.9×10^{-5}			
46	1886	7.3×10^{-5}			
49	1963	7.6×10^{-5}			
50	2209	8.6×10^{-5}			
53	1695	6.6×10^{-5}			
54	2649	1.0×10^{-4}			
57	1739	6.7×10^{-5}			
58	2856	1.1×10^{-4}			
61	3318	1.3×10^{-4}			
62	2949	1.1×10^{-4}			
63	4164	1.6×10^{-4}			
64	3165	1.2×10^{-4}			
65	4716	1.8×10^{-4}			
66	3871	1.5×10^{-4}	E	1375	

STK. NO. D-1-103

01-071-002

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

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SUBJECT ____ BY ____ WORK ORDER ____

MATER.: TANTALUM $F_{ty} = 5000$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
67	4919	1.9×10^{-4}	E	1375	BELL SHELL
68	4640	1.8×10^{-4}	E		
69	4820	1.9×10^{-4}	E		
70	5000	2.0×10^{-4}	P		
71	4428	1.7×10^{-4}	E		
72	4948	1.9×10^{-4}			
73	3804	1.5×10^{-4}			
74	4394	1.7×10^{-4}			
75	3040	1.2×10^{-4}			
76	3595	1.4×10^{-4}			
79	1600	6.2×10^{-5}			
80	2014	7.8×10^{-5}			
83	603	2.3×10^{-5}			
84	1012	3.9×10^{-5}	E		
89	5872	3.7×10^{-4}	P		NECK
90	6030	4.9×10^{-4}			
91	5778	1.1×10^{-3}			
92	5872	1.5×10^{-3}			
93	5802	2.6×10^{-3}			
94	5804	3.6×10^{-3}			
95	6104	5.4×10^{-3}			
96	6216	7.6×10^{-3}	P	1375	

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MATER.: TANTALUM $F_{ty} = 5000$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T° F	LOCATION
98	6973	1.3×10^{-2}	P	1375	BIMETALLIC TUBE
99	6603	1.1×10^{-2}			
102	7163	1.6×10^{-2}			
103	7056	1.5×10^{-2}			
106	7167	1.7×10^{-2}			
107	7359	1.8×10^{-2}			
112	7248	1.8×10^{-2}			
113	7415	1.9×10^{-2}			
121	7255	1.8×10^{-2}			
122	7445	1.9×10^{-2}			
128	7270	1.8×10^{-2}			
129	7454	2.0×10^{-2}			
134	7272	1.8×10^{-2}			
135	7462	2.0×10^{-2}			
138	7275	1.8×10^{-2}			
139	7467	2.0×10^{-2}			
142	7279	1.8×10^{-2}			
143	7472	2.0×10^{-2}			
146	7279	1.8×10^{-2}			
147	7474	2.0×10^{-2}			
150	7278	1.8×10^{-2}			
151	7474	2.0×10^{-2}	P	1375	

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AEROJET-GENERAL CORPORATION
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MATER.: TANTALUM $F_{TY} = 5000$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T° F	LOCATION
154	7276	1.8×10^{-2}	P	1375	BIMETALLIC TUBE
155	7472	2.0×10^{-2}			
158	7274	1.8×10^{-2}			
159	7470	2.0×10^{-2}			
162	7276	1.8×10^{-2}			
163	7468	2.0×10^{-2}			
166	7266	1.8×10^{-2}			
167	7472	2.0×10^{-2}			
170	7279	1.8×10^{-2}			
171	7435	1.9×10^{-2}			
174	7204	1.8×10^{-2}			
175	7312	1.8×10^{-2}			
178	7113	1.7×10^{-2}			
179	7336	1.9×10^{-2}	P	1375	

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QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

DATE ______

SUBJECT ______ BY ______ WORK ORDER ______

MATER.: 316 SS $F_{ty} = 15200$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
97	13366	1.8×10^{-3}	E	1375	BIMETALLIC TUBE
100	12996	8.1×10^{-4}	|	|	
101	12113	9.5×10^{-4}			
104	6069	3.0×10^{-4}			
105	10907	5.3×10^{-4}			
108	3103	1.5×10^{-4}			
109	3394	1.7×10^{-4}			
110	4323	2.1×10^{-4}			
111	9276	4.5×10^{-4}			
114	665	3.3×10^{-5}			
115	745	3.7×10^{-5}			
116	906	4.4×10^{-5}			
117	1177	5.8×10^{-5}			
118	1192	5.8×10^{-5}			
119	2792	1.4×10^{-4}			
120	5646	2.8×10^{-4}			
123	327	1.6×10^{-5}			
124	692	3.4×10^{-5}			
125	710	3.5×10^{-5}			
126	2313	1.1×10^{-4}			
127	4430	2.2×10^{-4}	|	|	
130	1596	7.8×10^{-5}	E	1375	

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QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

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SUBJECT ______ BY ______ WORK ORDER ______

MATER.: 316 SS F_{ty} = 15200 PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
131	1706	8.4×10^{-5}	E	1375	BIMETALLIC TUBE
132	2841	1.4×10^{-4}			
133	4583	2.2×10^{-4}			
136	3261	1.6×10^{-4}			
137	4437	2.2×10^{-4}			
140	3339	1.6×10^{-4}			
141	3761	1.8×10^{-4}			
148	3861	1.9×10^{-4}			
149	3759	1.8×10^{-4}			
152	3914	1.9×10^{-4}			
153	3925	1.9×10^{-4}			
156	3892	1.9×10^{-4}			
157	4050	2.0×10^{-4}			
160	3824	1.9×10^{-4}			
161	4149	2.0×10^{-4}			
168	3674	1.8×10^{-4}			
169	4293	2.1×10^{-4}			
172	3528	1.7×10^{-4}			
173	4242	2.1×10^{-4}			
176	4339	2.1×10^{-4}			
177	4207	2.1×10^{-4}	E	1375	

STK. NO. D-1-103

Fatigue life

Max loaded elements will be checked for fatigue life.

Method of attack: S.S. Manson's universal slope equation for multiaxial strain.

Max loaded elements are located in the bimetallic tube.

Tantalum element # 151
in the plastic range

316 SS element # 97
in the elastic range

Fatigue life of the element # 151

Material: Tantalum

Temperature: 1375° F

Material properties at 1375° F

$E = 25.8 \times 10^6$ $\quad F_{tu} = 13500$ PSI

$RA = .77$ reduction in area

effective strain: $\varepsilon_{EFF} = .01977$ "/"

Ductility:

$$D = \ln \frac{100}{100 - RA} = 1.47$$

$$D^{.6} = 1.26$$

$$\sigma_u = F_{tu} = 13500 \text{ PSI}$$

N_F – number of cycles

$$\Delta \varepsilon_T = \varepsilon_{EFF} = .0198$$

Modified universal slope equation:

$$\Delta \varepsilon_T = 3.03 \frac{\sigma_u}{E} N_F^{-.12} + D^{.6} N_F^{-.6}$$

$$\Delta \varepsilon_T = 3.03 \frac{13500}{25.8} 10^{-6} N_F^{-.12} + 1.26 N_F^{-.6} \quad \text{or}$$

$$.0198 = .001585 N_F^{-.12} + 1.26 N_F^{-.6}$$

Solution of the above equation is shown on pg. 15

$$N_F = 1050$$

In order to account for creep using "10% rule" we reduce the number of cycles to 105

Estimated number of cycles for max loaded tantalum element:

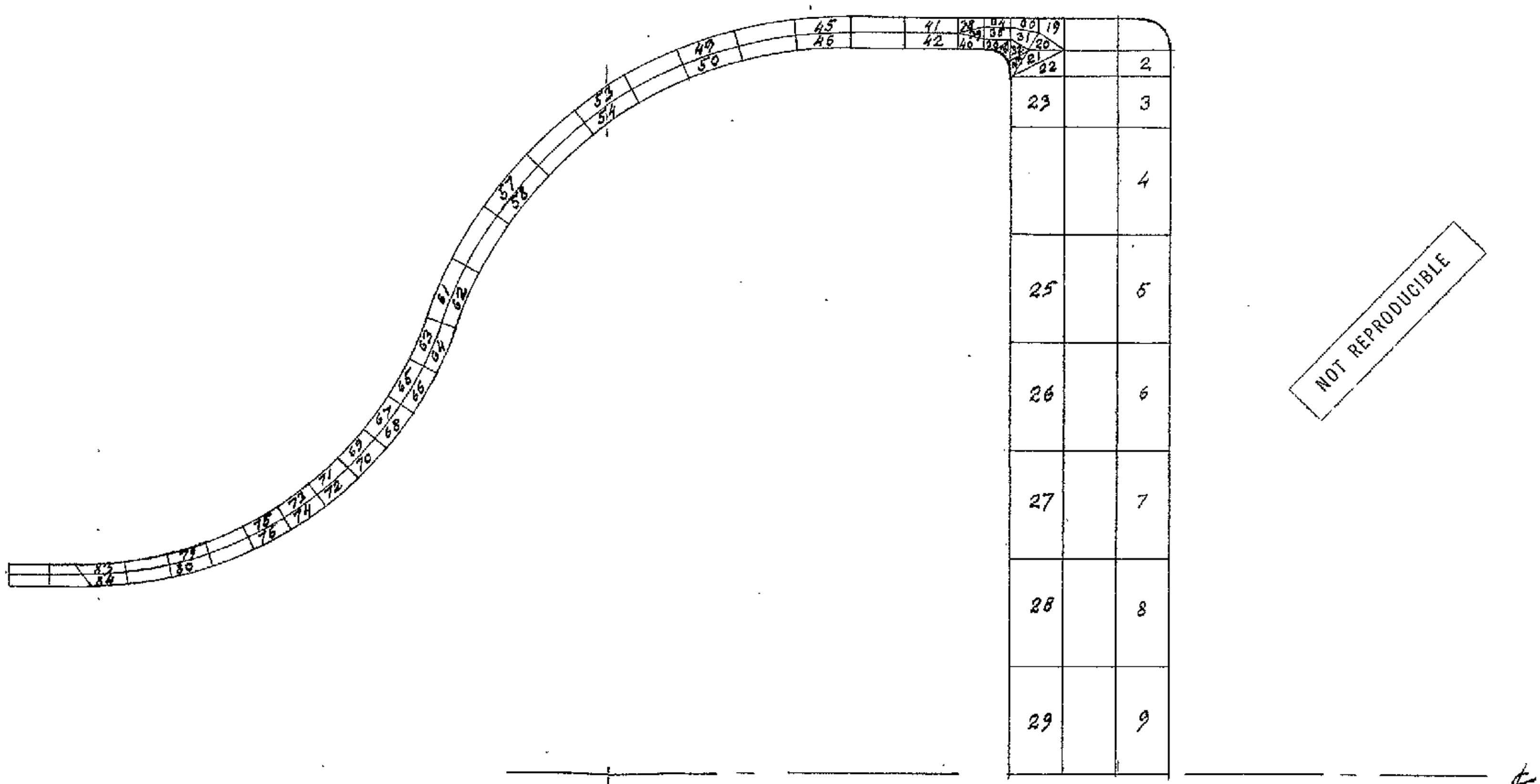
105

The cycling life of 316 SS is in the range above 100000 cycles.

```
ma, sign on: 7974, krikopulo
ACKNOWLEDGED AT 14:42 10-06-70
_
1  a=1.585e-3*x**(-.12)+1.26*x**(-.6)
2  x=x+50.
_   x=950.
X =  9.500000E+02
3  e:(2,1,4)*12
4  print x,a
_  p:3
ACKNOWLEDGED
X =  1.000000E+03   A =  2.066153E-02
X =  1.050000E+03   A =  2.008137E-02
X =  1.100000E+03   A =  1.954371E-02
X =  1.149999E+03   A =  1.904371E-02
X =  1.199999E+03   A =  1.857726E-02
X =  1.250000E+03   A =  1.814084E-02
X =  1.300000E+03   A =  1.773143E-02
X =  1.350000E+03   A =  1.734641E-02
X =  1.399999E+03   A =  1.698350E-02
X =  1.449999E+03   A =  1.664071E-02
X =  1.500000E+03   A =  1.631628E-02
X =  1.550000E+03   A =  1.600866E-02
EXECUTION COMPLETED
_
 drop: x=950.
X=950. NOT FOUND
_
sign off:
SIGNED OFF AT 14:47 10-06-70
_
```

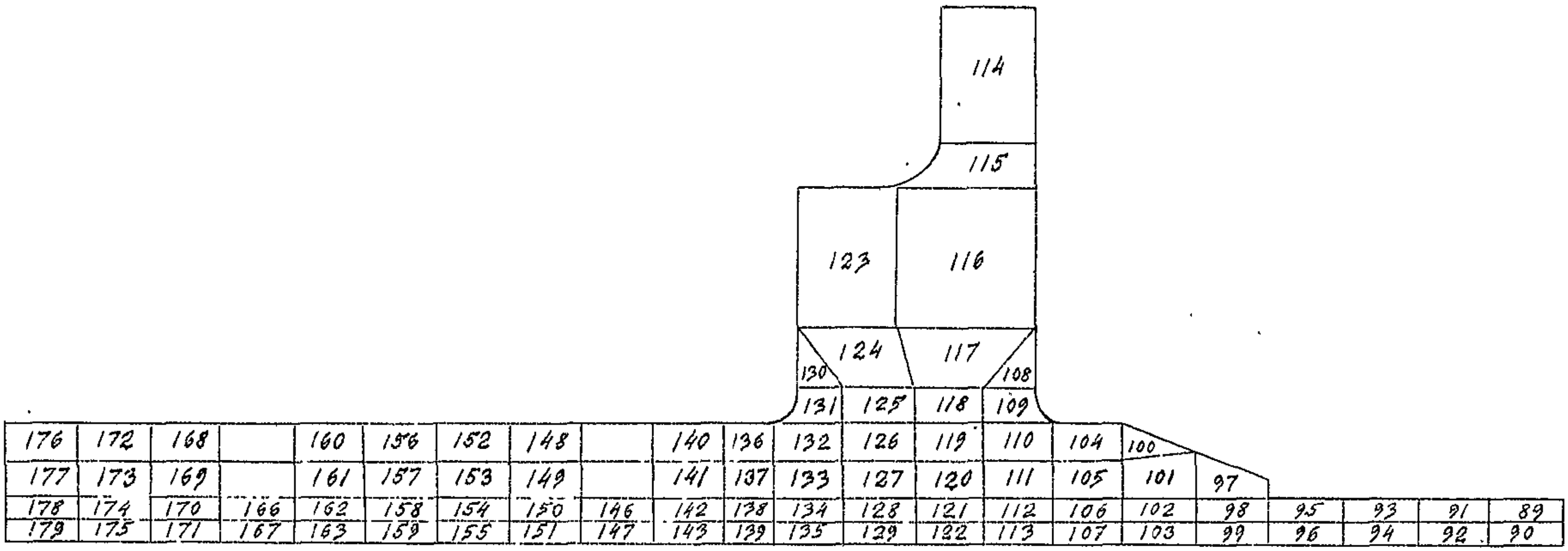
FOLDOUT FRAME 1

FOLDOUT FRAME 2



NOT REPRODUCIBLE

HG OUTLET SCALE 2:1 BRDC BOILER #5



HG OUTLET SCALE: 4:1

BRDC BOILER # 5

DATE 7-28-70

SUBJECT BRDC BOILER # 5 BY SK WORK ORDER

Mercury outlet

Comparison of stresses and strains in boiler #5 to those in boiler # 4

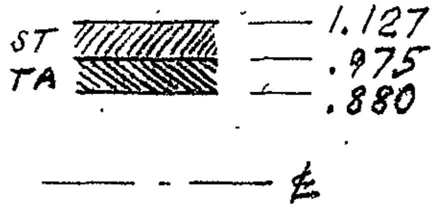
Part: bimetallic tube inner part - material Tantalum

Condition: Steady State

Temperature:	Boiler #5	Boiler # 4
uniform	1375° F	1300° F
Ppressure NAK:	30 PSI	30 PSI
" Mercury:	222 PSI	259 PSI

Geometry:

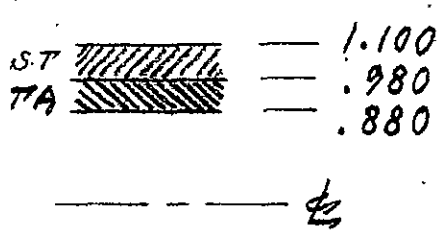
Boiler # 5



$T_{ST} = .150''$

$T_{TA} = .095''$

Boiler # 4



$T_{ST} = .120''$

$T_{TA} = .100''$

01-071-008

QUADRILLE WORK SHEET

AEROJET GENERAL

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AZUSA, CALIFORNIA

DATE ____

SUBJECT MERC. OUTLET BY ____ WORK ORDER ____

BIMETAL, TUBE TANTALUM

NOT REPRODUCIBLE

ELEM. #	BOILER # 5 STRESS	BOILER # 5 STRAIN	BOILER # 4 STRESS	BOILER # 4 STRAIN
91	[illegible]	.0011	[illegible]	[illegible]
92	[illegible]	.0015	[illegible]	[illegible]
93	5802	.0026	5935	[illegible]
94	5804	.0036	[illegible]	[illegible]
95	6104	.0055	[illegible]	[illegible]
96	6216	.0076	6219	[illegible]
98	6973	.0130	6875	.0126
99	6603	.0110	6670	[illegible]
102	7163	.0161	[illegible]	[illegible]
103	7056	.0152	7109	.0160
106	7167	.0168	7135	.0175
107	7359	.0180	7341	.0184
112	7248	.0178	7158	.0172
113	7415	.0189	7343	.0185
121	7255	.0180	7157	.0172
122	7445	.0194	7344	.0187
128	7270	.0181	7156	.0172
129	7454	.0196	7346	.0187
134	7272	.0182	7154	.0172
135	7462	.0197	7347	.0187

91-071-005

QUADRILLE WORK SHEET

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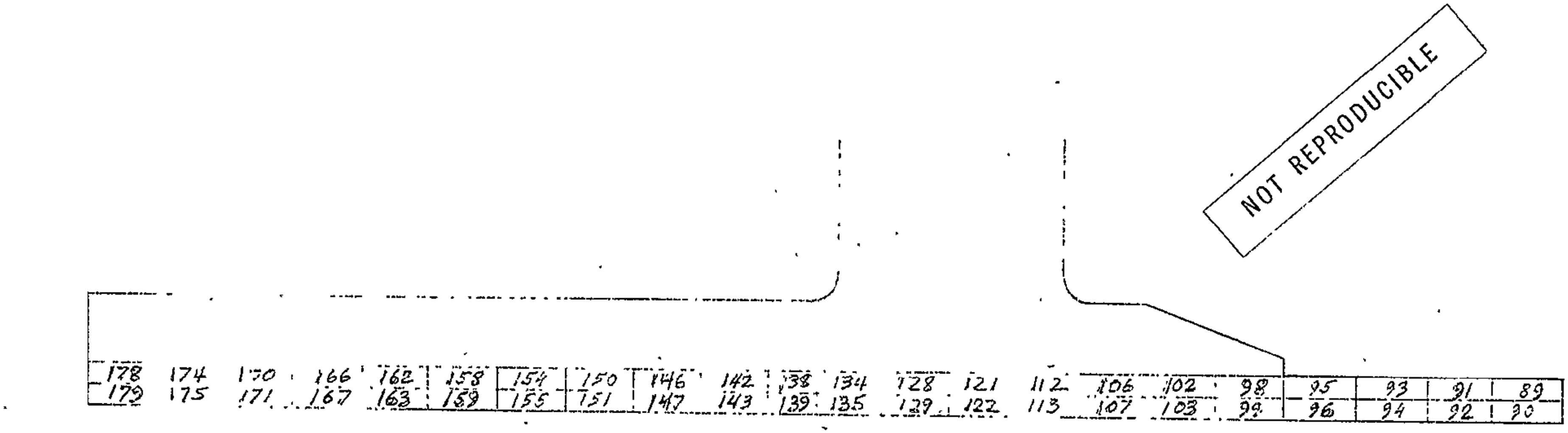
DATE ______

SUBJECT MERC. OUTLET BY ______ WORK ORDER ______

BIMET. TUBE TANTALUM

ELEM. #	BOILER # 5		BOILER # 4	
	STRESS	STRAIN	STRESS	STRAIN
138	7275	.0182	7155	.0172
139	7467	.0197	7349	.0187
142	7279	.0182	7155	.0172
143	7472	.0197	7350	.0187
146	7279	.0182	7153	.0172
147	7474	.0198	7349	.0187
150	7278	.0182	7150	.0172
151	7474	.0198	7346	.0187
154	7276	.0182	7149	.0172
155	7472	.0198	7339	.0187



HG OUTLET SCALE: 4:1

BRDC BOILER # 5

Dept. 4927

ANALYSIS NO. SA-248

DATE 4 September 1970

SUMMARY OF ANALYSIS

Project SNAP-8	Component Boiler No. 5	Distribution:
Part Oval Tube	Drawing No.	E. S. Chalpin
Subject Structural Analysis		G. L. Lombard
Reference(s) Memo E. Chalpin to W. Weleff/H. Derow, dated 6 July 1970, Subject: Operating Criteria for Stress Analysis		U.A.Pineda/H. Derow
Engineer S. Krikopulo	Approved W. Weleff	File: SS 1020-03

OBJECTIVE: Determine the stress levels and safety margin due to the given loading.

ASSUMPTIONS:

Maximum internal pressure of 30 PSI at 1211°F is the only load.

REFERENCES (Analysis Methods):

(1) AGC-10650 - Structural Design Criteria, SNAP-8
(2) Materials Manual H-100
(3) Hand calculations

RESULTS AND CONCLUSIONS:

Maximum calculated stress 6600 PSI (compression) MS is large (>1.5)

RECOMMENDATIONS AND COMMENTS:

Oval tubes are structurally sound for this application under the above stated load.

QUADRILLE WORK SHEET AEROJET-GENERAL CORPORATION AZUSA, CALIFORNIA

SUBJECT BRDC BOILER #5 BY SK

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DATE 10-20-70
WORK ORDER

OVAL TUBE

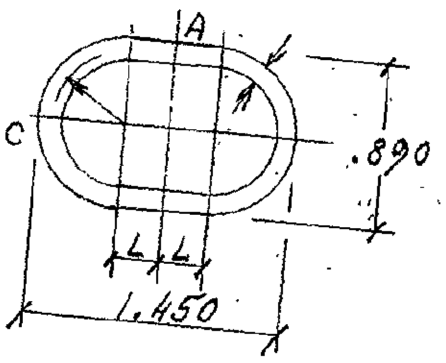

FIG. 1

Geometry as shown on Fig. 1

L = .280" R = .420"

T = .049"

Material: 316 SS

Based on the operating criteria chart critical condition is high schedule

NAK inlet: 60 PSI at 1211° F

Static NAK: 30 PSI at 1211° F

Inside pressure 30 PSI

outside " 60 "

Loading: external pressure of 30 PSI

Temperature: 1211° F

Materials properties at 1211°F:

$E = 21.8 \times 10^6$ $\quad F_{ty} = 16000$ PSI $\quad F_{tu} = 53000$ PSI

Bending moment at pt. A

$$M_A = WRL\left[\frac{L}{2R} + \frac{1 - \frac{1}{3}\left(\frac{L}{R}\right)^2}{\frac{\pi}{2} + \frac{L}{R}}\right] =$$

$$= 3.53\left(.334 + \frac{1 - .148}{1.57 + .667}\right) = 2.52 \text{ lb in/in}$$

$$\sigma_b = \frac{6M}{t^2} = 6300 \text{ PSI bend.}$$

$$\sigma_a = \frac{30 \times .445}{.049} = 273 \text{ PSI Compr.}$$

Total stress on the outer side:

$\sigma = 6600$ PSI Compr.

Total stress on the inner side:

$\sigma = 6000$ PSI Tens.

Bending moment at PT. C

$$M_c = WRL\left[1 - \frac{1 - \frac{1}{3}\left(\frac{L}{R}\right)^2}{\frac{\pi}{2} + \frac{L}{R}}\right] = 2.19 \text{ lb in/in}$$

$$\sigma_b = \frac{6 \times 2.19}{.0024} = 5480 \text{ PSI bend.}$$

$$\sigma_z = \frac{30 \times .725}{.049} = 445 \text{ PSI Compr.}$$

Total stress on the outer side:

$\sigma = 5930$ Compr.

Total stress on the inner side:

$\sigma = 5040$ PSI Tens.

$$MS = \frac{16}{6} - 1 = \text{Large}$$

Deflection at PT. A

From the chart of "The analysis of a thin Obround Ring" by J. C. Heap

$$\frac{\Delta_A EA}{W R^2} = 1.5$$

for $\frac{L}{R} = .667$

$A = .049 \ in^2 \qquad R^2 = .176$

Deflection Δ_A:

$$\Delta_A = \frac{1.5 \times 30 \times .176}{21.8 \times .049} 10^{-6} = 7.5 \times 10^{-6} \ ''$$

Dept. 7974

ANALYSIS NO. SA- B-249.

DATE 4 September 1970

SUMMARY OF ANALYSIS

Project SNAP-8	Component Boiler #5	Distribution:
Part Center Vacuum Tube	Drawing No. 1268605	E. S. Chalpin
Subject Structural Analysis		G. L. Lombard
Reference(s) Memo, E.S.Chalpin to W.Weleff/H.Derow, dtd 6 July 1970 Subj: Operating Criteria for Stress Analysis		U. A. Pineda/H. Derow
Engineer S. Krikopulo	Approved W. Weleff	File: SS 1020-03

OBJECTIVE:

Evaluate the structural integrity of the inner vacuum tube - Boiler #5

ASSUMPTIONS:

Critical loading conditions external pressure of 90 psi at 1485°F

REFERENCES (Analysis Methods):

AGC-10650 Structural Design Criteria SNAP-8
Materials Manual H-100

RESULTS AND CONCLUSIONS:

Critical buckling pressure 1980 psi > 90 psi

RECOMMENDATIONS AND COMMENTS:

The inner vacuum tube is capable of resisting the external pressure
Safety margin against buckling is high (> 2.0)

QUADRILLE WORK SHEET

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

DATE 9-3-70

SUBJECT BRDC BOILER #5 BY SK WORK ORDER

Summary of results of stress calculations.

Central vacuum tube

max external press. under which the tube don't collapse: $p = 1980$ PSI at $T = 1485°F$

Outer shell

Max stress under internal pressure

$\overline{\sigma_2} = 2650$ PSI hoop tension at $T = 1485°F$ $F_{ty} = 15000$ PSI

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Vacuum insulators

Shell

min pressure under which the shell will collapse; $p = 1060$ PSI at $T = 1485^{\circ}F$

Plate

Will collapse under pressure of 24 PSI at $T = 1485^{\circ}F$

STK. NO. D-1-103

Vacuum Tube

Max cond. $T = 1485°F$ $p = 90 PSI$

will be checked for stability

$L = 25.0''$ $r = 1.72''$ $t = .125''$

Material: 316 SS $E = 20.0 \times 10^6$

$$Z_L = \frac{L^2}{rt}(1-\nu^2)^{1/2} = 2780$$

$K_y = 60$ NACA TN 3783

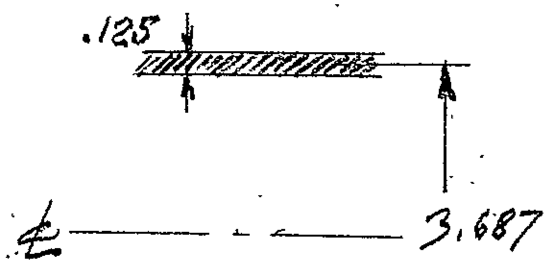
$$\sigma_{cr} = \frac{K_y \pi^2 E}{10.92}\left(\frac{t}{L}\right)^2 = 27200 \text{ PSI}$$

critical pressure:

$$p = \frac{27200 \times .125}{1.72} = 1980 \text{ PSI}$$

MS = Large

Outer shell



cond.: MAX

$T = 1485°F$

$p = 90$ PSI

FIG. 1

$R = 3.687''$ $t = .125''$

Material: 316 SS

$F_{ty} = 15000$ PSI $F_{tu} = 31000$ PSI

Hoop stress:

$$\sigma_2 = \frac{pR}{t} = \frac{90 \times 3.687}{.125} = 2650 \text{ PSI}$$

MS = Large

Dept. 7974

ANALYSIS NO. -B- SA- 250

DATE 4 September 1970

SUMMARY OF ANALYSIS

Project SNAP-8	Component Boiler #5	Distribution:
Part Vacuum Insulator	Drawing No.	E. S. Chalpin
Subject Structural Analysis		G. L. Lombard
Reference(s) Memo, E. S. Chalpin to W. Weleff/H. Derow, dtd 6 July 1970, Subj: Operating Criteria for Stress Analysis		U. A. Pineda/H. Derow
Engineer S. Krikopulo	Approved W. Weleff	File: SS 1020-03

OBJECTIVE:

Evaluate the structural integrity of the vacuum insulators

ASSUMPTIONS:

Wall thickness for the toroidal and flat plate insulator 0.050 in. A support ring at 2 in. diameter is provided at center of the flat plate insulator.

REFERENCES (Analysis Methods):

AGC-10650 - Structural Design Criteria SNAP-8

Materials Manual H-100

RESULTS AND CONCLUSIONS:

Critical pressure was found as follows: for the toroidal insulator 1060 psi
for the flat plate insulator 220 psi

RECOMMENDATIONS AND COMMENTS:

The toroidal and flat plate insulators are capable of resisting the operational external pressure of 90 psi at 1485°F

SUBJECT BRDC BOILER # 5 BY SK WORK ORDER

Vacuum Insulator

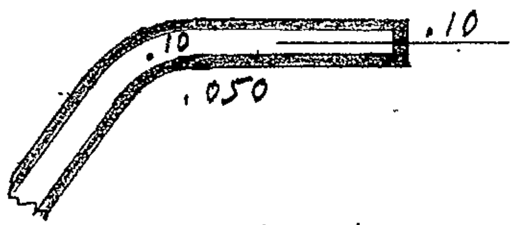


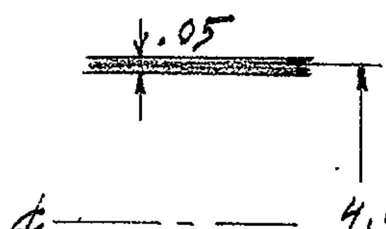
FIG. 1

Temperature: 1485 °F

Pressure: 90 PSI

Material: 316 SS

Material properties: $E = 20.0 \times 10^6$



$R = 4.0''$ $\quad t = .05''$

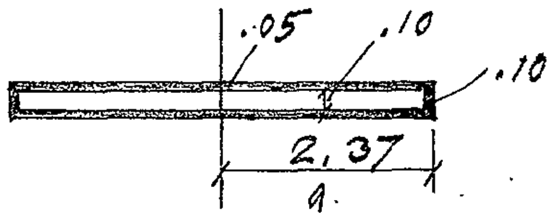
Critical pressure for cylinder:

$$\bar{V}_{cr} = \frac{K_y \pi^2 E}{12(1-\nu^2)}\left(\frac{t}{L}\right)^2 =$$

$$= \frac{7.5 \times 9.87 \times 20 \times 625}{10.92} = 85000 \text{ PSI}$$

min critical press. $p = \frac{8.5 \times 10^4 \times .05}{4.0} = 1060 \text{ PSI}$

Plate - Vacuum Insulator



Outside pressure: 90 PSI

FIG. 1

Temperature: 1485°F

$a = 2.37''$ $t = .05''$

Material: 316 SS $E = 20.0 \times 10^6$

$$D = \frac{Et^3}{12(1-\nu^2)} = .00023 \times 10^6$$

Assuming clamped edges, deflection at center:

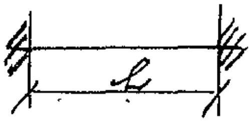
$$w = \frac{qa^4}{64D}; \quad q = 24 \text{ PSI}$$

assuming $w = .05''$

min a for $q = 90$ PSI and $\Delta = .015''$

$$a^4 = \frac{64 D \Delta}{q} = 2.45 \qquad a = 1.25''$$

There should be a support between the edge and center.



Beam FIG. 2

FIG. 2 $$y = \frac{W l^3}{384 E I}$$

$l = 1.4''$ $W = 126^{\#}$

$$I = \frac{.05^3}{12} = .00001 \text{ in}^4$$

$y = .0045''$

location of support:

$a \cong 1.0''$

Dept. 4927

ANALYSIS NO. SA-B-251

DATE 10-15-70

SUMMARY OF ANALYSIS

Project SNAP-8	Component BRDC Boiler #5	Distribution:
Part Mercury Inlet	Drawing No.	E. S. Chalpin
Subject Stress Analysis		G. L. Lombard
Reference(s)		H. Derow/L.P. Lopez
		U. A. Pineda
Engineer S. Krikopulo	Approved W. Welty	File: SS 1020-03

OBJECTIVE: Calculate the stresses as well as fatigue life due to internal pressure and thermal load.

ASSUMPTIONS:

Calculations were performed for two different loading conditions: I. (a) Uniform Temperature T = 600°F., (b) Internal Pressure = 470 psi; II. (a) Variable Temperature Distribution, (b) Internal Pressure - 470 psi.

REFERENCES (Analysis Methods):

Finite element computer program and S.S. Manson's universal slope equation.

RESULTS AND CONCLUSIONS:

Maximum stresses were found in the bimetallic tube in both conditions. These stresses are above the yield strength of the material for the corresponding temperatures. Plastic deformations are taking place. Calculated slow cycle fatigue life: 920 cycles.

RECOMMENDATIONS AND COMMENTS:

MERCURY INLET

Geometry

Mercury inlet consists of three parts:

1 Header - circular plate - tantalum

2 Reducer - ellipsoidal shell - tantalum

3 Bimetallic tube - inner tube tantalum
outer tube 316 stainless steel

See sketch #1 on pg. 2

Condition:

mercury inlet will be checked in two different conditions:

1. Cond. I

Uniform temperature $T = 600°F$ $p = 470$ PSI

2. Cond. II

Variable temperature $p = 470$ PSI

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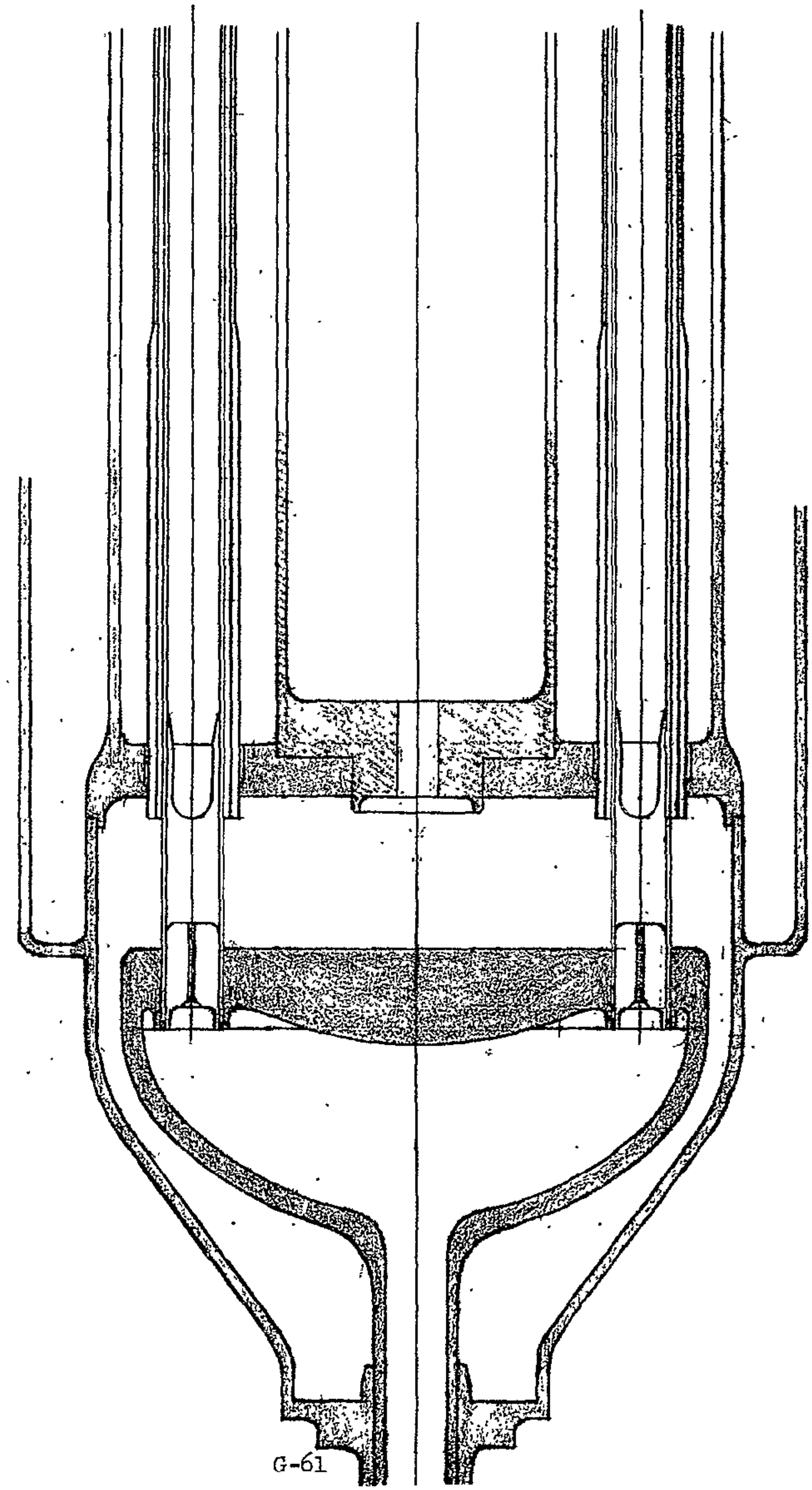

MERCURY INLET

SCALE: 1:2

FIG. 1

Dimensions of the bimetallic tube:

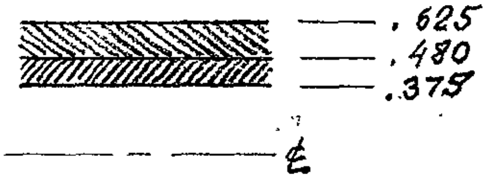

FIG. 2

Wall thickness:

$t_{ST} = .145''$ $t_{TA} = .105''$

Method of attack

Finite element computer program for calculating stresses and strains.

Computer solution yields stresses and strains after six approximations.

Material properties as used in the computer program are tabulated on the following page.

Material properties

Tantalum

T °F	E ×10^6	α ×10^-6	F_{ty}
250	27.1	3.56	13500
600	26.73	3.70	6800
900	26.35	3.84	6200
1200	25.95	3.98	5400

316 Stainless Steel

T °F	E ×10^6	α ×10^-6	F_{ty}
250	27.4	9.35	26500
400	26.7	9.65	24400
600	26.1	9.90	21800
1100	22.5	10.65	16700

Ellipsoidal shell

Equation used to calculate the shape of ellipsoidal shell:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \qquad \text{where}$$

$a = 3.575''$

$b = 1.702''$

ratio $\frac{a}{b} = 2.1$

The above ratio was selected on the basis of min membrane stress due to internal pressure.

Coordinates and basic dimensions of the ellipsoidal shell are shown on FIG. 2 and 3 pgs. 6 and 7

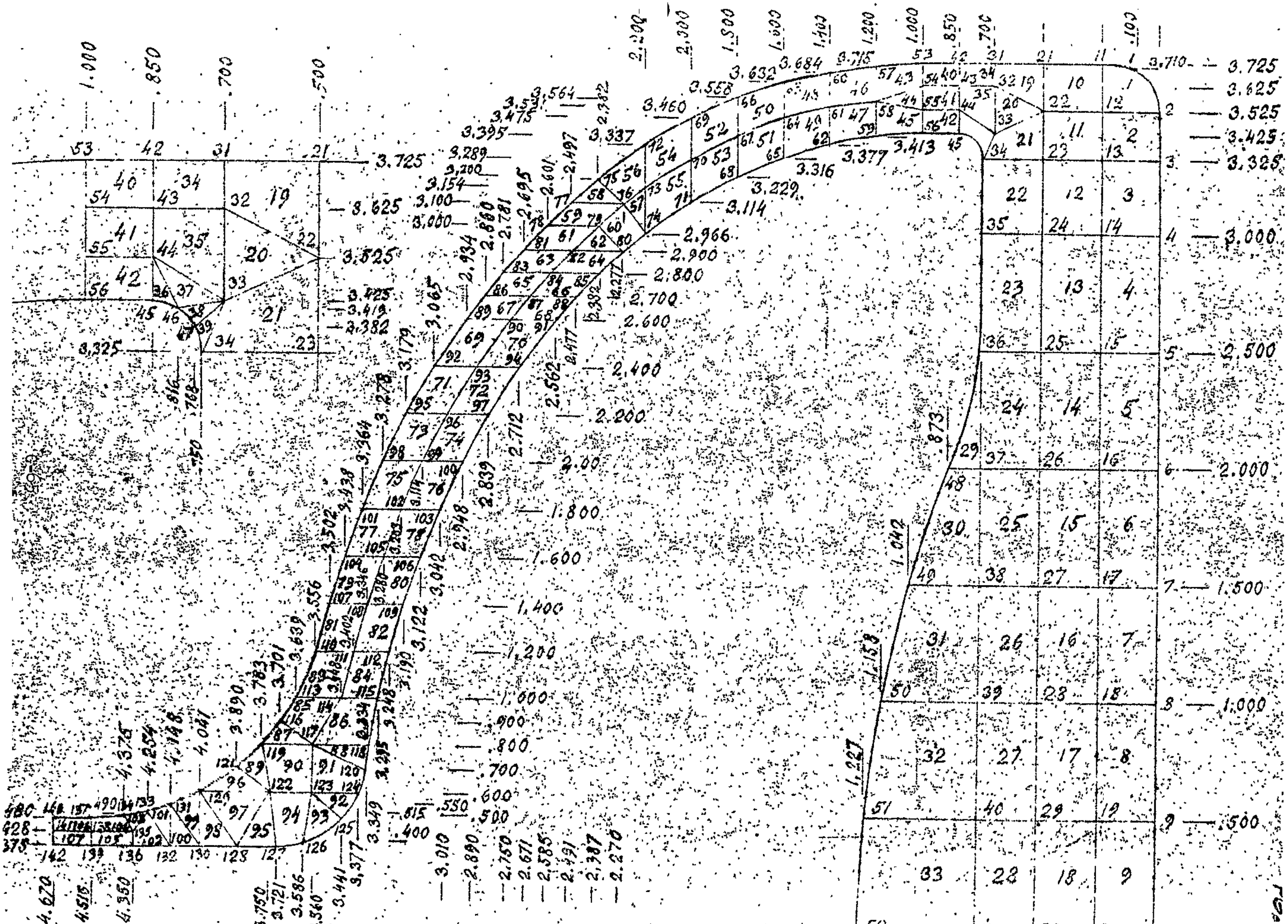

FIG. 2

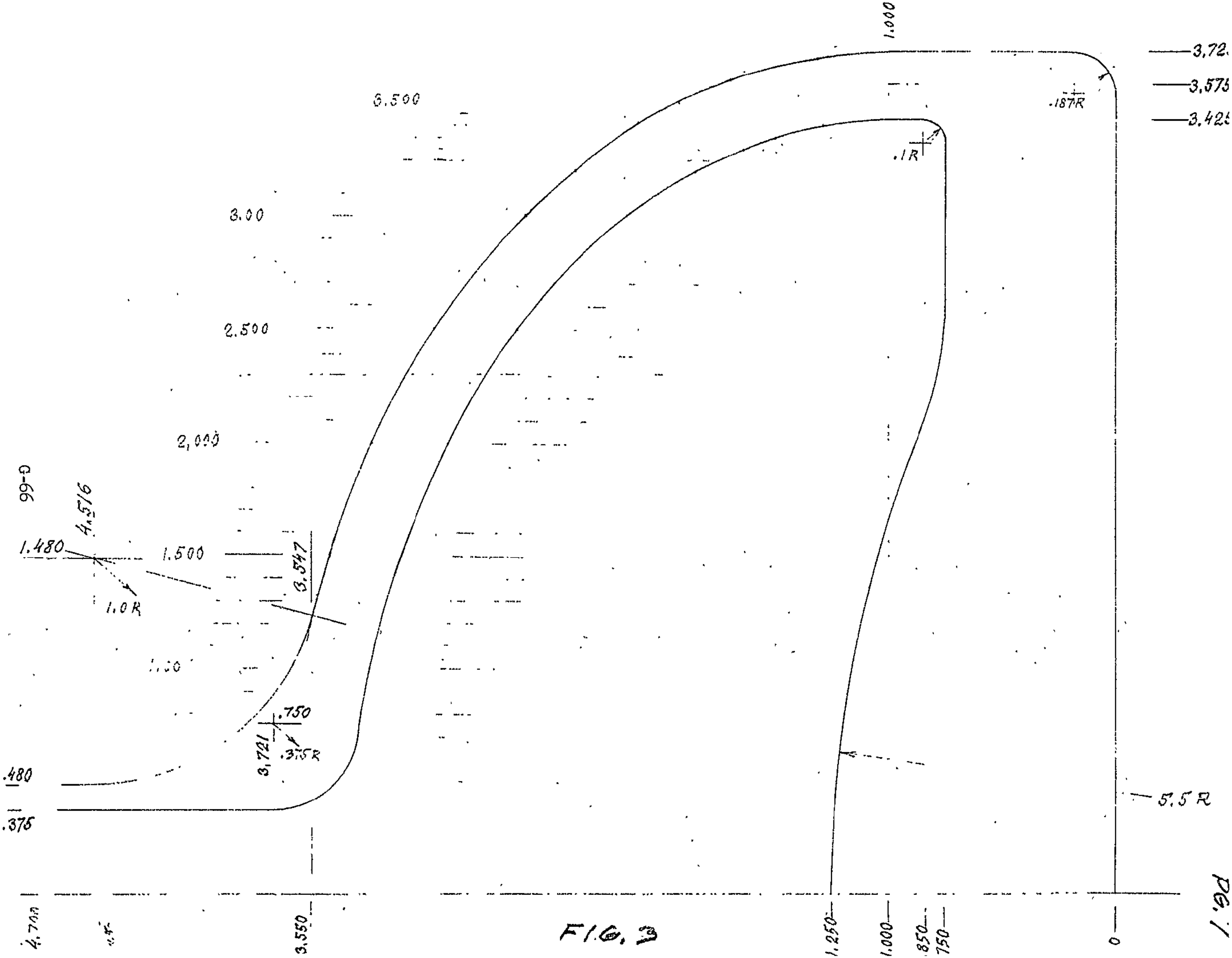
1.000
3,72
3,575
3,425
.187R
.1R
3.500
3.00
2.500
2,000
1.500
4.516
1.480
1.0R
3.547
.750
3,721
.375R
.480
.375
5.5 R
3.550
1.250
1.000
.850
750
0
G-66

FIG. 3

PG. 1

01-071-002

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Temperature distribution in cond. II

Figures 4 and 5 show temperature distribution - see pgs. 9 and 10.

Computer solution yields stresses and strains after six approximations. Stresses and strains are tabulated on the following pages.

The whole crossection is divided into four parts:

1 Header Tantalum

2 Ellips. shell "

3 Neck "

4 Bimetallic tube Tantalum and 316 SS

Effective stress is the total combined stress.

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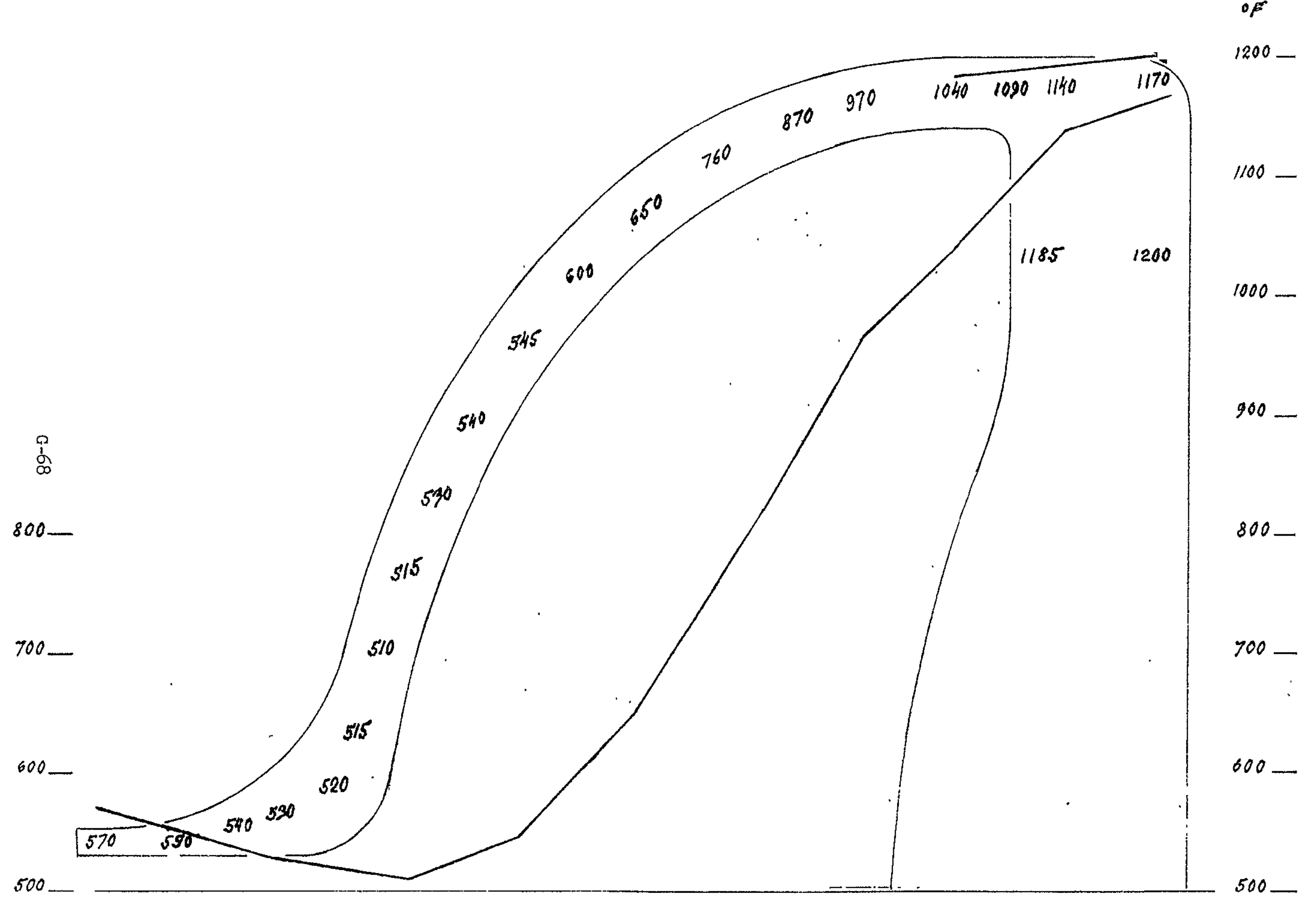


HG INLET θ_3 - 45"

FIG. 4

G-68

FG. 9

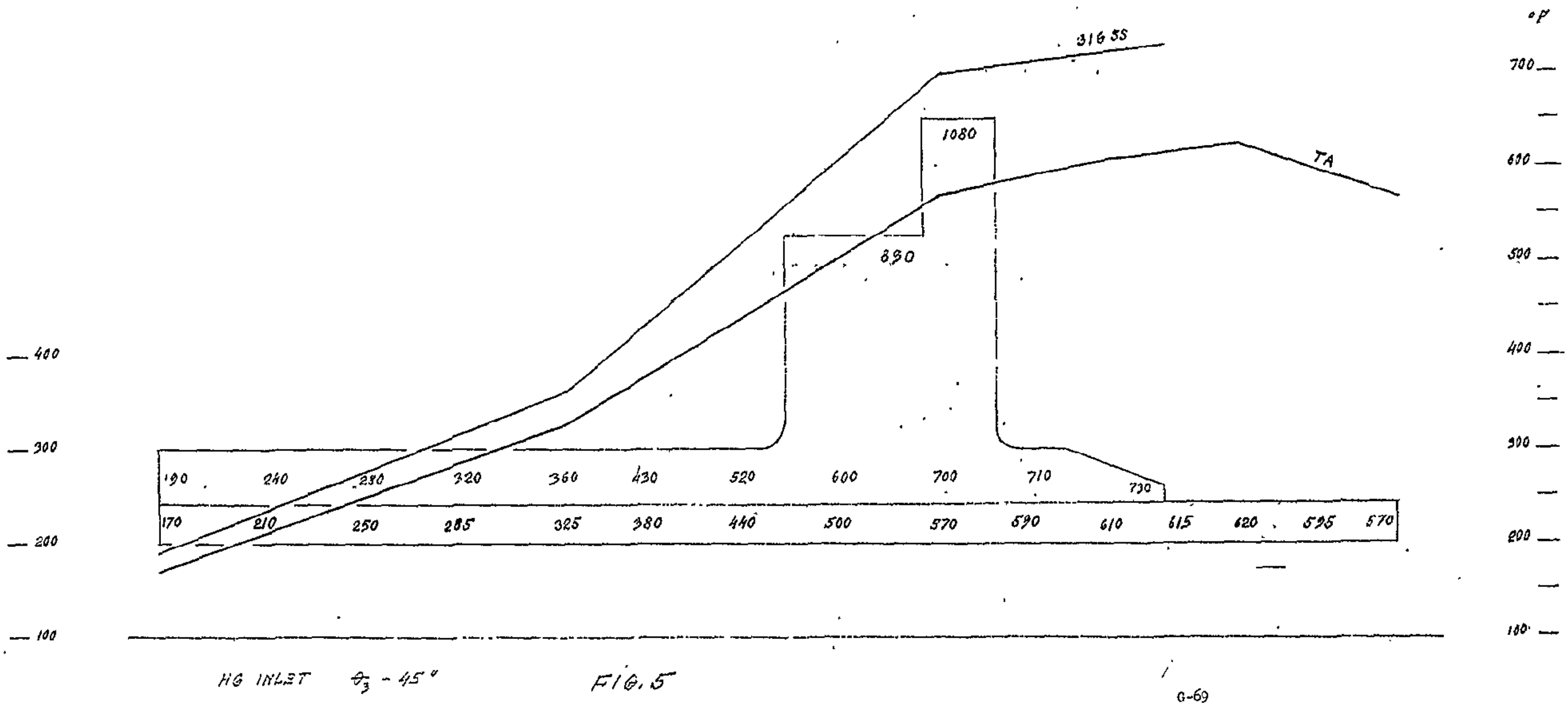

°F
700
600
500
400
300
200
100
316 SS
TA
1080
890
190
240
280
320
360
430
520
600
700
710
730
170
210
250
285
325
380
440
500
570
590
610
615
620
595
570
HG INLET θ_3 - 45°

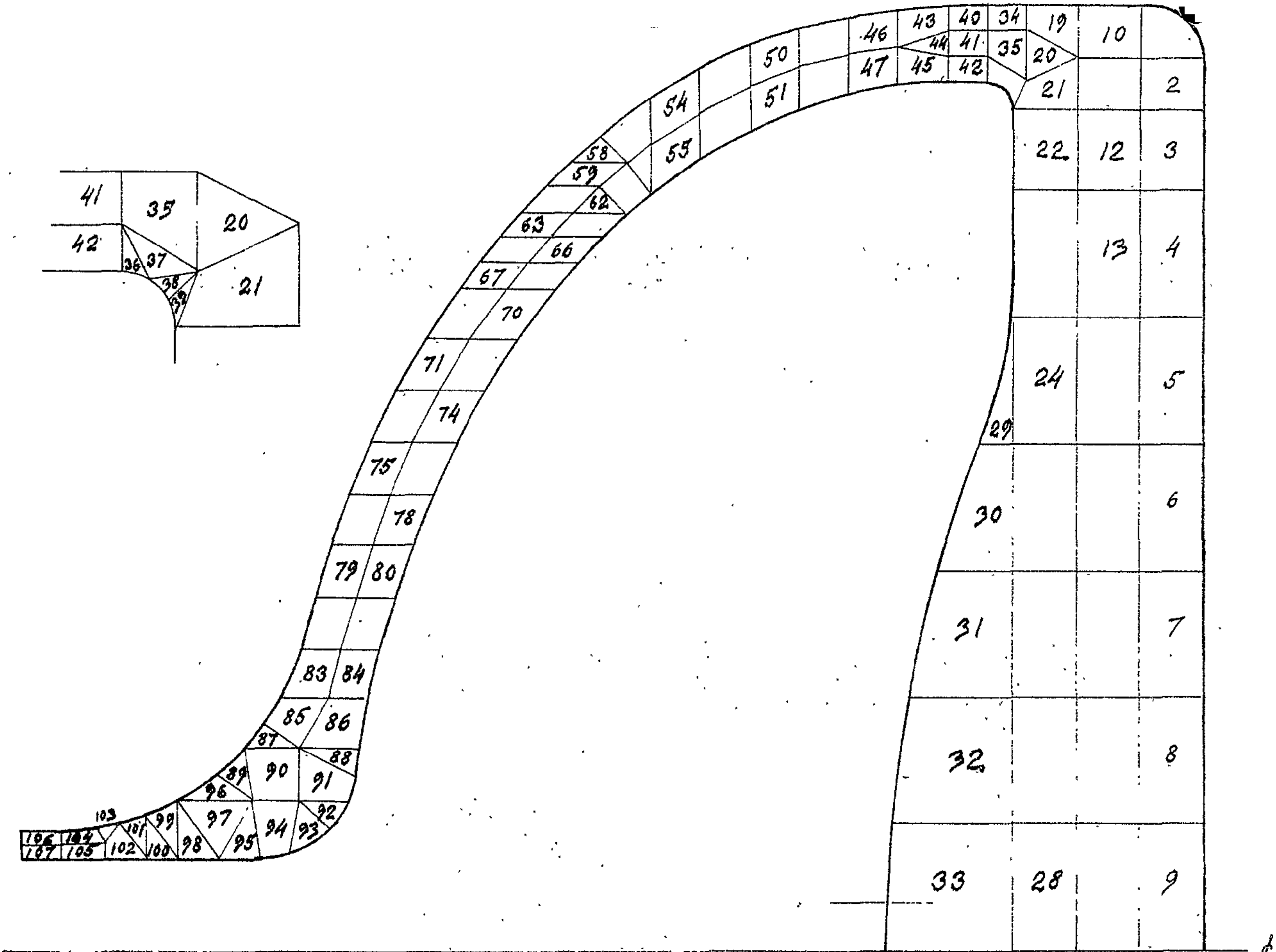
FIG. 5

Effective strain is the total combined strain corresponding to calculated effective stress.

In the "Range" column E stands for elastic and P for plastic stress.

Figures 6 and 7 on pgs. 12 and 13 show the crossection with the numbered elements as it was set up for the computer program.
The numbers of the tabulated elements correspond to those on the crossection.
The stresses in the unnumbered elements are identical or close to the adjacent and therefore ommited.

G-71



41
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100
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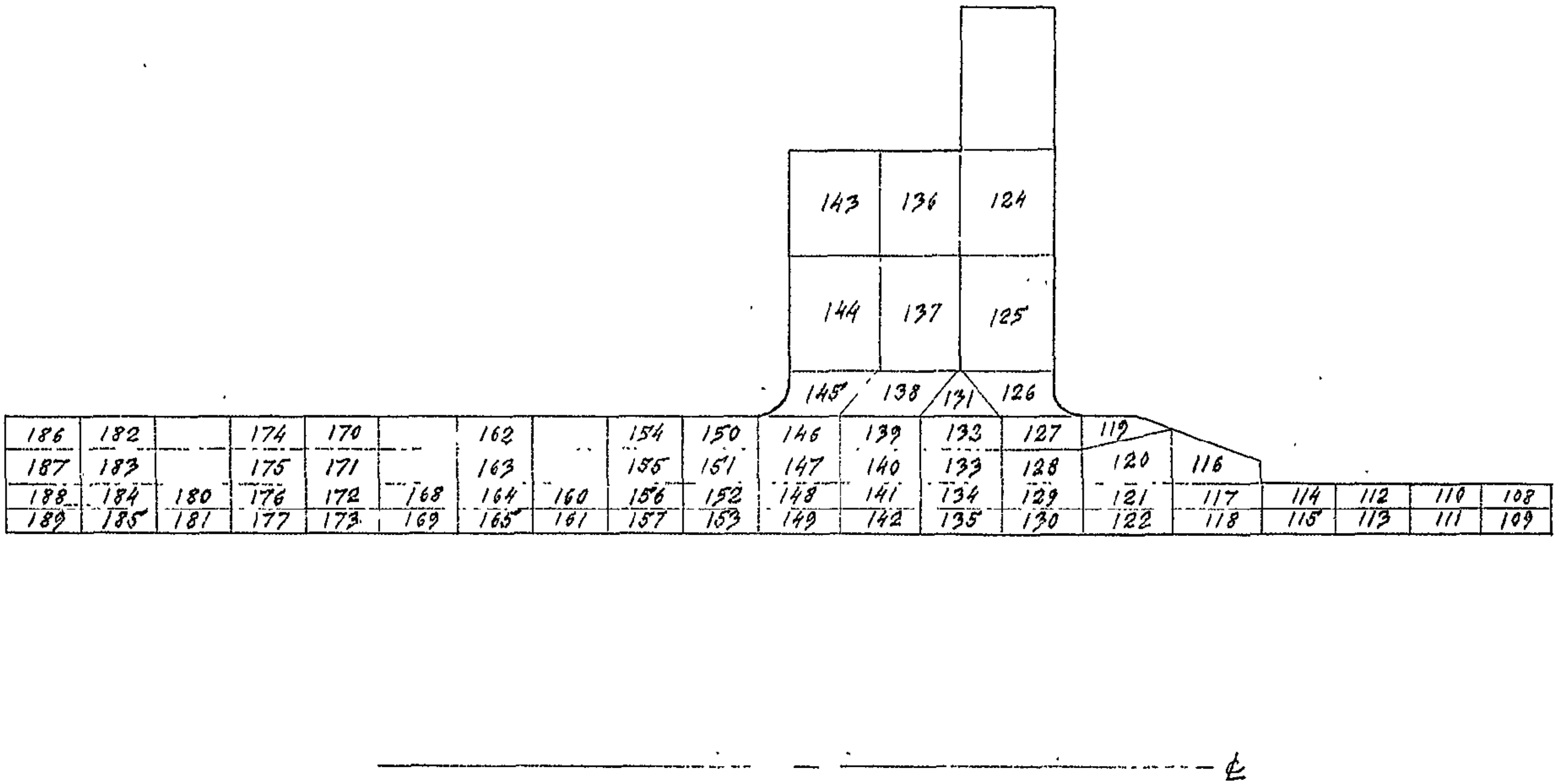
28
9

FIG. 6

PG.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142
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113
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109
℄

FIG. 7

Cond. I

Stresses and strains are tabulated on pgs. 15-22

Fatigue life calculated on pgs. 23-26

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MATER: TANTALUM F_{ty} = 6800 PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
2	2043	7.60×10^{-5}	E	600	HEADER
3	2399	9.00×10^{-5}			
4	2994	1.1×10^{-4}			
5	3570	1.3×10^{-4}			
6	3892	1.5×10^{-4}			
7	3941	1.5×10^{-4}			
8	3940	1.5×10^{-4}			
9	4031	1.5×10^{-4}			
10	566	2.1×10^{-5}			
12	2253	8.4×10^{-5}			
13	2218	8.3×10^{-5}			
19	1004	3.8×10^{-5}			
20	1715	6.4×10^{-5}			
21	3163	1.2×10^{-4}			
22	2205	8.2×10^{-5}			
24	2115	7.9×10^{-5}			
28	733	2.7×10^{-5}			
29	4455	1.7×10^{-4}			
30	3762	1.4×10^{-4}			
31	3497	1.3×10^{-4}			
32	3400	1.3×10^{-4}			
33	3320	1.2×10^{-4}	E	600	

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MATER.: TANTALUM $F_{ty} = 6800$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
34	2159	8.1×10^{-5}	E	600	ELLIPSOIDAL SHELL
35	2938	1.1×10^{-4}	E		
36	7075	5.0×10^{-4}	P		
37	4725	1.8×10^{-4}	E		
38	7028	4.8×10^{-4}	P		
39	6880	3.3×10^{-4}	P		
40	2290	8.6×10^{-5}	E		
41	3481	1.3×10^{-4}	E		
42	6864	3.0×10^{-4}	P		
43	2146	8.0×10^{-5}	E		
44	4205	1.6×10^{-4}	E		
45	5788	2.2×10^{-4}	E		
46	2382	8.9×10^{-5}			
47	4840	1.8×10^{-4}			
50	2455	9.2×10^{-5}			
51	3735	1.4×10^{-4}			
54	2503	9.4×10^{-5}			
55	3024	1.1×10^{-4}			
58	2540	9.5×10^{-5}			
59	2698	1.0×10^{-4}			
62	2792	1.0×10^{-4}			
63	2846	1.1×10^{-4}	E	600	

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MATER.: TANTALUM F_{ty} = 6800 PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
66	2859	1.1×10^{-4}	E	600	ELLIPSOIDAL SHELL
67	3021	1.1×10^{-4}			
70	2914	1.1×10^{-4}			
71	3363	1.3×10^{-4}			
74	3114	1.2×10^{-4}			
75	3745	1.4×10^{-4}			
78	3292	1.2×10^{-4}			
79	4086	1.5×10^{-4}			
80	3346	1.3×10^{-4}			
83	3934	1.5×10^{-4}			
84	3437	1.3×10^{-4}			
85	3248	1.2×10^{-4}			
86	3652	1.4×10^{-4}			
87	2893	1.1×10^{-4}			
88	3978	1.5×10^{-4}			
89	1796	6.7×10^{-5}			
90	2916	1.1×10^{-4}			
91	4166	1.6×10^{-4}			
92	4929	1.8×10^{-4}			
93	4965	1.9×10^{-4}			
94	3811	1.4×10^{-4}			
95	2985	1.1×10^{-4}	E	600	

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MATER.: TANTALUM $F_{ty} = 6800$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
96	1595	6.0×10^{-5}	E	600	ELLIPS. SHELL
97	1897	7.1×10^{-5}			
98	1616	6.0×10^{-5}			
99	1300	4.9×10^{-5}			
100	1316	4.9×10^{-5}			
101	1206	4.5×10^{-5}			
102	1360	5.1×10^{-5}			
103	889	3.3×10^{-5}			
104	952	3.6×10^{-5}			
105	1180	4.4×10^{-5}			
106	899	3.4×10^{-5}			NECK
107	1005	3.8×10^{-5}			
108	1001	3.7×10^{-5}			
109	1987	7.4×10^{-5}			
110	2848	1.1×10^{-4}			
111	3857	1.4×10^{-4}	E		
112	7504	3.5×10^{-4}	P		
113	7692	6.3×10^{-4}			
114	8272	1.4×10^{-3}			
115	9219	2.3×10^{-3}	P	600	

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MATER.: TANTALUM $F_{ty} = 6800$ PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T° F	LOCATION
117	11020	4.2×10^{-3}	P	600	BIMETALLIC TUBE
118	11286	4.5×10^{-3}			
121	12429	5.7×10^{-3}			
122	13199	6.5×10^{-3}			
129	12756	6.1×10^{-3}			
130	14118	7.4×10^{-3}			
134	12991	6.3×10^{-3}			
135	14395	7.7×10^{-3}			
141	13026	6.4×10^{-3}			
142	14479	7.8×10^{-3}			
148	12998	6.4×10^{-3}			
149	14463	7.8×10^{-3}			
152	12954	6.3×10^{-3}			
153	14414	7.7×10^{-3}			
156	12902	6.3×10^{-3}			
157	14356	7.7×10^{-3}			
160	12861	6.2×10^{-3}			
161	14306	7.6×10^{-3}			
164	12853	6.2×10^{-3}			
165	14289	7.6×10^{-3}			
168	12867	6.2×10^{-3}			
169	14300	7.6×10^{-3}	P	600	

MATER.: TANTALUM F_{ty} = 6800 PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T° F	LOCATION
172	12880	6.2×10^{-3}	P	600	BIMETALLIC TUBE
173	14299	7.6×10^{-3}	|	|	
176	12843	6.2×10^{-3}	|	|	
177	14199	7.5×10^{-3}	|	|	
180	12645	6.0×10^{-3}	|	|	
181	13827	7.1×10^{-3}	|	|	
184	12306	5.6×10^{-3}	|	|	
185	12763	6.0×10^{-3}	|	|	
188	12586	5.7×10^{-3}	|	|	
189	11337	4.5×10^{-3}	P	600	

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MATER.: 316 SS F_{ty} = 21800 PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T° F	LOCATION
116	20883	9.6×10^{-4}	E	600	BIMETALLIC TUBE
119	6215	2.4×10^{-4}			
120	13644	5.2×10^{-4}			
124	5079	1.9×10^{-4}			
125	3314	1.3×10^{-4}			
126	2786	1.1×10^{-4}			
127	6567	2.5×10^{-4}			
128	11872	4.5×10^{-4}			
131	4205	1.6×10^{-4}			
132	6172	2.4×10^{-4}			
133	9546	3.7×10^{-4}			
136	991	3.8×10^{-5}			
137	1261	4.8×10^{-5}			
138	3372	1.3×10^{-4}			
139	6009	2.3×10^{-4}			
140	8624	3.3×10^{-4}			
143	1262	4.8×10^{-5}			
144	1713	6.6×10^{-5}			
145	4100	1.6×10^{-4}			
146	7199	2.8×10^{-4}			
147	9318	3.6×10^{-4}			
150	9516	3.6×10^{-4}	E	600	

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MATER.: 316 SS F_{ty} = 21800 PSI

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
151	10536	4.0×10^{-4}	E	600	BIMETALLIC TUBE
154	10099	3.9×10^{-4}			
155	11696	4.5×10^{-4}			
162	9899	3.8×10^{-4}			
163	12081	4.6×10^{-4}			
170	9054	3.5×10^{-4}			
171	11123	4.3×10^{-4}			
174	8037	3.1×10^{-4}			
175	10911	4.2×10^{-4}			
182	6705	2.6×10^{-4}			
183	13272	5.1×10^{-4}			
186	13666	5.2×10^{-4}			
187	18514	7.1×10^{-4}	E	600	

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Fatigue life

Max loaded elements will be checked for fatigue life.
Method of attack: S.S. Manson's universal slope equation for multiaxial strain.

Max loaded elements are located in the bimetallic tube.

Tantalum element #142
in the plastic range

316 SS element #116
in the elastic range

Fatigue life of the element # 142

Material: Tantalum

Temperature: 600° F

Material properties at 600° F

$E = 26.73 \times 10^6$ $\quad F_{tu} = 24000$ PSI

$RA = .985$ reduction in area

effective strain: $\varepsilon_{EFF} = .00781$ "/"

Ductility:

$$D = \ln \frac{100}{100 - RA} = 4.2$$

$$D^{.6} = 2.366$$

$$\sigma_u = F_{tu} = 24000 \text{ PSI}$$

N_F – number of cycles

$$\Delta \varepsilon_T = \varepsilon_{EFF} = .00781$$

Modified universal slope equation:

$$\Delta \varepsilon_T = 3.03 \frac{\sigma_u}{E} N_F^{-.12} + D^{.6} N_F^{-.6}$$

$$\Delta \varepsilon_T = 3.03 \frac{24000}{26.73} 10^{-6} N_F^{-.12} + 2.366 N_F^{-.6} \quad \text{or}$$

$$.00781 = .00272 N_F^{-.12} + 2.366 N_F^{-.6}$$

Solution of the above equation is shown on pg. 26

$$N_F = 16500$$

In order to account for creep using "10% rule" we reduce the number of cycles to 1650

Estimated number of cycles for max loaded Tantalum element: 1650

The cycling life of 316 SS is in the range above 100000 cycles.

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```
ma, sign on: 7974, krikopulo
ACKNOWLEDGED AT 11:01 10-14-70

1  a=2.72e-3*x**(-.12)+2.366*x**(-.6)
2  x=x+500.
_  x=14000.
X =  1.399999E+04
3  e:(2,1,4)*15
4  print x,a
_  p:3
ACKNOWLEDGED
X =  1.449999E+04    A =  8.398320E-03
X =  1.500000E+04    A =  8.243062E-03
X =  1.550000E+04    A =  8.095815E-03
X =  1.600000E+04    A =  7.955938E-03
X =  1.649999E+04    A =  7.822826E-03
X =  1.699999E+04    A =  7.695976E-03
X =  1.750000E+04    A =  7.574919E-03
X =  1.800000E+04    A =  7.459230E-03
X =  1.850000E+04    A =  7.348541E-03
X =  1.899999E+04    A =  7.242497E-03
X =  1.949999E+04    A =  7.140800E-03
X =  2.000000E+04    A =  7.043150E-03
X =  2.050000E+04    A =  6.949316E-03
X =  2.100000E+04    A =  6.859034E-03
X =  2.149999E+04    A =  6.772104E-03
EXECUTION COMPLETED
_
   sign off:
SIGNED OFF AT 11:05 10-14-70
```

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Condition II

Stresses and strains are tabulated on pgs. 28-35

Fatigue life is calculated on pgs. 36-42

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MATER.: TANTALUM

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
2	5533	2.6×10^{-4}	P	1167	HEADER
3	5451	2.1×10^{-4}	P	1183	
4	5089	2.0×10^{-4}	E	1195	
5	5371	2.1×10^{-4}	E	1196	
6	5458	2.2×10^{-4}	P	1196	
7	5166	2.0×10^{-4}	E	1197	
8	4796	1.8×10^{-4}	E	1197	
9	4827	1.9×10^{-4}	E	1197	
10	5559	2.3×10^{-4}	P	1141	
12	3412	1.3×10^{-4}	E	1168	
13	2205	8.5×10^{-5}	E	1186	
19	5738	3.0×10^{-4}	P	1109	
20	5803	3.6×10^{-4}	P	1108	
21	3945	1.5×10^{-4}	E	1118	
22	3202	1.2×10^{-4}	E	1150	
24	5531	2.5×10^{-4}	P	1174	
28	3247	1.3×10^{-4}	E	1186	
29	5910	6.2×10^{-4}	P	1172	
30	5825	4.9×10^{-4}	|	1178	
31	5799	4.1×10^{-4}	|	1180	
32	5757	3.6×10^{-4}	|	1182	
33	5732	3.3×10^{-4}	P	1184	

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QUADRILLE WORK SHEET

PAGE 29 OF ______ PAGES

DATE ______

SUBJECT ______ BY ______ WORK ORDER ______

MATER.: TANTALUM

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
34	5951	4.5×10^{-4}	P	1081	ELLIPSOIDAL SHELL
35	5403	2.1×10^{-4}	|	1075	
36	5700	3.4×10^{-4}	|	1071	
37	5602	2.1×10^{-4}	|	1076	
38	6606	1.1×10^{-3}	|	1090	
39	6350	8.6×10^{-4}	|	1105	
40	5909	4.1×10^{-4}	P	1055	
41	5159	2.0×10^{-4}	E	1051	
42	5702	2.4×10^{-4}	P	1047	
43	5663	2.2×10^{-4}	P	1024	
44	4995	1.9×10^{-4}	E	1028	
45	3292	1.3×10^{-4}	|	1014	
46	4039	1.5×10^{-4}	|	990	
47	2503	9.5×10^{-5}	|	980	
50	2616	9.9×10^{-5}	|	875	
51	4365	1.7×10^{-4}	|	865	
54	2544	9.6×10^{-5}	E	733	
55	6624	3.1×10^{-4}	P	710	
58	5829	2.2×10^{-4}	E	654	
59	3054	1.1×10^{-4}	E	646	
62	6881	3.2×10^{-4}	P	619	
63	1536	5.8×10^{-5}	E	615	

STK. NO. D-1-103

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QUADRILLE WORK SHEET

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DATE ______

SUBJECT ______ BY ______ WORK ORDER ______

MATER.: TANTALUM

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
66	7543	5.2×10^{-4}	P	583	
67	3538	1.3×10^{-4}	E	565	
70	8120	4.0×10^{-4}	P	539	
71	2480	9.3×10^{-5}	E	546	
74	6853	2.6×10^{-4}		533	
75	1180	4.4×10^{-5}		528	
78	5586	2.1×10^{-4}		522	
79	1033	3.9×10^{-5}		524	
80	5180	1.9×10^{-4}		514	
83	1791	6.7×10^{-5}		515	
84	4552	1.7×10^{-4}		505	
85	1656	6.2×10^{-5}		518	ELLIPSOIDAL SHELL
86	4100	1.5×10^{-4}		506	
87	1475	5.5×10^{-5}		521	
88	3883	1.4×10^{-4}		506	
89	1706	6.4×10^{-5}		526	
90	1867	7.0×10^{-5}		520	
91	3842	1.4×10^{-4}		510	
92	4206	1.6×10^{-4}		510	
93	4275	1.6×10^{-4}		511	
94	3023	1.1×10^{-4}		516	
95	2563	9.6×10^{-5}	E	523	

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QUADRILLE WORK SHEET

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DATE ______
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MATER.: TANTALUM

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T ° F	LOCATION
96	1055	3.9×10^{-5}	E	531	ELLIPS. SHELL
97	1084	4.0×10^{-5}		533	
98	1044	3.9×10^{-5}		536	
99	1449	5.4×10^{-5}		543	
100	894	3.3×10^{-5}		539	
101	1356	5.1×10^{-5}		547	
102	1499	5.6×10^{-5}		547	
103	1317	4.9×10^{-5}		558	
104	288	1.1×10^{-5}		563	
105	1947	7.3×10^{-5}		551	
106	224	8.4×10^{-6}		571	NECK
107	1902	7.1×10^{-5}		560	
108	801	3.0×10^{-5}		584	
109	2079	7.8×10^{-5}		574	
110	2755	1.0×10^{-4}		601	
111	3876	1.4×10^{-4}		591	
112	6240	2.3×10^{-4}	E	617	
113	7764	8.1×10^{-4}	P	607	
114	8278	1.5×10^{-3}	P	623	
115	9869	2.9×10^{-3}	P	613	

STK. NO. D-1-103

MATER.: TANTALUM

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
117	12101	5.3×10^{-3}	P	621	BIMETALLIC TUBE
118	12955	6.2×10^{-3}		610	
121	14627	7.9×10^{-3}		617	
122	15993	9.2×10^{-3}		599	
129	15575	8.7×10^{-3}		593	
130	17897	1.1×10^{-2}		578	
134	16410	9.0×10^{-3}		563	
135	18571	1.1×10^{-2}		552	
141	16386	8.4×10^{-3}		534	
142	18575	1.0×10^{-2}		521	
148	16191	7.3×10^{-3}		485	
149	18308	9.2×10^{-3}		474	
152	16056	6.2×10^{-3}		435	
153	17919	7.8×10^{-3}		424	
156	15702	5.1×10^{-3}		395	
157	17360	6.6×10^{-3}		385	
160	15336	4.0×10^{-3}		355	
161	16780	5.2×10^{-3}		345	
164	15044	3.1×10^{-3}		325	
165	16218	4.1×10^{-3}		315	
168	14820	2.5×10^{-3}		305	
169	15766	3.3×10^{-3}	P	295	

01-071-002

QUADRILLE WORK SHEET

AEROJET GENERAL

AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

DATE ____

SUBJECT ____ BY ____ WORK ORDER ____

MATER.: TANTALUM

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
172	14718	2.1×10^{-3}	P	285	BIMETALLIC TUBE
173	15505	2.7×10^{-3}	|	275	
176	14698	1.7×10^{-3}	|	265	
177	15376	2.2×10^{-3}	|	254	
180	14674	1.3×10^{-3}	|	246	
181	15280	1.6×10^{-3}	|	231	
184	14645	8.7×10^{-4}	|	223	
185	15124	1.0×10^{-3}	P	206	

STK. NO. D-1-103

QUADRILLE WORK SHEET

AEROJET GENERAL
AEROJET-GENERAL CORPORATION
AZUSA, CALIFORNIA

DATE ______

SUBJECT ______ BY ______ WORK ORDER ______

MATER.: 316 SS

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T °F	LOCATION
116	20358	1.4×10^{-3}	E	684	BIMETALLIC TUBE
119	17501	7.0×10^{-4}		740	
120	14352	5.6×10^{-4}		680	
124	19061	9.9×10^{-4}		906	
125	17344	7.1×10^{-4}		848	
126	13796	5.6×10^{-4}		790	
127	19978	9.1×10^{-4}		735	
128	22257	1.5×10^{-4}		655	
131	19686	7.9×10^{-4}		765	
132	20481	8.6×10^{-4}	E	720	
133	23037	1.7×10^{-3}	P	636	
136	19231	9.9×10^{-4}	E	889	
137	13969	5.7×10^{-4}		824	
138	11093	4.4×10^{-4}		731	
139	21443	9.6×10^{-4}		658	
140	23674	1.8×10^{-3}	E	591	
143	19827	1.2×10^{-3}	P	870	
144	20175	1.0×10^{-3}	P	801	
145	19103	7.5×10^{-4}	E	694	
146	20848	8.4×10^{-4}	E	588	
147	23990	1.4×10^{-4}	P	520	
148	16191	7.3×10^{-3}	E	485	

STK. NO. D-1-103

MATER.: 316 SS

EL. #	EFF. STRESS PSI	EFF. STRAIN IN/IN	RANGE	T° F	LOCATION
151	16590	6.3×10^{-4}	E	468	BIMETALLIC TUBE
154	21599	1.0×10^{-3}		466	
155	4495	1.7×10^{-4}		421	
162	17700	6.6×10^{-4}		355	
163	10367	3.8×10^{-4}		340	
170	13001	4.8×10^{-4}		305	
171	11197	4.1×10^{-4}		295	
174	11035	4.0×10^{-4}		280	
175	11250	4.1×10^{-4}		273	
182	8457	3.1×10^{-4}		238	
183	12668	4.6×10^{-4}		233	
186	13210	4.8×10^{-4}		208	
187	17017	6.2×10^{-4}	E	200	

Fatigue life

Max loaded elements will be checked for fatigue life.
Method of attack: S.S. Manson's universal slope equation for multiaxial strain.

Max loaded elements are located in the bimetallic tube.

Tantalum element # 142
in the plastic range

316 SS element # 133
in the plastic range

Fatigue life of the element # 142

Material: Tantalum

Temperature: 521° F

Material properties at 520° F

$E = 26.85 \times 10^6$ $\qquad F_{tu} = 25000$ PSI

$RA = .98$ $\qquad$ reduction in area

effective strain: $\varepsilon_{EFF} = .0103$ %

Ductility:

$$D = \ln \frac{100}{100 - RA} = 3.9$$

$$D^{.6} = 2.259$$

$$\sigma_u = F_{tu} = 25000 \text{ PSI}$$

N_F – number of cycles

$$\Delta \varepsilon_T = \varepsilon_{EFF} = .0103$$

Modified universal slope equation:

$$\Delta \varepsilon_T = 3.03 \frac{\sigma_u}{E} N_F^{-.12} + D^{.6} N_F^{-.6}$$

$$\Delta \varepsilon_T = 3.03 \frac{25000}{26.85} 10^{-6} N_F^{-.12} + 2.259 N_F^{-.6} \quad \text{or}$$

$$.0103 = .00282 N_F^{-.12} + 2.259 N_F^{-.6}$$

Solution of the above equation is shown on pg. 39

$$N_F = 9200$$

In order to account for creep using "10% rule" we reduce the number of cycles to 920

Estimated number of cycles for max loaded Tantalum element: 920

```
ma, sign on: 7974, krikopulo
** NO TERMINAL ID FOUND


ma, sign on: 7974, krikopulo
ACKNOWLEDGED AT 15:10 10-14-70

1  a=2.82e-3*x**(-.12)+2.259*x**(-.6)
2  x=x+300.
_  x=8000.
X =   8.000000E+03
3  e:(2,1,4)*15
4  print x,a
_  p:3
ACKNOWLEDGED
X =   8.300000E+03    A =   1.101192E-02
X =   8.600000E+03    A =   1.079587E-02
X =   8.899999E+03    A =   1.059149E-02
X =   9.199999E+03    A =   1.039779E-02
X =   9.500000E+03    A =   1.021388E-02
X =   9.800000E+03    A =   1.003896E-02
X =   1.010000E+04    A =   9.872384E-03
X =   1.039999E+04    A =   9.713485E-03
X =   1.069999E+04    A =   9.561706E-03
X =   1.100000E+04    A =   9.416554E-03
X =   1.130000E+04    A =   9.277556E-03
X =   1.159999E+04    A =   9.144306E-03
X =   1.189999E+04    A =   9.016420E-03
X =   1.220000E+04    A =   8.893560E-03
X =   1.250000E+04    A =   8.775416E-03
EXECUTION COMPLETED

_  sign off:
SIGNED OFF AT 15:13 10-14-70
_
```

Fatigue life of the element # 133

Material: 316SS

Temperature: 636° F

Material properties at 640° F

$E = 25.9 \times 10^6$ $\quad F_{tu} = 70000$ PSI

$RA = .59$ reduction in area

effective strain: $\varepsilon_{EFF} = .00174$ "/"

Ductility:

$$D = \ln \frac{100}{100 - RA} = .892$$

$$D^{.6} = .933$$

$$\sigma_u = F_{tu} = 70000 \text{ PSI}$$

N_F - number of cycles

$$\Delta\varepsilon_T = \varepsilon_{EFF} = .00174$$

Modified universal slope equation:

$$\Delta\varepsilon_T = 3.03 \frac{\sigma_u}{E} N_F^{-.12} + D^{.6} N_F^{-.6}$$

$$\Delta \varepsilon_T = 3.03 \frac{70000}{25.9} 10^{-6} N_F^{-.12} + .933 N_F^{-.6} \quad \text{or}$$

$$.00174 = .0082 N_F^{-.12} + .933 N_F^{-.6}$$

Solution of the above equation is shown on pg. 42

$$N_F \geqq 1000000$$

In order to account for creep using "10% rule" we reduce the number of cycles to 100000

Estimated number of cycles for max loaded 316 SS element > 100000

```
ma, sign on: 7974, krikopulo
ACKNOWLEDGED AT  9:23 10-15-70

1  a=8.2e-3*x**(-.12)+.933*x**(-.6)
2  x=x+15000.
_  x=700000.
X =  7.000000E+05
3  e:(2,1,4)*20
4  print x,a
_  p:3
ACKNOWLEDGED
X =  7.149999E+05    A =  1.913276E-03
X =  7.300000E+05    A =  1.905680E-03
X =  7.449999E+05    A =  1.898291E-03
X =  7.600000E+05    A =  1.891099E-03
X =  7.750000E+05    A =  1.884095E-03
X =  7.899999E+05    A =  1.877270E-03
X =  8.050000E+05    A =  1.870617E-03
X =  8.199999E+05    A =  1.864129E-03
X =  8.350000E+05    A =  1.857795E-03
X =  8.500000E+05    A =  1.851612E-03
X =  8.649999E+05    A =  1.845574E-03
X =  8.800000E+05    A =  1.839673E-03
X =  8.949999E+05    A =  1.833906E-03
X =  9.100000E+05    A =  1.828266E-03
X =  9.250000E+05    A =  1.822746E-03
X =  9.399999E+05    A =  1.817345E-03
X =  9.550000E+05    A =  1.812059E-03
X =  9.699999E+05    A =  1.806880E-03
X =  9.850000E+05    A =  1.801808E-03
X =  1.000000E+06    A =  1.796838E-03
EXECUTION COMPLETED

   sign off:
SIGNED OFF AT  9:27 10-15-70
_
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Moore Business Forms, Inc

AEROJET GENERAL

SNAP-8

DATE 26 August 1970 ENGINEERING FILE NO. PCS-G-S-403.0

W.O. 1475-02-0402 EDF SERIAL NO. D7993-70-0485

ENGINEERING DESIGN FILE

SUBJECT:

Conceptual Boiler Mounting Configuration, PCS, SNAP-8

ABSTRACT:

A conceptual boiler mounting configuration was determined by means of the MEC-21 piping flexibility analysis program. The PCS S-shaped boiler configuration is defined by Drawing AGC-1268489 N/C.

Various mounting methods were analyzed considering allowable boiler attachment points and PCS frame mounting locations. The objective of the mounting study was to obtain a configuration that distributed the boiler weight as evenly as possible on the supports, provided low thermal loads on the supports, and produced boiler shell stresses below the maximum allowable stress during operation. The maximum operating temperature was considered to be 1300°F and the boiler shell is constructed from 316 stainless steel. A maximum allowable thermal stress of 5,140 psi was calculated from data contained in AGC-10650, H-100, and the nuclear power piping code - USAS B31.7. The moment of inertia for the boiler (outer shell, static NaK oval tubes, and inner liner) was calculated to be 30.436 in.^{4}. For the MEC-21 program, a 7.5 in. O.D. x 0.188 in. wall pipe with a moment of inertia of 28.5 in.^{4} was used. The wet weight of the boiler including insulation was calculated to be 1109.5 lb. The mounting configuration that satisfied the requirements is shown in Figure 1 and described as follows:

The boiler is anchored at Point A to eliminate load interactions between the TAA Hg inlet and the boiler through the vapor line due to boiler thermal movement. The boiler is cold sprung at Point D, 0.5 in. in the -X direction and -1.0 in. in the -Y direction to reduce operating thermal stresses.

Individual support description:

(a) Support A is fixed in all directions.

(b) Support B is a saddle-type support which allows the boiler to move in the +Y direction, ±X direction, and rotate about the X and Z axes.

(c) Support C is a spring support providing an initial force of 500 lb on the boiler in the +Y direction and having a spring rate of 300 lb/in. The

DISTRIBUTION: B Breindel, ES Chalpin, H Derow, JN Hodgson, AH Kreeger, GL Lombard, LP Lopez, RW Marshall, UA Pineda, JR Pope, JC Shen, RL Tome', DR Ward, W Weleff BR Fanton

KEY WORDS: MEC-21 piping flexibility analysis program; boiler, PCS; boiler supports, PCS; cold springing, stress analysis, PCS.

AUTHOR	DATE	REVIEWED	DATE	APPROVED	DATE
R.L.Tome' R.L. Tome'	9/3/70			B.Breindel B. Breindel	9/3/70

support allows the boiler to move in the ±Y direction, ±X direction, and rotate about the Z axis.

(d) Support D allows the boiler to rotate about the Z axis.

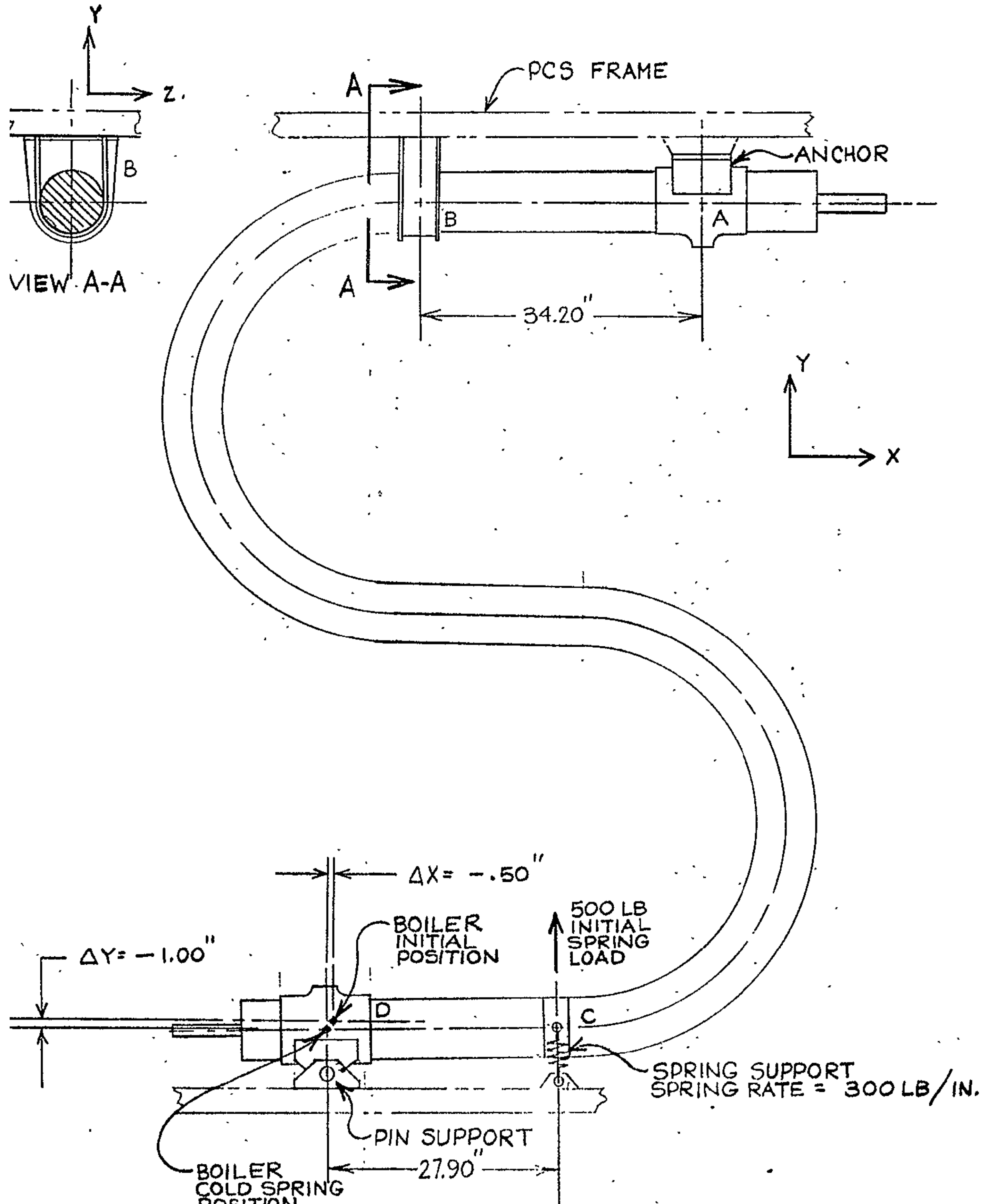

FIGURE 1
BOILER SUPPORT CONFIGURATION

APPENDIX H

FAILURE MODES AND EFFECTS ANALYSIS

POWER SYT[redacted] DIVISION
FAILURE MODES AND EFFECTS ANALYSIS

PART NO. 1268600
PART NAME BRDC Boiler #5
LOOP ____ ITEM NO. ____

DESCRIPTION OF FUNCTION:
TRANSMIT HEAT FROM NaK LOOP TO Hg
RANKINE LOOP OF SNAP-8 PCS

PAGE 1 OF 3
DATE 21 Sept. 1970
INITIAL ☐ REVISION ☒

1	2	3 EFFECT ON SNAP-8		4 PROBABILITY OF OCCURRENCE*	5 CRITICALITY OF FAILURE**	6
FAILURE MODE	FAILURE CAUSE	COMPONENT	SYSTEM			REMARKS AND RECOMMENDATIONS
A. Boiler shell or tee failure	Cracks due to thermal stress or interface loads.	repair or replacement required	Shutdown; can be significant hazard	High	Critical	Thorough thermal analysis indicates that use of honeycomb in end housings and other design changes will significantly relieve thermal gradients.
	Material, fabrication, or weld defect.	same as above	same as above	Low	Critical	Thorough inspection and non-destructive testing of parts and assemblies, use of adequate cleaning procedures
B. Boiler center tube failure	same as (A)	repair or replace at opportune time	could cause replacement of vacuum with flowing NaK inventory	Low	Major Critical	Same as (A)
C. Static NaK tube failure	thermal stress; interface loads	repair or replace at opportune time	no effect if no other failure.	Mod.	Minor	Changes in end housing should reduce probability of recurrence.
	material fabrication, or weld defect	same as above	same as above	Low	Minor	Thorough inspection and non-destructive testing of parts and ass'ys.

* HIGH - Two or more occurrences of failure mode in testing.
MODerate - One recorded occurrence.
LOW - No recorded occurrences.

** CRITICAL - Failure which aborts the test in progress or creates an intolerable safety hazard.
MAJOR - A failure or performance degradation in excess of tolerance limits.
MINOR - Failures other than critical or major which have no significant effect on the ability of the system to perform its primary function.

4925:67:0126

POWER SYT[redacted] DIVISION
FAILURE MODES AND EFFECTS ANALYSIS

PART NO. 1268600
PART NAME BRDC Boiler #5
LOOP ______ ITEM NO. ______

DESCRIPTION OF FUNCTION:

PAGE 2 OF 3
DATE 21 Sept. 1970
INITIAL ☐ REVISION ☒

1	2	3 EFFECT ON SNAP-8		4 PROBABILITY OF OCCURRENCE*	5 CRITICALITY OF FAILURE**	6
FAILURE MODE	FAILURE CAUSE	COMPONENT	SYSTEM			REMARKS AND RECOMMENDATIONS
D. Static NaK leak at end housing	Thermal stress; interface loads; material fab., or weld defect.	Repair or replace	May adversely affect heat transfer by causing gradients.	Low	Minor/ major	Adequate design inspection, and test should reduce probability of occurrence.
E. Leak in vacuum chamber in end housing.	Thermal stress; faulty material or fab.	Repair or replace	May adversely affect heat transfer by causing thermal gradients	Low	Minor/ Major	Adequate design and inspection should reduce probability of occurrence.
F. Tantalum (Hg) tube failure	Thermal stress or interface loads	Replacement required	shutdown	Low	Critical	Adequate design should keep probability low.
	Material, fabrication, or weld defect	Same as above	Same as above	Low	Critical	Adequate inspection and non-destructive tests should keep probability low.
G. Excessive Hg side Pressure drop	Design or fabrication deficiency	Repair	Poor performance or shutdown	Mod.	Major	Adequate design and fab. should reduce probability
	Contamination (mass transfer deposits or dirty loop)	Clean or replace	Poor performance or shutdown	Low	Major	Originally clean loop will prevent occurrence

* HIGH - Two or more occurrences of failure mode in testing.
MODerate - One recorded occurrence.
LOW - No recorded occurrences.

** CRITICAL - Failure which aborts the test in progress or creates an intolerable safety hazard.
MAJOR - A failure or performance degradation in excess of tolerance limits.
MINOR - Failures other than critical or major which have no significant effect on the ability of the system to perform its primary function.

4925:67:0126

POWER SYTE[redacted] DIVISION

FAILURE MODES AND EFFECTS ANALYSIS

PART NO. 1268600
PART NAME BRDC Boiler #5
LOOP ________ ITEM NO. ________

DESCRIPTION OF FUNCTION:

PAGE 3 OF 3
DATE 21 Sept. 1970
INITIAL ☐ REVISION ☒

1 FAILURE MODE	2 FAILURE CAUSE	3 EFFECT ON SNAP-8: COMPONENT	3 EFFECT ON SNAP-8: SYSTEM	4 PROBABILITY OF OCCURRENCE*	5 CRITICALITY OF FAILURE**	6 REMARKS AND RECOMMENDATIONS
H. Deconditioned boiler	Hg loop contamination	Clean or replace	Poor performance or shutdown	High	Major	Loop or test failure not chargable to boiler; (no known mat'l. to overcome contamination effects)
I. Excessive NaK side pressure drop	Design or fabrication deficiency, loose swirl wire	Clean or replace	Poor performance or shutdown	Low	Major	Adequate design and fab. should prevent occurrence
J. Plugged Hg tubes	Contamination, mass transfer	Replace	Poor performance or shutdown	Low	Minor/ Major	Adequate loop cleanliness should keep prob. low.
K. Excessive corrosion or erosion	Oxide contamination	May lead to rupture, replace	Can lead to premature wear-out	Low	Major	Latest materials should reduce incidence, loop cleanliness is significant factor
L. Bimetal tube debond	Fab. deficiency	Reduced life	Reduced life	Low	Major	No evidence to date; continue C-scan and other inspection
M. Manufacturing problems leading to fab. deficiencies	Complexity of design	Difficult to manufacture	Program delay	Low	Minor	Detailed evaluation by Mfg. Eng. to establish optimum mfg. procedures.

* HIGH - Two or more occurrences of failure mode in testing.
MODerate - One recorded occurrence.
LOW - No recorded occurrences.

** CRITICAL - Failure which aborts the test in progress or creates an intolerable safety hazard.
MAJOR - A failure or performance degradation in excess of tolerance limits.
MINOR - Failures other than critical or major which have no significant effect on the ability of the system to perform its primary function.

4925:67:0126

APPENDIX I

DESIGN REVIEW CHECK LIST

POWER SYSTEMS DIVISION

DESIGN REVIEW CHECK LIST

SUBJECT UNDER REVIEW (Name, Part No.): BRDC BOILER #5
P/N 1268600

This Design Review Check List is an integral part of the design review documentation package, required by Power Systems Division Procedure I-A6c, "Design Review Plan."

The items specified on the Design Review Check List provide the basis for a comprehensive review. However, they are not necessarily all inclusive. The design engineer shall be guided by the basic requirement for a thorough and detailed evaluation of a design, as stated under Section 3, "SCOPE," of this procedure, and shall expand the list where necessary.

Check List entries shown herein provide current information on the design under review and are intended to reflect the basis for and readiness of the design for entry into its next evolutionary phase.

REVIEWED BY:

W. Wolff 10-21-70
Stress Date

B. Amstradter 10/22/70
Reliability Date

E S Chalfin for 10/21/70
Quality Assurance Date

PRESENTED BY:

E S Chalfin 3 Sept. 1970
Design Engineer Date

DESIGN APPROVAL:

[illegible] 10/22/70
Department Manager Date

4925:66:107

PSD DESIGN REVIEW CHECK LIST

SUBJECT NAME: BRDC Boiler #5

P/N 1268600

DESIGN ENGINEER: [signature] DATE 2 Sept 1970

Item No.	General	YES	NO	N/A	REFERENCE DOCUMENT
1.	Is the basic design objective clearly defined?	X			appendix A
2.	Are the performance parameters and output requirements definitive and not subject to misinterpretation?	X			"
3.	Are performance tolerances delineated?	X			"
4.	Are failure criteria delineated?	X			appendix H
5.	Were alternate designs considered in selecting the present design?	X			memo 7961-70-0567 "18 June 1970 Preliminary Conceptual Design Review BRDC #5 Boiler"
6.	Were redundancy needs analyzed and results used in the design?	X			"
7.	Were simplification techniques applied?	X			
8.	Was a failure modes and effects analysis made?	X			appendix H
9.	Have adequate safety margins been incorporated for each important failure mode?	X			
10.	If item has a limited life, is it so designated?	X			appendix A
11.	Have maintainability requirements been considered?	X			Dwg. 1268600
12.	Have previous test data and failure reports been reviewed and results used in the design?	X			appendix C
13.	Is the method of component identification specified? (The method of marking and location must be compatible with use-environment.)	X			Dwg 1268600
14.	If documentation of inspection findings is required, are the characteristics to be observed and their frequency and method of inspection defined?			X	
15.	If operational or functional acceptance testing is required, are the parameters, mode of testing, and equipment defined?		X		

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SUBJECT NAME: BRDC Boiler #5

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DESIGN ENGINEER: Ed Chalpin DATE 9-3-70

Item No.	General	YES	NO	N/A	REFERENCE DOCUMENT
16.	Are required special inspection equipments, tools, and gages defined?	X			Dwg. 1268600
17.	Has a procurement plan for this material been established?			X	LeRC Fab.
18.	Have qualified and preferred parts been used where applicable?	X			appendix F.
19.	Is the design notebook and file up to date and ready for audit?	X			
20.	Have provisions been made for preservation, packaging, handling, storage, and shipping?	X			Drawing 1268600
21.	Were trade-off studies made and utilized in selecting the design?	X			Memo 7961-70-0567
22.	Does the design minimize the probability of human errors during installation, checkout, and operation, such as reversed connections, parts installed backward, no lubrication during startup, etc.?	X			
23.	Does the design make appropriate use of "fail-safe" devices or techniques?	X			
24.	Does the design comply with all applicable specifications?	X			
25.	Were the action items from the previous Design Review carried out?			X	
26.	Is the design compatible with the requirements of the end item?	X			Dwg 1268489

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SUBJECT NAME: BRDC BOILER #5

P/N 1268600

DESIGN ENGINEER: Ed Chalpin DATE 9-3-70

Item No.	Mechanical	YES	NO	N/A	REFERENCE DOCUMENTS
1.	Has a stress analysis been made?	X			appendix G.
2.	Have areas of high stress concentrations such as sharp corners, radii, and re-entrant angles been eliminated?	X			
3.	Has a thermal analysis been made?	X			appendix B
4.	Is thermal expansion likely to have adverse effects on dimensions and tolerances?		X		appendix A
5.	Has a tolerance analysis been made to verify proper fitting of parts under extremes of tolerance buildup?	X			
6.	Did the tolerance analysis consider operating loads and temperatures?	X			appendix G.
7.	Were static, dynamic and magnetic balances and their tolerances considered?			X	
8.	Has a wearout analysis for all rubbing and rolling parts been made?			X	
9.	Have the installation torques and tolerances of all fasteners and their stress effects been evaluated?			X	
10.	Is the inspectability of the component assured? (Are the true positioning and contour requirements designed to enable inspection of part?)	X			
11.	Has the mechanical compatibility with the complete system been verified?	X			Appendix A
12.	Does mechanical design reflect simplest method, from manufacturing view, to meet needed parameters?	X			
13.	Were environmental effects (including those of nuclear radiation) considered along with safety requirements during design?	X			

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DESIGN ENGINEER: E S Chalpin DATE 9-3-70

Item No.	Electrical	YES	NO	N/A	REFERENCE DOCUMENTS
1.	Are the design essentials adequately defined, including performance, longevity, and repetitive operation requirements?			X	
2.	Is the design compatible with the life cycle conditions to which the equipment will be exposed?			X	
3.	Have the stability and drift requirements and the effects of environments on these characteristics been considered?			X	
4.	Was a simplification study made and applied?			X	
5.	Is redundancy employed where beneficial; are possible side effects taken into consideration?			X	
6.	Were reliability characteristics considered and documented in parts and materials selection?			X	
7.	Are the part tolerances consistent with design requirements?			X	
8.	Was adequate derating employed, including sufficient margin for transients and other excessive stresses?			X	
9.	Can the parts operation result in undesirable conditions of temperature, voltage, current, or RFI for other parts or assemblies? If so, was this info used in the design?			X	
10.	Are the dielectric breakdown and insulation resistance properties adequate for the most severe environments?			X	
11.	Is hermetic sealing employed where beneficial?			X	
12.	Are type of connections employed reliable?			X	

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DESIGN ENGINEER: Ed Chalpin DATE 9-3-70

Item No.	Electrical	YES	NO	N/A	REFERENCE DOCUMENTS
13.	Have all applicable specifications been called out?			X	
14.	Have the preferred parts lists (JPL Specification No. 20061C and CSFC-PPL-1) been used?			X	
15.	Has expected hot spot temperatures been determined and considered?			X	
16.	Has effect of component operation on primary power wave form been considered?			X	
17.	Has nuclear radiation environment effects been considered?			X	

NOTE: The following electrical characteristics should be considered: inductance, capacitance, resistance, sensitivity, leakage, insulation, shielding; distortion, gain, phase, attenuation; slope, harmonics, eddy currents; time, spikes, peaks, contact resistance, contact rating, torque, wire size

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SUBJECT NAME: BRDC BOILER #5

P/N 1268600

DESIGN ENGINEER: Ed Chalpin DATE 9-3-70

Item No.	Materials	YES	NO	N/A	REFERENCE DOCUMENT
1.	Are all materials adequately identified by MIL, Fed, AGC, or comparable specifications?*	X			Dwg 1268600
2.	Is the source of supply specified for qualified/ preferred materials?			X	LeRC FAB.
3.	Are the strength characteristics of the materials including tensile, compressive, shear, yield, bending, creep, and fatigue satisfactory for intended use?	X			appendix G.
4.	Is each material employed within limits defined by its endurance limit curve?	X			"
5.	Have adequate safety margins been used to provide protection from failure due to corrosion, vibration, shock, fatigue, and other stress factors?	X			"
6.	Are the hardness, ductility, and other characteristics suitable for both the manufacturing processes and application?	X			
7.	Will the material characteristics be significantly changed by exposure to environments, particularly radiation?		X		
8.	Are the special inspection and test processes compatible with the parts and materials?	X			appendix F.
9.	Are the thermal expansion characteristics suitable for the intended use?	X			appendix G.
10.	Will the materials be compatible with mating parts, fluids, and gases and not act as catalytic agents?	X			Reference (d)
11.	Does each material have suitable electrical and magnetic properties for its application?			X	

* The order of precedence for specifications must meet MIL-STD-143 requirements.

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P/N 1268600

DESIGN ENGINEER: El Chalpin DATE 9-3-70

Item No.	Materials	YES	NO	N/A	REFERENCE DOCUMENTS
12.	Have adequate metallurgical controls been imposed to assure that each material conforms to its specification?	X			Dwg. 1268600
13.	Are all tolerances specified and are they compatible with the materials and required manufacturing methods?	X			"
14.	If mechanical, metallurgical, and/or chemical testing is required, are the necessary samples, coupons, or test bars defined, and test methods established?			X	

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SUBJECT NAME: BRDC BOILER #5

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DESIGN ENGINEER: E S Chalpin DATE 9-3-70

Item No.	Manufacturing Processes	YES	NO	N/A	REFERENCE DOCUMENTS
1.	Are the specified fabrication methods suited to the design and materials?	X			BRDC Boiler #4
2.	Are the process capabilities consistent with component requirements?	X			"
3.	Is heat treating, stress relief, nitriting, flame hardening, or other special process required?		X		
4.	Will processing and assembly affect the dimensions?		X		
5.	Are process specifications and tolerances designated?	X			Dwg 1268600
6.	Are requirements after processing and assembly specified?	X			"
7.	Have joining methods (welding, brazing, soldering, fastening) been selected to minimize effect on tolerances and part variations?	X			"
8.	Are special inspection and test processes such as radiograph, helium leak test, and penetrant dye check required?	X			Dwg. 1268600
9.	If so, are acceptance criteria specified?	X			"
10.	Has the most suitable cleaning method been specified?	X			"
11.	Is a protective coating required?		X		
12.	If so, will protective coating affect mating parts?			X	
13.	Are special assembly requirements such as alignment, torque, lock wiring, static balancing, or dynamic balancing defined and documented?			X	
14.	Is there an assembly instruction or specification?		X		

SUBJECT NAME: BRDC BOILER #5	YES	NO	N/A	REFERENCE DOCUMENTS
P/N 1268600				
DESIGN ENGINEER: Ed Chalpin DATE 9-3-70				
Item No. **Manufacturing Processes**				
15. Are the clean room environmental characteristics defined (such as maximum particle size, count, temperature, flow rate, etc.)?			X	LeRC FAB.
16. Are there special packaging, handling, or storage requirements?	X			Dwg. 1268600
17. Are the special process operator and equipment qualification requirements specified?	X			"
18. Are the surface finish, waviness, and lay adequately defined?			X	
19. Are workmanship acceptance standards defined?	X			Dwg 1268600
20. Are the applicable workmanship specifications referenced?	X			"
21. Is a Build-up and Assembly Log required?		X		

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SUBJECT NAME: BRDC BOILER #5

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DESIGN ENGINEER: E S Chalpin DATE 9-3-70

Item No.	Environment	YES	NO	N/A	REFERENCE DOCUMENTS
1.	Have the environmental exposures, levels, and durations been fully determined?	X			AGC-10680
2.	Have the environmental effects on component performance, longevity, and reliability been evaluated?	X			Memo 4923:69:9180 "Effect of Nuclear Radiation on SNAP-8 Gallery Materials"
3.	Does operation of the component generate environments which are detrimental to the component or to other assemblies or subsystems?		X		
4.	Can the component withstand external and self-generated environments without employment of isolation devices?	X			
5.	Is adequate protection from environments specified in detail where required?	X			Figure 5
6.	Were the relationships between environments and modes of failure considered in the failure mode and effects analysis?	X			Appendix H

NOTE: The following environments should be considered: heat, cold, thermal shock, high pressure, vacuum, pressure shock, humidity; vibration, acoustic noise, acceleration, shock, RFI-radiated, RFI-conducted, RFI-susceptibility; explosive atmosphere, solar radiation, nuclear radiation, salt atmosphere, fungus, meteoroids, zero-gravity, sand, dust, wind.

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SUBJECT NAME: BRDC BOILER #5 P/N 1268600 DESIGN ENGINEER: E.S. Chalpin DATE 9-3-70	YES	NO	N/A	REFERENCE DOCUMENT
Item No. **Instrumentation**				
1. Have accuracy and precision requirements been specified for performance parameters?			X	
2. Have provisions been made for instrumentation to meet these requirements?			X	
3. Have sensor installation requirements, including hermetic sealing and removal or replacement, been considered?			X	
4. Will the insertion of sensors affect the operation of the component?			X	
5. Is adequate instrumentation available for anticipated operating conditions?			X	
6. Is an instrumentation development program necessary?			X	
7. Are written calibration instructions available for the calibration of data gathering equipment?			X	
8. Has an adequate and reliable instrumentation wiring system been defined?			X	

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