TK27-490-76-09
February, 1976

DOUBLE-WALL STEAM-GENERATOR TUBE AND WELD-DEVELOPMENT STUDY

AT03-76SF74027

PREPARED FOR USERDA
UNDER CONTRACT AT(04-3)-893
TASK 27

BY

GENERAL ELECTRIC
FAST BREEDER REACTOR DEPARTMENT
SUNNYVALE, CALIFORNIA

893/27/8-2 ltr dtd 3/10/76

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NOTICE

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1.0 INTRODUCTION

1.1 Objective

The objective of this effort was to evaluate and initiate development on double-wall tubing and tube/tubesheet welds of various configurations for application in LMFBR steam generators. The scope of this effort was limited to one material (2¼Cr-1Mo), two T/TS weld types (IBW and Orbital) and relatively small tube dimensions (∿CRBR reference steam generator). It was recognized that larger tubes are, in general, easier to weld and that other combinations of tube materials (Incoloy 800, Inconel 600, 9Cr-1Mo) are feasible; however, metalurgical properties for these materials are being determined in the Advanced Alloy program and are beyond the scope of this effort. The double-wall tubing types evaluated for this study were also limited to tubes with water/steam on the tube side and sodium on the shell.

1.2 Background

A number of Steam Generator units for sodium-cooled reactors have been built which employed a double-wall tube as a barrier between the sodium and water. One of the first applications of a double-wall tube to separate reactive metals from water/steam was developed by GE-KAPL for the Navy submarine reactor steam generators. Double-wall tubes of 2¼Cr-1Mo with helium in the gap were filled with flowing sodium and used to boil water in the shell side. The steam generators for the SRE (Sodium Reactor Experiment) built by B&W for Southern California Edison contained Type 304SS double-wall tubes with flowing mercury in the gap to provide improved heat transfer and leak detection. Steam generators in the Hallam Nuclear Power Facility (HNPF) contained sodium-filled double-wall tubes which boiled water on the shell side. The gap contained helium flowing through grooves which was used to detect and monitor leaks from either the water or sodium side. A 2¼Cr-1Mo double-wall tube steam generator design without intermediate fluid was used for the EBR-II steam generators. Some of these units (which were built by ANL) contained metallurgically-bonded tubes and some contained mechanically-bonded (no diffusion couple formed) tubes. The single tube Small Steam Generator Model (SSGM) built by W-Tampa contained grooved, double-wall 2¼Cr-1Mo tubes with intermediate pressure helium in the gap for leak detection.

2.0 DISCUSSION---DOUBLE-WALL TUBE CONFIGURATION

2.1 Requirements

Double-wall tubing may be categorized in a number of ways: bonded/unbonded, with or without a third material between inner and outer tube, gas or solid as a gap material, etc., (see Table I). Before discussing the advantages and disadvantages of each type of double-wall tube, a brief review of its functions is presented below. The prime function of the double-wall tube is to increase the reliability of the pressure boundary between the sodium and water. This increase in reliability is accomplished because the probability of a breach of both inner and outer walls is lowered. This is lowered because it is the product of the probabilities of defects occuring simultaneously in both walls. This advantage can be realized, if the materials and processes used for the double-wall tube and tube/tubesheet joint do not introduce additional defects not inherent in the single-wall concept and if there is no tube-to-tube interdependence. As discussed later, this is not thought to be the case with the approaches investigated in this report. The double-wall tubing discussed in this report is classified as follows:

A. Bonded
   1. Metallurgically Bonded
   2. Mechanically Bonded (Pre-Stressed)

B. Unbonded

If the double-wall tube is unbonded, then a gap is present. (For pre-stressed tubes the gap is essentially zero at ambient temperatures.) Furthermore, the gap enlarges when the tube wall is subjected to temperature gradients caused by the heat fluxes present in sodium-heated steam generators. Therefore, gap materials are introduced to minimize the decrease in the overall thermal resistance of a double wall tube which accompanies the increase in wall thickenss, the presence of a gap between the walls, and the opening of the gap under heat flux. If a partial vacuum is formed because of reaction of trapped air in the gap with the steel or because of differential thermal expansion between inner and outer tube, the overall decrease in thermal conductivity may be unacceptable. The presence of the gap material must not compromise the structural integrity of the walls. This may happen by either corrosive attack or in the case of a solid gap material, mechanical interference such as galling or wear.

A secondary function of the gap material is to act as a barrier to the communication of sodium and water along the gap. A solid gap material has an obvious advantage over a gas in this respect in that either the sodium or the water/steam must corrode through another barrier after having traversed through either of the steel boundaries. An inert gaseous gap material such as helium offers a non-reactive environment which may mitigate the effects of an intrusion of highly reactive sodium into the gap. Helium can also be used to permit detection of a leak.

2.2 Bonded Double-Wall Tubes

The first category of double-wall tubes considered are those which are bonded. There are basically two types of bonding: 1) metallurgical, or diffusion-bonding and 2) mechanical, produced by an interference fit between the two tubes. In either type axial or circumferential loads produced on one tube may be transmitted to the other because of the continuity of bond across the interface. Unbonded tubes will transmit much less load, and that occurs only because of friction at the interface.

2.2.1 Metallurgical-Bonding

A metallurgical bond occurs when the unoxidized surface of two pieces of metal are brought into contact at a high enough temperature and for a long enough time for metallic, atomic bonds to form across the interface. Metallographic examination of the region will reveal the absence of the interface (if the metals are of the same composition; if not, compounds may form); the two pieces of metal have become one. The strength of the bond is the same as that of the base metal, and this type of bond produces no added thermal resistance to the overall double-wall resistance. This type of bond is therefore the most desirable. However, it is more difficult (and therefore more expensive) to make than the mechanical bond. It is difficult to ensure the required strict cleanliness of the contacting metal surfaces in a large production process at the high temperatures normally required to achieve the bond. If the bond were made between two tubes of the same composition a defect originating from either side of the tube wall would encounter no barrier as it traversed the wall. For this reason a third material is placed in the gap and bonding is effected between it and the two tube walls to form a monolithic three-part wall. In the case of the EBR-II double-wall tubes a nickel-phosphorus braze alloy was applied to the outer surface of the inner tube prior to drawing the outer one down over it. The combination was subsequently diffusion-bonded at brazing temperatures. Subsequent shear tests on the bond confirmed the integrity of the bond. The nickel layer apparently served its function in the ten years of service it has seen (See ANL - 8146, February, 1975).

2.2.2 Mechanical-Bonding (Pre-stress)

A mechanical bond occurs when stresses are introduced into two contacting metal surfaces in such a way as to restrict transverse movement at the interface. These stresses can be applied actively by the service conditions or passively (residual) during the fabrication of the tubing.

Active stresses could be applied by an external load but for the system considered here that is not a feasible alternative. Pressurizing one tube against the other would only work if the inner tube were much thinner than this concept allows; i.e., this discussion does not consider the double-wall tube as a single-wall tube with a liner. Producing compressive stresses in each tube by operating the inner tube hotter than the outer one is also unfeasible since the fluid inside the tube (water) is being heated by the fluid outside the tube (sodium).

Residual, passive stresses can be introduced by mechanical or thermal methods. In the thermal method one of the tubes is maintained hotter or colder than the other one during assembly of the one inside the other. If the outer tube is hotter, its inner diameter at room temperature must be slightly smaller than the outer diameter of the cold inner tube. If the inner tube is colder its room temperature outer diameter must be slightly larger than the inner diameter of the outer tube. The difference in diameter must be large enough to provide an assembly clearance. The amount of interference fit between the tubes is increased by increasing the temperature difference between the tubes during assembly.

With the mechanical method one of the tubes is strained more than the other as the one is either expanded into the other or contracted over the other (or both as in EBR-II). An interference fit is more difficult to obtain in relatively thin-walled tubes using this method because the strain distribution through both walls is nearly the same for a given internal or external pressure. In thick-walled cylinders under internal pressure the strain at the inner surface is significantly higher than that at the outer surface. The inner surface yields before the outer surface and when the pressure is relieved metal at the outer circumference still under elastic strain will shrink onto the metal at the inner circumference.

If the residual stresses compressing the mating surfaces of the two tubes are sufficiantly high the true area of contact is large enough to result in significant reductions in the thermal resistance of the interface. Most of the heat transfer occurs across contacting metal at flattened micropeaks; little of the heat transfer depends upon conduction/convection across the gap. Transverse movement at the interface becomes more resistant as the residual stresses between the two tubes increase because the friction between the two tubes increases. However, the "bond" between the two tubes is still much weaker than that of a metallurgically bonded tube; the stress required to break the mechanical bond being the product of the friction factor and the residual compressive stress, a value much lower than the ultimate shear stress of the metal.

Regardless of the method of introducing residual stresses into the tube the possibility of stress relaxation must be considered. If the design temperature chosen is below that temperature at which significant relaxation occurs, consideration must still be given to abnormal temperature increases which may occur during emergency, upset or faulted conditions in the reactor system. The stresses may relax rather rapidly over a relatively short period of time if the temperature is high enough.

2.3 Unbonded Double-Wall Tubes

A second category of double-wall tubes to be considered is unbonded double-wall tubes. There are two basic types of tubes: those with gas-filled gaps and those with metal-filled gaps. In either type, axial or circumferential loads produced on one tube will not be significantly transmitted to the other because the tubes are relatively free to slip past each other.

2.3.1 Gas-Filled Gap

A double-wall tube fabricated in air will contain small amounts of air trapped in the very narrow (0.0001 to 0.0010 inch thick) gap between the tubes. When the ends of the tube are welded into single tubesheets no more air can enter the gap. If two tubesheets are employed on each end of the tube then the air can be flushed out with helium. When the tube welded into a single tubesheet gets hot during operation, the oxygen and nitrogen (which make up most of the air) will react with the steel walls and a partial vacuum will form in the gap. The thermal resistance of the gap will increase to economically prohibitive levels. For the purpose of steam generator sizing, therefore, a gap thermal resistance has been calculated assuming the presence of a gas which remains constant and doesn't disappear due to chemical reactions. The gas normally used is helium, an inert gas possessing high thermal conductivity. Other gases were considered, however, and those will be briefly discussed before talking about helium.

2.3.1.1 Mercury Vapor

Mercury vapor may be introduced into the gap of a double-wall tube by the decomposition of a mercuric oxide coating. The coating may be applied to either of the mating surfaces of the tubes prior to bringing them into contact. Upon subsequent heating the HgO dissociates at 350°C into mercury vapor and oxygen (the small amount produced will form a very thin oxide layer which will not interfere appreciably with heat transfer). The mercury vapor has a thermal conductivity as good as air and should't attack the steel at design temperatures. Hg may form compounds with both H_2O and Na which might tend to plug up small leaks.

2.3.1.2 Nitrogen, Carbon Dioxide

Either of these gases may be introduced in the gap of a double-wall tube by the decomposition of carbonates ($FeCO_3$ at 420^oC; $PbCO_3$ at 500^oC; or $ZnCO_3$ at 360^oC) and/or nitrides (Fe_4N, CrN or Mo_2N) which are applied as coatings on one of the mating surfaces. The carbonates decompose into CO_2 and oxides (which again are small in quantity and shouldn't interfer with heat transfer) and the nitrides decompose into N_2 and metals. These gases have thermal conductivities as good as air and shouldn't attack the steel at design temperatures. Both of these gases would also react with sodium to form self-plugging compounds; however little reaction with H_2O is expected.

2.3.1.3 Hydrogen

Hydrogen possesses a thermal conductivity higher than any other gas. However, it also possesses a high diffusivity through steels at the operating temperature of the steam generator. As shown in Appendix III the hydrogen molecule (H_2) also dissociates at temperatures above 200^oC (392^oF). It therefore, is unlikely that enough hydrogen can be retained in the gap to improve the overall thermal conductivity of the double-wall tube.

2.3.1.4 Inert Gases Other Than Helium

Next to hydrogen, helium has a thermal conductivity higher than all other gases. The thermal conductivity of neon is about 30% that of helium, argon is 12%, xenon is 4% and krypton is 6%. Neon is relatively rare and although argon is more abundant its lower conductivity doesn't warrant its use.

2.3.1.5 Helium

Helium has a thermal conductivity 6 times that of air. This factor produces a decrease in the overall effective thermal conductivity of the double-wall tube by 55%. This decrease was a large enough incentive to use helium as the reference gas for gas-filled gaps. The helium may be introduced into the gap by two methods: small reservoirs of helium located in the tubesheets with direct access path to the gap (the passive system), and an active pressurization system involving either ports drilled in the tubesheets connecting external lines to individual tubes (for single tubesheet design) or a helium-filled plenum between two tubesheets with external lines to the plenum.

2.3.1.5.1 Active Helium Pressurization

If the helium pressure can be controlled then it can be increased above the sodium or even the steam pressure. This would be done in order to prevent H_2O from entering small defects. The high pressure helium may not be effective in preventing sodium from entering through small defects because the high surface tension of sodium will literally pull it through along the walls of the defect, even against the high helium pressure. This system could also possibly alleviate the effects of small amounts of H_2O which might enter through defects during the low temperature shutdown. These could subsequently expand (in a constant volume condition) and overstrain the tube walls when they are heated up above the critical temperature for H_2O ($375^{\circ}C$) in the superheater.

2.3.1.5.2 Passive Helium Pressurization

An alternative method of independently introducing helium into the gap of each tube is to provide small reservoirs of high-pressure helium in a region that is accessible to the gap of each double-wall tube. Inserts containing helium-filled microballoons are placed in an annular groove surrounding the inner tubes of the double-wall tube as it passes through the tubesheet to be seal-welded on the front face of the tubesheet, Figure 1. The inserts are made by encapsulating the glass microballoons in either a resin or urethane. Encapsulation in urethane may be required to provide flexibility during placement of the insert into the annulus. The process for encapsulating the fragile glass microballoons has been developed (@ GE-ND, St. Petersburg, Fla.) and inserts can be made containing up to 25% by volume of the microballoons. The helium is introduced into the glass microballoon by heating a mixture of empty microballoons and helium in a retort at high pressure (10 to 1000 atmospheres) to 200 to 500°C. The helium diffuses through the glass wall of the microballoon and fills it. The mixture is rapidly cooled resulting in microballoons containing the helium at the retort pressure. The helium diffuses out of the microballoons and flows from the ends of the tubes to the center as the heat exchanger is heat treated at 600 to 700°C after the tubes have been welded into the tubesheets; the insert material decomposes at these temperatures.

One disadvantage with the passive system is that retention of the Helium in the gap during the life of the steam generator may be a problem. Leakage of Helium through weld defects at the lower limit of detection with mass spectrometric devices may be excessive. Also, Na and water or steam can communicate more readily in case of leaking from both the sodium and steam sides. As previously discussed a water side leak at shutdown temperatures (200°C) may introduce water into the gap, which can subsequently pressurize the gap at the higher operating temperature of the superheater (500°C) due to expansion of the water under constant volume conditions. However, introduction of water into the gap through a 5-10 mil hole is unlikely. (Depends on Wettability of H_2O).

2.3.2 Metal-Filled Gap

The gap may be filled by either liquid or solid metal. In either case two new gaps should not be created which have high thermal resistance. The thermal resistance of these gaps can be substantially lowered in the liquid metal by insuring that it wets the adjacent surfaces of the inner and outer tubes and that the thermal expansion is large enough. With a solid metal the resistance can be lowered by selecting a metal which is thick enough so that it expands when heated more than the gap opens up when subject to the high heat flux characteristic of the steam generator tubes. If the proper thickness is selected the solid metal will fill the gap without being overstressed or without excessively interfering with either of the two tubes.

2.3.2.1 Solid Metal

Two metals which have thermal expansion co-efficients higher that of 2¼Cr-1Mo are aluminum and copper. Neither of these metals will react violently with stagnant sodium if it were to leak through the outer tube and both are inert to H_2O at the steam generator operating temperatures. A solid metal gap-filler of aluminum or copper will therefore effectively act as a barrier to the communication of sodium and H_2O if leaks in both tubes occurs simultaneously. However, stresses could be introduced in either of the tubes if the solid metal expands too much circumferenctially or radially. This potential problem might be alleviated by relieving the overexpansion with slots in the insert Al or Cu tube. Also, the gap resistance of the new gaps formed will not be as low as that of the tube surface wet with the liquid metal.

2.3.2.2 Liquid Metal

The co-efficient of thermal expansion of Pb-Bi eutectic alloy is considerably higher than 2¼Cr-1Mo steels. Consequently, Pb-Bi eutectic alloy will fill up the gap created under heat transfer conditions. Thermodynamic data indicate that neither Pb nor Bi react with water or steam at the reactor operating temperatures. Both Pb and Bi react with liquid sodium to form a high melting (1000-1100°F) intermetallic compound. Consequently, any small leak created at the outer tube will tend to be self healing. The radial stresses developed on the outer tube due to the higher expansion co-efficient of the solid metal inserts are circumvented by the use of Pb-Bi liquid eutectic in the gap. The initial gap after duplexing is expected to be minimal. Due to the good wetting behavior of liquid Pb-Bi alloy with steels, the contact resistance is expected to be negligible.

However, the compatibility of liquid Pb-Bi alloy with 2¼Cr-1Mo steels is not well established, although existing data on corrosion of carbon steels by Pb-Bi alloys show that compatibility is acceptable. Although embrittlement of steels by liquid Pb-Bi alloys has not been reported, this phenomenon needs further investigation.

3.0 TUBE FABRICATION

3.1 Review of Methods

The fabrication of individual tubes which make up the double wall tube is done by conventional methods. The quality of these tubes will therefore be the same as that of tubes used for single-wall applications. The individual tubes are brought into contact (after the smaller one is inserted into the larger one) by either of two methods; reducing the outer tube diameter by either drawing or swaging down or increasing the inner tube diameter by either hydrostatic pressurizing or pulling an oversize mandrel through the tube. These operations can be controlled in such a way as to bring the outer and inner tube into contact with varying amounts of interference. If a third solid material is inserted between the inner and outer tube any of these methods can still be used to bring all three materials in contact. If grooves are desired in the double wall tube they can be made during the drawing of the individual tubes. It may be desirable to make the grooves in the inner surface of the outer tube in order to avoid placing stress risers in the highly stressed inner tube. This can be done by pulling a mandrel (with appropriately shaped dimples on the outside) through the outer tube as a final step in the fabrication of the tube. Diffusion bonding of the two tubes can be accomplished applying high contact pressure between the inner and outer tubes at high temperature (1200-1600°F). Since this is difficult to do with drawing of long lengths of tubing it is done during the fabrication of the shorter tube hollows by a hot-extrusion process. The bonded thick-walled tube hollow remains bonded during the subsequent drawing operation. The fabrication of the double wall tube will be considered part of the fabrication of the steam generator unit. A minimum amount of cold work (5-10%) will occur during the processing of the tube (either reduction of the outer tube onto the inner tube or expansion of the inner tube into the outer tube). This amount is within the limits normally permitted for cold working without re-annealing.

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The method of insertion of the gap material depends on the type of material. Gaseous material like helium must be supplied to the gap from some sort of reservoir. This may be located either external to the tube (an active, high pressure system with some sort of passage ways to each tube) or within each tube (a passive system, e.g., helium-filled microballoons). Liquid metal materials like Pb-Bi may be applied as a solder to one of the mating surfaces of the two tubes prior to bringing them in contact, or fabricated into sections of thin-walled tubing. These sections can be inserted between the inner and outer tubes and all three tubes can then be brought into contact in the same manner as for a solid metal material like Al or Cu.

NDE of any double-wall tube would probably be some sort of heat transfer test to determine if the effective wall thermal conductivity is within design limits. Conventional eddy-current or ultrasonic techniques appear inadequate for unbonded tubes. As mentioned before only 5-10% cold work is to be introduced into either tube as they are brought into contact, no defects are expected to be produced by this.

3.2 Progress to Date

The program was directed toward providing a production lot (100 tubes) of full length, double-wall 2¼Cr-1Mo tubing for a prototype steam generator. Since the reference design was not completed the reference tubing was not defined at the beginning of the program. It was recognized, however, that the starting material for making some configuration of double-wall tubing would be required at some point in the program. A small lot (15 tubes of each of two sizes) of full length (70 feet) 2¼Cr-1Mo tubing was therefore purchased. It was fabricated in accordance with Code standard SA213-T22 with additional requirements to meet the intent of M3-33. Since this lot of tubing was not made from VAR or ESR 2¼Cr-1Mo it was decided to take advantage of the availability of ingots of this material (from which tube hollows could be made) and purchase enough to make tubing for a prototype steam generator. Two thousand pounds of each type of material were purchased and processed in a manner simmilar to that used for the CRBR steam generator tubing. It was decided during the latter portion of the program to demonstrate the feasibility of duplexing double-wall tubes with metal gap material. Short lengths (4 feet) of double-wall tubing containing solid metal (aluminium) and liquid metal (lead-alloys which are liquid at steam generator temperatures) gap materials were swaged to dimensions similar to those of the reference design. The aluminum gap material was thick enough to expand and fill the gap when a temperature gradient was imposed across the double wall thereby maintaining contact with the inner and outer tubes (see Figure 2). The lead alloy was applied to the outer surface of the inner tube prior to duplexing by a hot dipping technique, similar to that used in the production of galvanized pipe. The lead alloy uniformly filled out the gap during subsequent duplexing by swaging the coated inner tube and an outer tube (see Figure 3).

4.0 TUBE/TUBESHEET WELDING

4.1 Review of Methods

If two tubesheets are employed in the steam generator design, the weld on the inner wall of the double wall tube will be made on the water-side of the upper tubesheet using a conventional socket welding technique or in some cases can be an internal bore weld (IBW) as used in the CRBR reference steam generator design. The weld on the outer tube is an orbital weld, probably on the sodium side of the bottom tubesheet, in a manner similar to that used by W-Tampa for the SSGM, Figure 4. As discussed in a later section, no weld head vendor has equipment capable of making an orbital weld in the tight clearance specified between tubes for sodium-heated steam generators.

If one tubesheet is employed in the steam generator design two types of welds can be made on the sodium side of the tubesheet; an internal bore weld and an orbital weld (similar to that for the double tubesheet design). The inner tube would still be joined to the water side of the tubesheet with a conventional socket welding technique. The internal bore weld would actually require two welds; the first to join the outer tube to the sodium side of the tube sheet and the second to join the inner tube to a short tube inserted through the tubesheet (see Figure 5). NDE of both types of welds would probably be internal bore X-ray examination through both walls. Internal bore welding heads are available from weld head vendors for making single-wall welds; it remains to be shown whether they can be adapted to the technique required for the double-wall welds.

4.2 Tube/Tubesheet Welding-Progress to Date

The program was directed toward providing working welding equipment capable of demonstrating the feasibility of making orbital fillet welds and internal borewelds and developing the appropriate parameters to complete a number of successful simulated tube/tubesheet welds in a qualification test.

4.2.1 Orbital Welding

The orbital weld offers the potential benefit of two welds per tubesheet rather than the three associated with the internal bore weld. This reduction in the number of welds theoretically reduces the overall probability of introducing defects into the sodium/water boundary since the welds are considered sites with higher probability of undetected defects.

Initial contact with welding equipment vendors indicated that orbital weld heads were available but the relatively small clearance between tubes in the CRBR reference steam generator designs might pose a problem, Figure 6. One vendor (Astro-Arc) agreed to demonstrate that their existing weld head (used for making butt-welds in tubes) could make the orbital fillet weld on a single tube. The demonstration was successful; Figures 7a, 7b and 7c. However, they said that a major redesign of their head would be required to fit it into the small clearance between tubes (about 3/8 in.). A parallel effort was made to design an orbiting fillet weld head from scratch. A consulting engineering firm (Olympic Engineering) was contacted whose expertise had been demonstrated to GE previously in the area of precision electromechanical devices of a similar nature (including an orbiting electrode welder used to make repair welds in heat exchanger tubing for the SEFOR project). The requirements specified by GE were successfully incorporated into a finished design by maintaining close liaison between the vendor and GE.

This weld head (see Figure 8) consists of an electrode in a removable electrode holder which is positioned in a ceramic ring. The ceramic ring is made up of two halves which are clamped around the tube to be welded and pinned together. The ring is rotated by a knurled belt connected to a sprocket which is driven by a motor mounted on an adjacent tube. The power cord and cooling gas tube are partially coiled around the tube to be welded prior to welding so that during the welding cycle the semi-coiled cord and tube will unwind without hindering the drivebelt function. The feasibility of positioning and rotating this device in a real array of tubes was demonstrated on a simulation of a segment of a tubesheet containing two rows of tubes and a tube spacer, (Figure 9). In addition an estimate of the cost of fabrication of a prototype was furnished by the vendor.

A preliminary study was initiated to investigate the potential problem of insufficient penetration due to an inherently narrow electrode angle, 30° or less to the tube axis associated with this design. The code requires a minimum weld of 2/3 of the tube wall. This was achieved by ASTRO-ARC, using an electrode at 90° to the tube axis. Using a modified welder available at General Electric, successful welds were made, as shown in Figure 10 , with the electrode at 30°.

4.2.2 Internal Bore Welding

The internal bore weld offers the advantage of having been developed for the single-wall tube steam generator. The modifications necessary to adapt the welding head for use on the double-wall tube/tubesheet joint are minimal.

Vendors were requested to quote on supplying production models of weld heads capable of making both welds on the back-side (sodium-side) of the tubesheet with the electrode drive and power supply on the front side (water-side). The lowest bidder to the GE specification (ASTRO-ARC) promised to demonstrate the capability of using a modification of their production model to make welds on steel mockups provided by GE. After the contract was awarded another vendor (Hobart) also offered to demonstrate their capability on GE-supplied steel mockups.

Both vendors have demonstrated that their equipment can make full-penetration butt welds on double-wall tubing in both the horizontal and vertical positions. These demonstrations, however, were made on a relatively small number of tubes and the test parameters were not developed to the point where GE feels prepared to begin qualification welds. One feature of the internal bore weld which concerned GE was the proximity of the inner IBW to the outer tube (see Figure 5). This weld could potentially bond itself to the outer tube. Tests were conducted at GE which involved butt welding two outer tubes that were slid over an inner tube with a 0.010 inch thick refractory (Ta, Al_2O_3) backing strip. These tests showed that no bonding occurred with any of the materials used as backing strip. Tests without any backing strip (but with a 0.010 inch gap) also showed no bonding; apparently the gap provided enough thermal resistance (an oxide crucible effect) to prevent melting of the inner surface of the outer tube, Figure 11. There are, however, indications that bonding will occur across very small gaps (less than 0.003 inch thick) and further tests are required to determine an optimum thickness. Since the tube/tubesheet welds are not in a zone of high heat transfer this reduction in thickness of the inner tube wall (0.003 - 0.010 inch) could be accomodated in the design because the steam corrosion allowance is smaller in regions without heat transfer.

4.3 NDE Requirements for Tube/Tubesheet Welds

Radiographic examination by internal bore methods of the orbital weld requires radiation penetration of both the walls of the tube in addition to the fillet weld. That of the internal bore weld requires penetration of one wall after the first weld (on the sodium side) and penetration of two walls after the second weld (on the H_2O side). Acceptance standards will be similar to those normally employed.

5.0 CONCLUSION/RECOMMENDATION

All of the candidate double-wall tube concepts discussed in this report have distanct advantages and disadvantages, and no concept appears significantly superior to the others in all aspects. However, two double-wall tube types were selected as preferred concepts which appear feasible and warrant further development activities to confirm their viability in an LMFBR steam generator. The two types recommended for further study are the liquid metal insert and the active (pressurized) helium concepts.

The metal insert (Pb-Bi eutectic) material provides a barrier to the communication between water/steam and sodium. Heat transfer is not degraded due to ΔT across the wall and, therefore, the penalties in additional surface area is minimal. Inspection of the tube fo- presence of the interface material before fabrication and during service is readily accomplished using existing techniques. More importantly in terms of reliability, this concept permits each heat transfer tube to act independently and does not transmit defects. Compatibility of Pb-Bi with 2¼Cr-1Mo must be verified.

The high-pressure helium offers the hope of blocking water/steam in small defects; it can not block sodium from wetting the surface of a small defect and subsequently passing through by capillary action. The helium filled tubes will be easier to fabricate, mainly because there are fewer steps in the process. Welding techniques will be similar regardless of the gap material.

The welding technqiues described in section 4.0 were investigated in sufficient detail to permit GE to conclude that both methods are feasible. Further work is needed to confirm this (e.g., weld head prototypes, fabrication mockup and qualification tests) and to determine is one method is superior to the other in terms of cost, reliability, inspectability, repairability, etc.

Several of the principle key feature tests which should be conducted to confirm the viability of the selected double-wall tube concepts and tube-tubesheet weld methods are presented in Appendix 1. Should both double-wall tubing concepts prove to be equally feasible from both fabrication and operating standpoints, the Pb-Bi appears preferrable to the flexibility and simplicity of the design (i.e., no additional helium system). This selection is highly dependent on the steam generator design and operating goals, and must be evaluated in conjunction with a specific component design.

6.0 ACKNOWLEDGEMENTS

The author wishes to thank F.E.Tippets, C.W.Dillmann, and P.C.Miller for their guidance in defining engineering requirements for the study, and to H.J.Busboom, R.T.Hartle, R.Akbari-Kenari, and P.Roy for their assistance in the development/test of tubing and welds and preparation of portions of this document.

The cooperation of W-Tampa in providing double wall tube samples developed previously under Task 27 is appreciated.

Table I Categories of Double-wall tubes

- Double-wall tube
  - Bonded
    - Metallurgical
      - Nickel brazed
      - Nickel alloys
    - Mechanical
      - Prestressed
      - Pressurized liners
  - Unbonded
    - Gas-filled
      - Helium (Active or passive pressurization)
      - Other (H_2, N_2, CO_2, etc.)
    - Metal-filled
      - Solid (Aluminum, copper, etc.)
      - Liquid (Lead alloys)

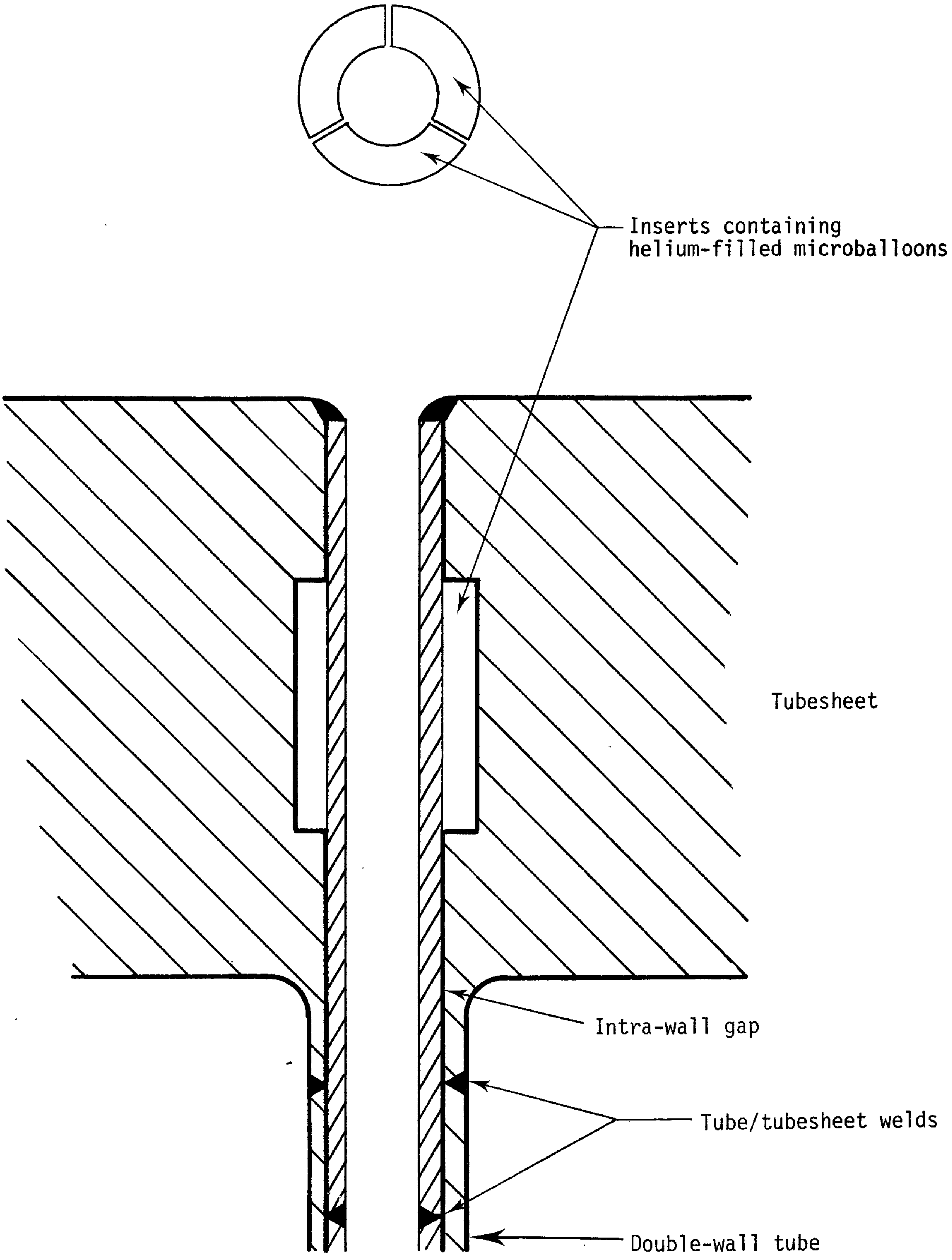


Figure 1 Helium mini-reservoir in double-wall tube/tubesheet joint

Figure 2. Double-wall tube with aluminum gap material

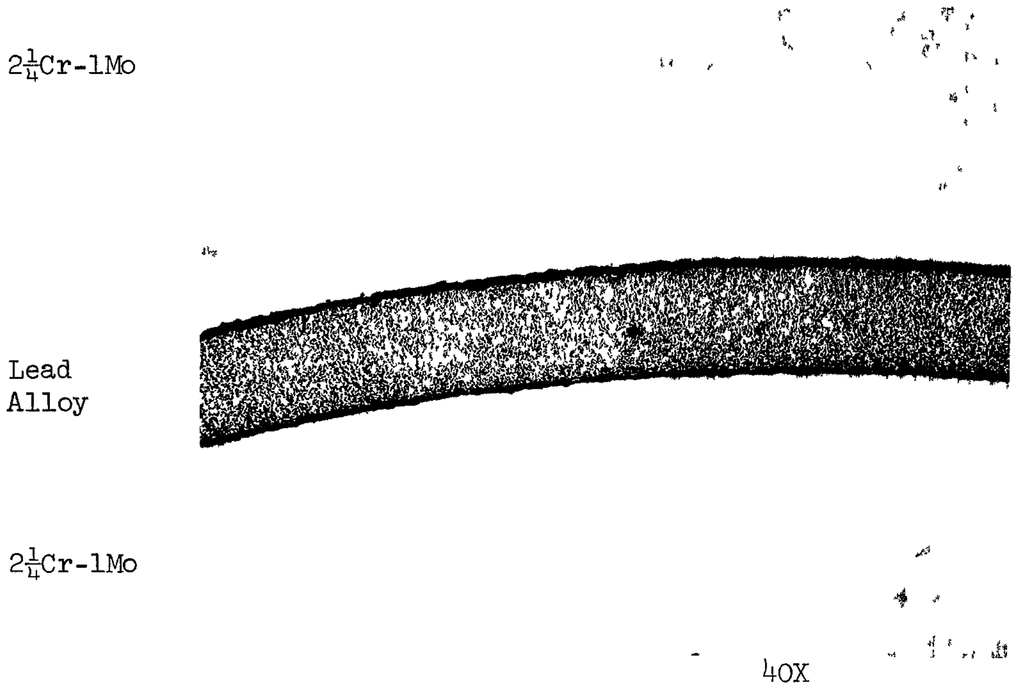


Figure 3. Double-wall tube with lead-alloy gap material

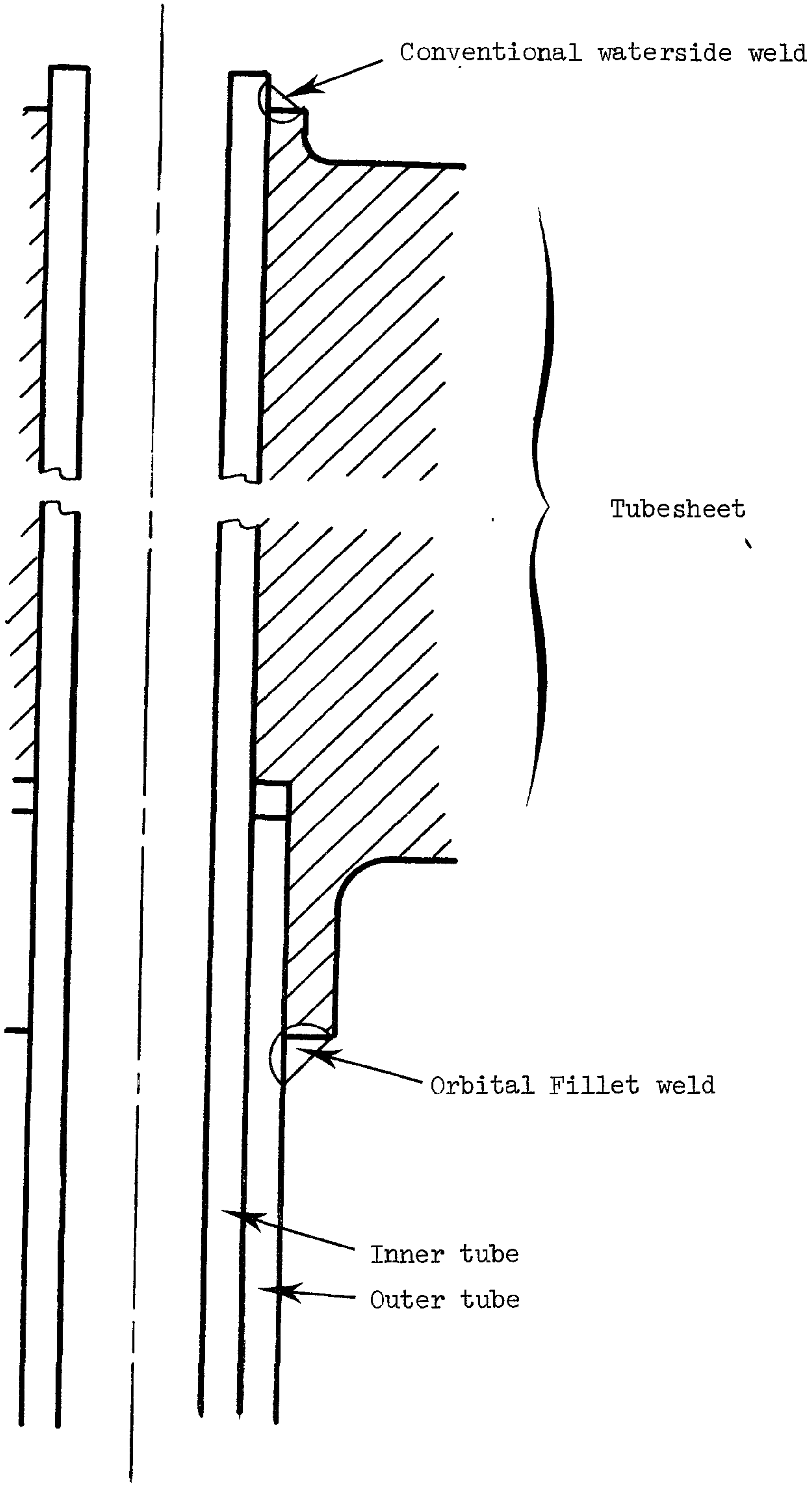


Figure 4. Orbital Weld for Double-wall tube/tubesheet joint

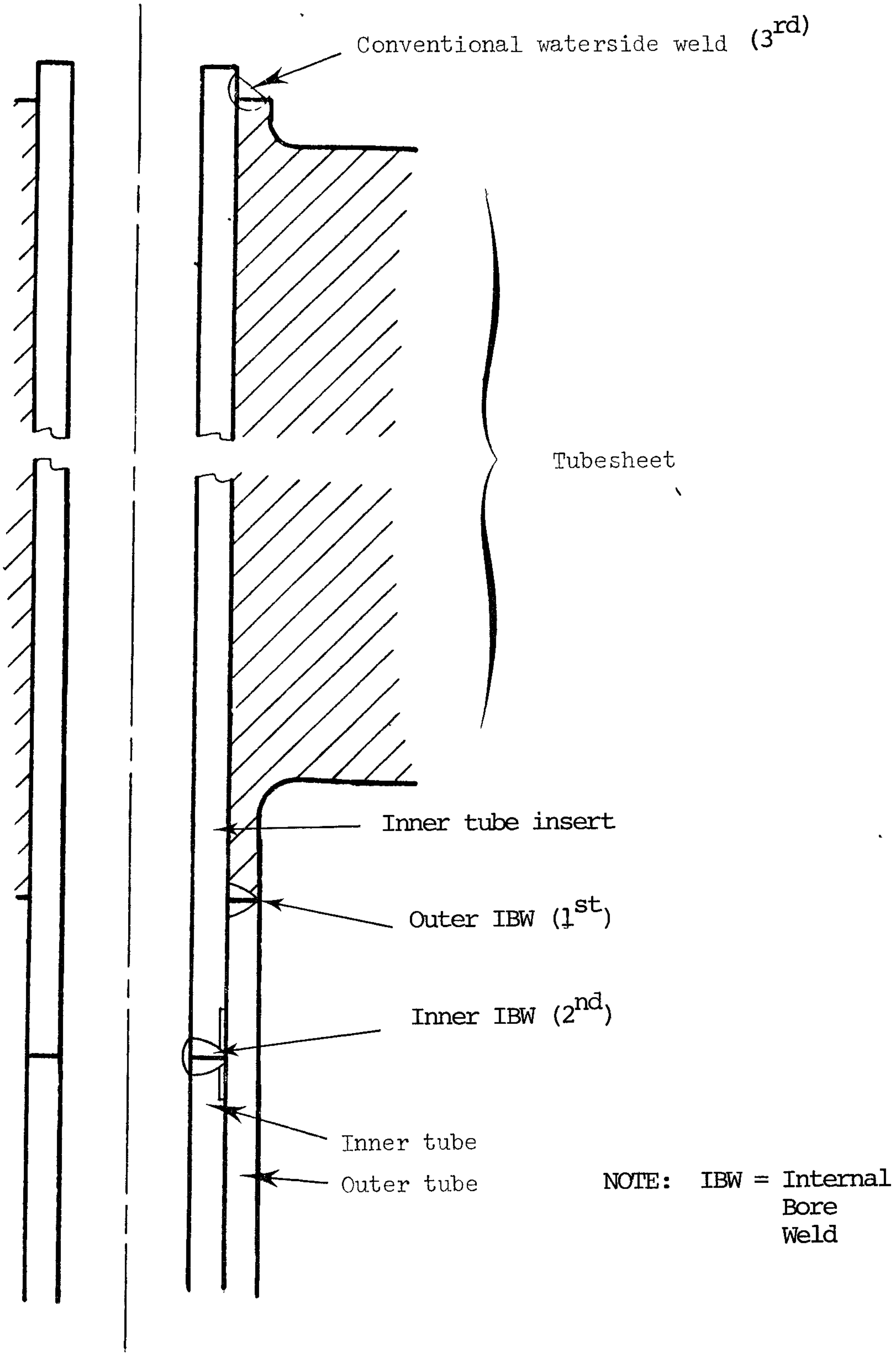


Figure 5. Internal Bore weld for Double-wall tube/tubesheet joint

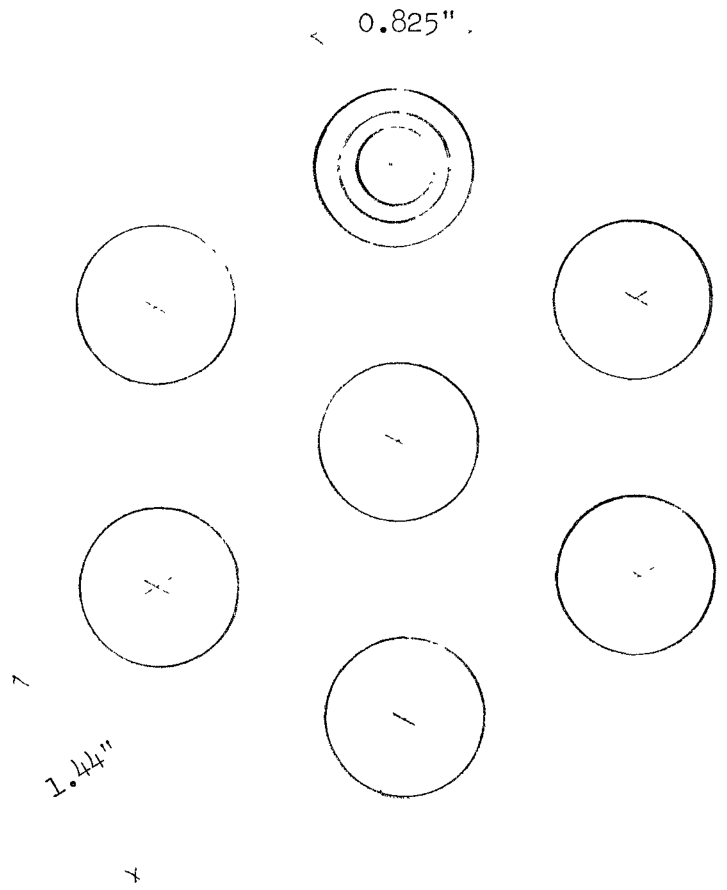


Figure 6. Tube spacing in CRBR reference steam generator

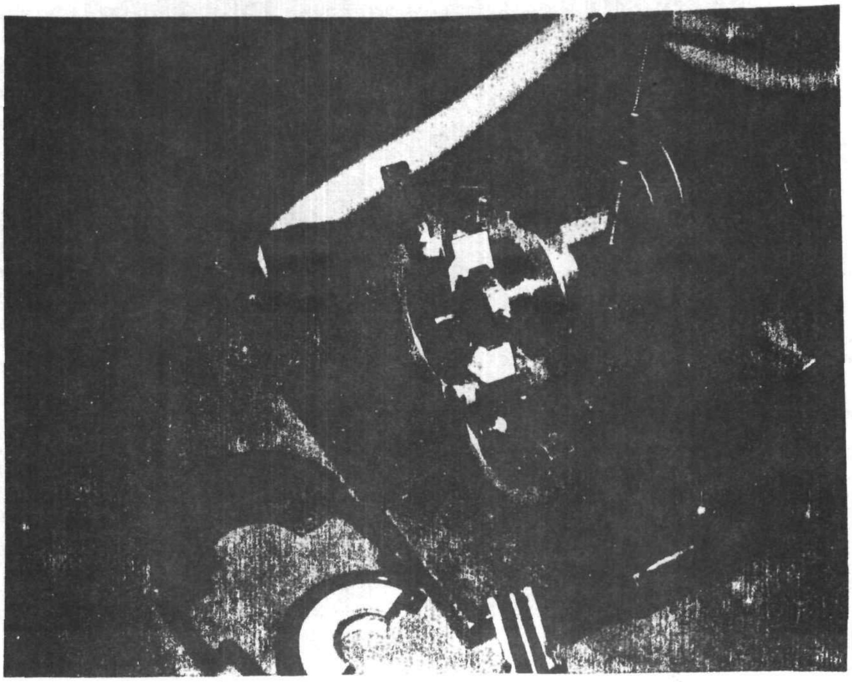


FIGURE 7(a)

Simulated Tube/Tubesheet Orbital Fillet Welding Set-up
with Astro-Arc's Welding Head

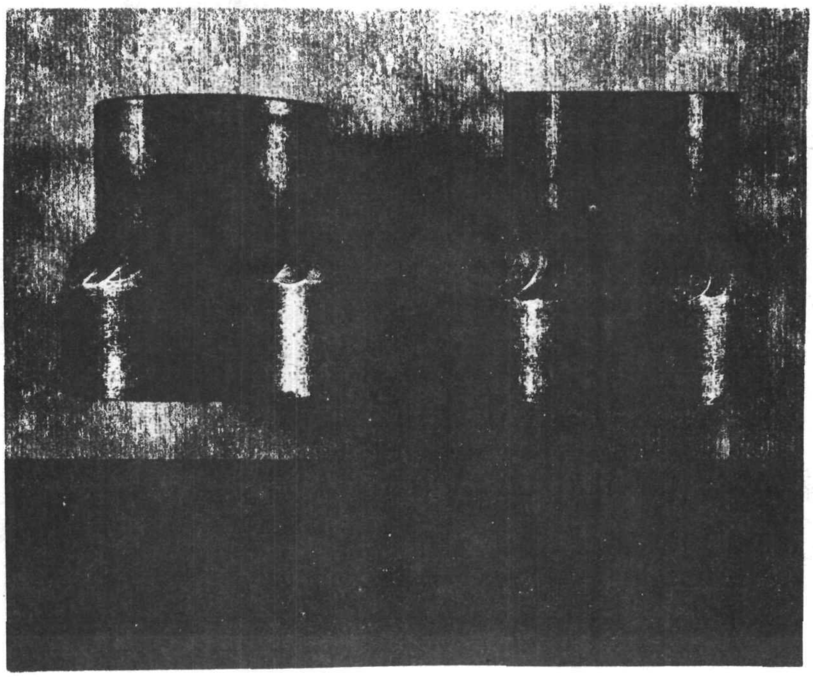


FIGURE 7(b)

Simulated Tube/Tubesheet Orbital Fillet Welds
Made with Astro-Arc's Model K-1500-2T Head

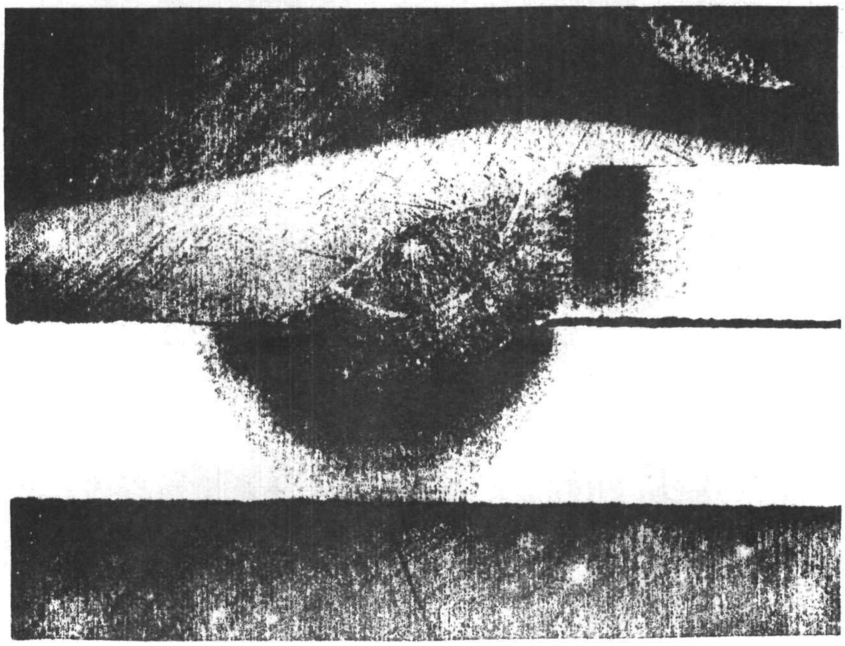


Figure 7(c) Microstructure of simulated tube/tubesheet orbital fillet welds made with Astro-Arc's Model K-1500-2T

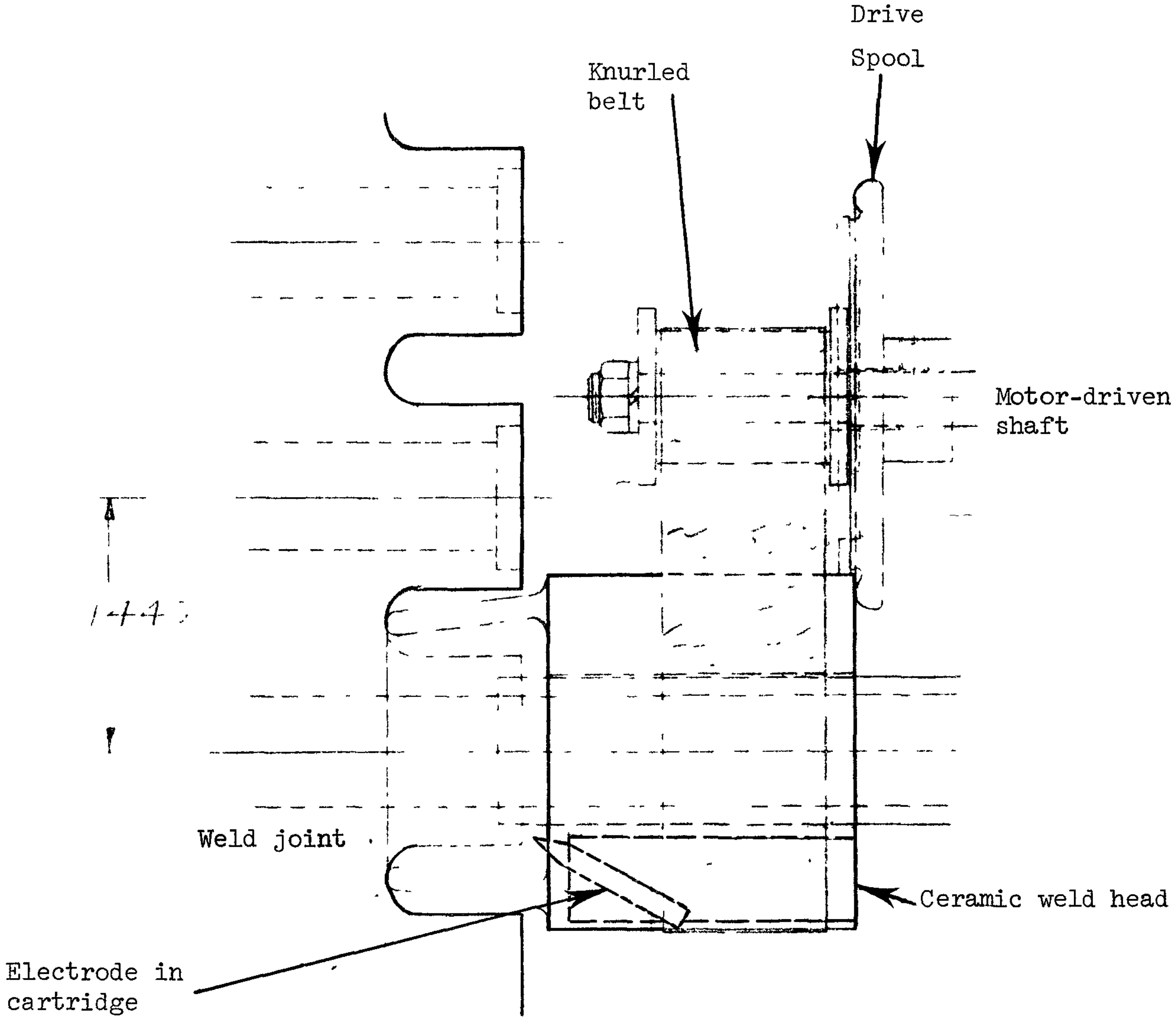


Figure 8.GE/Olympic Engineering Orbital Weld Head

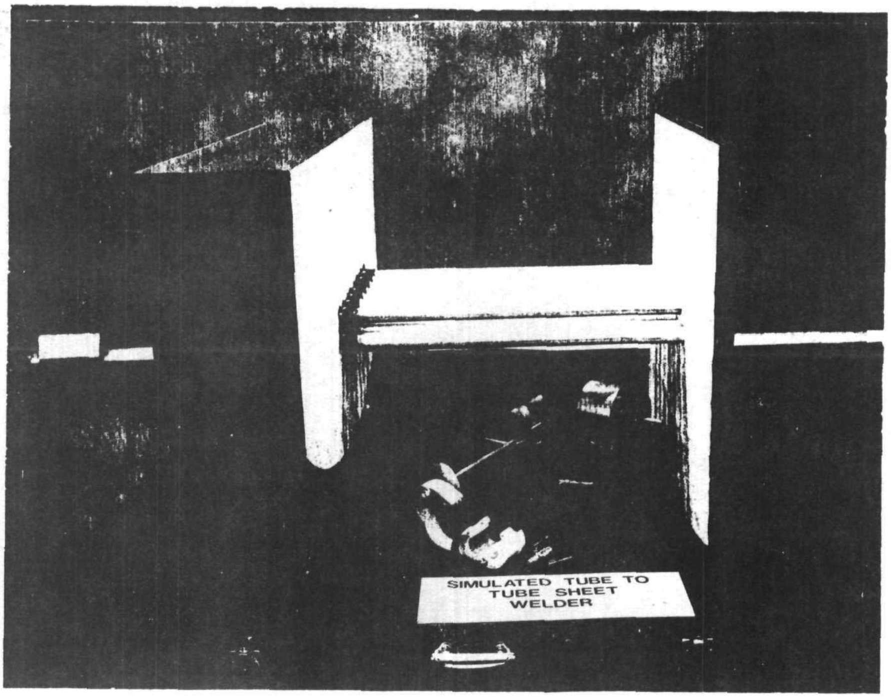


Figure 9(a) TUBE TO TUBE SHEET WELDING MOCK-UP DISPLAYED WITH PARTIAL SEGMENT OF TUBE SHEET WITH TUBES ARRAYED AS THEY WOULD BE IN A NORMAL MANUFACTURING SEQUENCE.

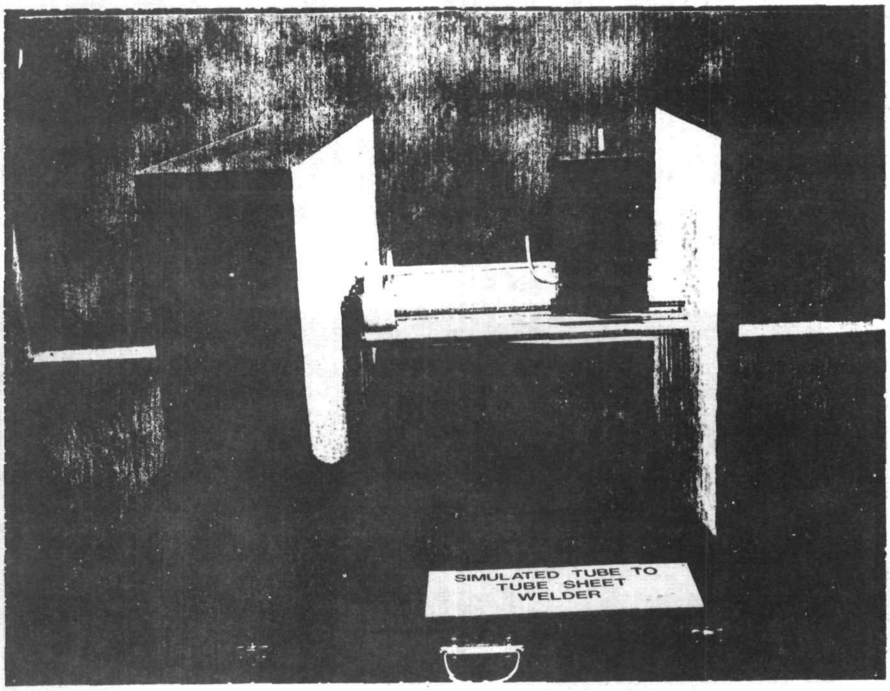
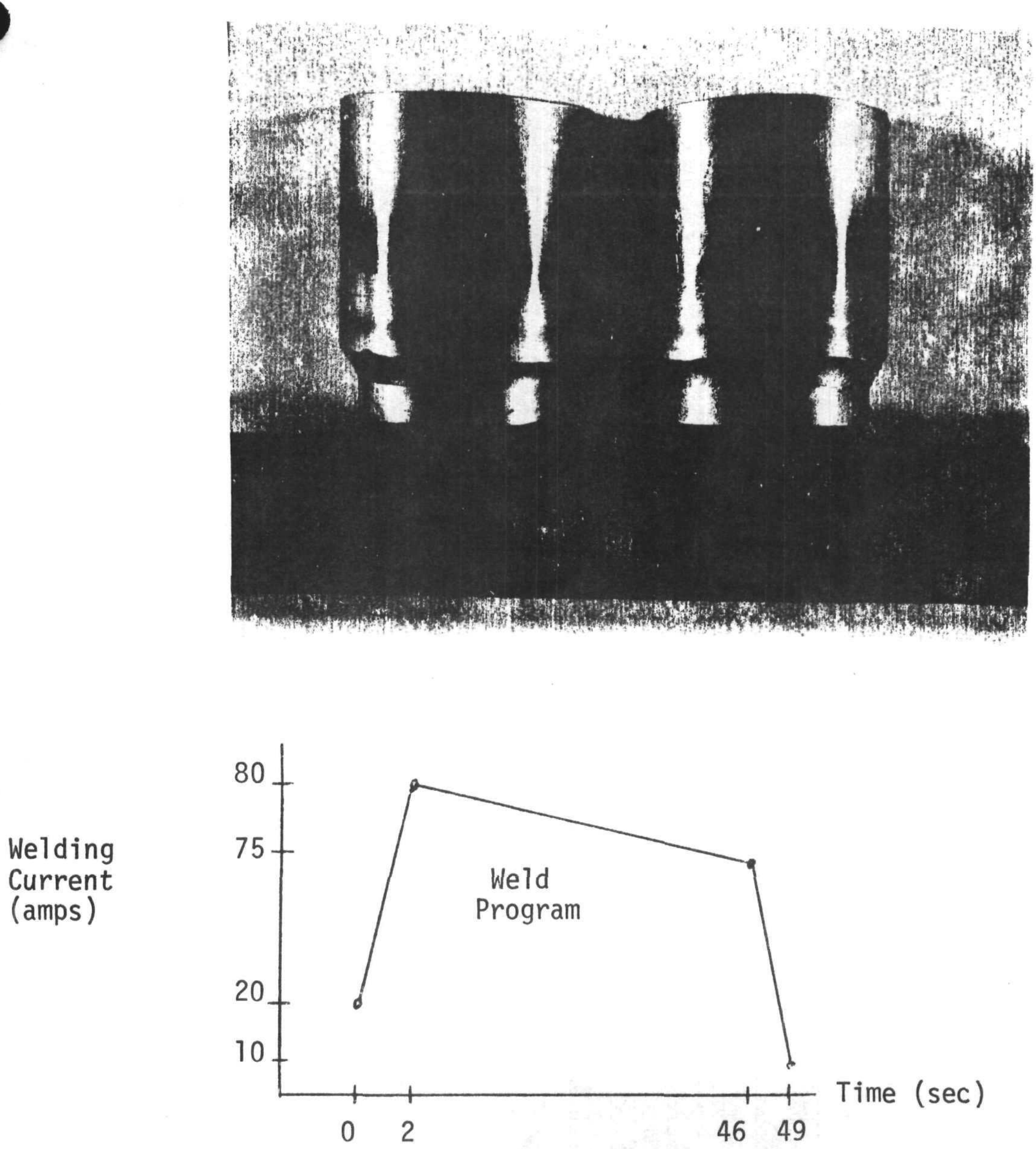


Figure 9(b) WELD HEAD DRIVE SHAFT PULLEY ENGAGED WITH WELD HEAD DRIVE BELT (LEFT) AND SUPPORTING FIXTURE CLAMPED TO TUBE TO BE WELDED. (VIEWED FROM OPERATORS SIDE OF MOCK-UP TUBE BUNDLE)



Welding Parameters:

Electrode Angle	30°
Electrode Gap	.020 in.
Electrode (W, 2% Th)	.060 in. dia.
Cover Gas	75% He/25% Ar

FIGURE 10

Simulated Tube/Tubesheet Orbital Fillet Welds
Made with an Available General Electric Welding Machine

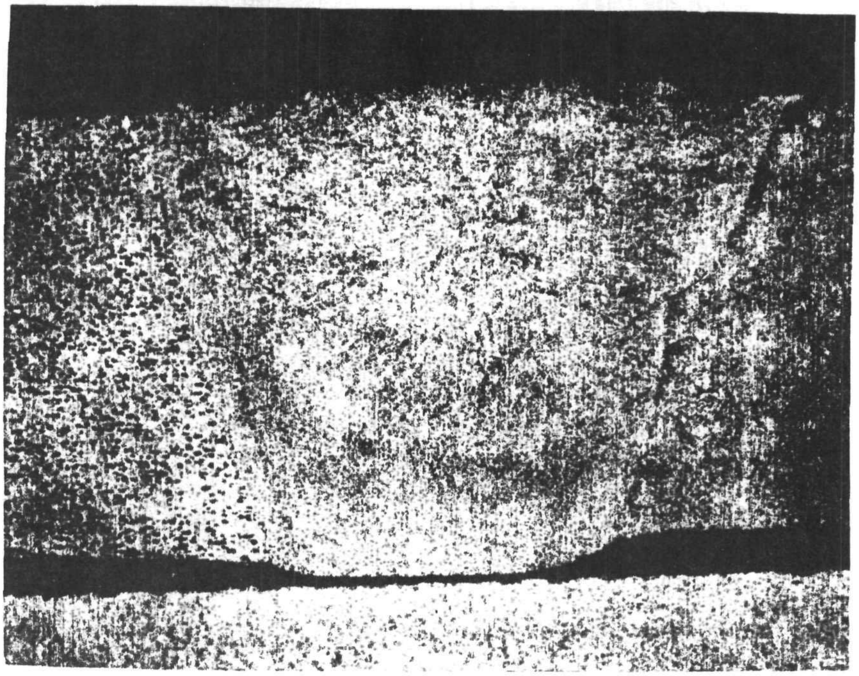


FIGURE 11

Simulated Internal Bore Tube/Tubesheet Weld Configuration Demonstrating No Burnthrough with a .010 in. Interfacial Gap

Appendix I

Proposed Key Feature Tests for Double-Wall Tubing Development

1) Pb-Bi/2¼Cr-1Mo Compatibility

Prototypic tubing samples will be stressed by pressurizing in a rig used for testing single-wall tubing. After testing at design stress levels and temperatures the samples will be sectioned for metallographic examination for intergranular attack by the Pb-Bi alloy.

2) Filling of gap near T/TS Welds

The intra-wall gap near the tube sheet will be filled after the T/TS welds are made by either expansion of the Pb-Bi during heating of a full length tube or by draining (by capillary action) a small reservoir of Pb-Bi in an annulus in the tubesheet. The test will involve heating long Pb-Bi-filled capillaries and shorter capillaries connected to Pb-Bi-filled reservoirs and determining the extent of migration of the Pb-Bi along the capillaries.

3) Fabrication of Double-Wall Tubing

Conventional techniques for applying thin (5-10 mil) coating of Pb-Bi on the outer surface of the inner tube will be demonstrated. The coated inner tube and the outer tube will then be assembled and brought into contact by some combination of sinking the outer tube into the inner tube and expanding the inner tube out against the outer tube.

4) Simplified Heat Transfer Test as an NDE Tool for Double-Wall Tubing (Details are Discussed in Appendix II)

A small heat transfer loop will be built to remove the 35,000 Btu/hr required to maintain a prototypic temperature gradient across the gap and the two walls of the double-wall tube. This heat flux will be supplied by immersion heaters placed in a liquid metal capsule surrounding the double-wall tube under test. The success of the test loop will be demonstrated by its ability to provide reproducible effective thermal conductivity values.

5) H_2O Penetration and Retention in Gap

Short lengths of double-wall tubing containing defects on the H_2O side and sodium side will be exposed and the penetration and retention of H_2O and sodium will be measured.

6) H_2O - Trapping in the Intra-Wall Gap

Short lengths (1-2 feet) of double-wall tubing, sealed at both ends containing small amounts of H_2O in the intra-wall gap will be heated to design temperatures to determine whether the expanding liquid H_2O will generate high pressures and collapse and/or expand the inner and outer tubes respectively. Tube diameters will be accurately measured before and after the test to determine the extent of damage.

7) High-Pressure Helium as a Barrier to H_2O Penetration Through Small Wall Defects

Short lengths (1-2 feet) of double-wall tubing with the intra-wall gap filled with high pressure helium (3,000 psig) and with one of the walls containing a small defect will be exposed to H_2O at 600^oF (316^oC) in an autoclave. The penetration of H_2O into the gap will be revealed either actively with a H_2O-detector on the helium pressurization system or passively by doping the H_2O with a specific ion which can be detected after the test in the gap of a disassembled double-wall tube.

8) DNB Corrosion/Fatigue of Inner Tube

Because of the larger wall thickness of the double-wall tube the thermal strains caused by unstable nucleate-to-film boiling may be different than for the single-wall tube. Following analysis fo the problem a single-tube sodium-heated evaporator will be designed to provide DNB. It will be built and tested in the existing DNB-test loop. Test parameters will be similar to those presently employed in the DNB-test loop. The test section will be destructively examined after the test.

9) In-Service Inspection of Double-Wall Tubes

An eddy-current device will be developed to detect defects in the outer tube which could arise from tube-tubesupport interaction. Efforts will be coordinated with ANL and ORNL who have made cursory investigations on double-wall ISI in the past.

Appendix II

HEAT TRANSFER TEST AS AN NDE TOOL FOR DOUBLE-WALL TUBING

INTRODUCTION

The size of a steam generator is rather sensitive to the thermal resistance of the tube wall. If the thermal resistance of the tubes is higher than the value used in the design calculation the unit will not deliver the required amount of steam. Since the thermal resistance of the double-wall tubes plays a larger role in the overall heat transfer coefficient than that of the single-wall tube the value must be known and consistent from lot to lot of tubing. The most straightforward check on the consistency of the double-wall thermal resistance can be made with a simple heat transfer test on selected sections of tubing from each lot of tubing.

Since the thermal resistance of the double-wall tube is sensitive to the tendency for the gap to open up when a temperature gradient is imposed across the two walls the test must be done under high heat flux conditions approaching those in the steam generator.

In order to exactly duplicate the sodium-heated steam generator system, sodium and water must be used as the heat transfer fluid. However, the purpose of this task is to evaluate only the gap conductivity of the steam generator tubes at the expected wall temperatures. This purpose can be achieved by transferring a known quantity of heat on the outside of the tube and removing it by heating a high temperature heat transfer fluid. For this reason and the fact that a sodium-water system is quite expensive and time-consuming to design and construct a liquid metal Therminol 66 system is designed.

TEST DESCRIPTION

A sketch of the proposed test is shown in Figure 1. It consists of a test section, a venturi, a cooler, a pump, and a storage tank. The tubing is 1 in. diameter and connected with swagelok fittings.

The test section is composed of an insulated housing containing the Pb-Bi liquid metal, mixers, heaters, and the duplex tube. The mixers will maintain a uniform liquid metal temperature. The heat generated from the heaters will convect naturally and uniformly to the outside of the duplex tube. The heat will be removed from the tube by the Therminal fluid flowing inside of the duplex tube.

The inside and outside wall temperature of the duplex tube will be measured by means of the thermocouples. The test section is designed so that the duplex tube can easily be removed without cutting the lines or breaking any weld.

THEORETICAL DISCUSSION

The following nomenclature defines the symbols used in this section:

A_o - Tube outside area, ft^2
Cp - Specific heat of fluid, BTU/lb - °F
D - Diameter, ft.
h - Inside tube convective heat transfer coefficient, BTU/hr-ft^2-°F
K - Thermal conductivity, BTU/hr-ft.-°F
L - Tube length, ft.
m - Mass flowrate, lb/hr
Q - Rate of heat flow, BTU/hr
r - Radius, ft.
R - Thermal resistance, hr-ft^2-F/BTU
T - Temperature, °F

$\overline{\Delta T_L}$ - Logarithmic mean temperature difference, °F

U_o - Overall heat transfer coefficient based on the outside tube area, Btu/hr-ft^2-°F

υ - Fluid velocity, ft/sec

Greek Symbols

μ - Fluid viscosity lbm/ft-sec
ρ - Fluid density lbm/ft^3

The shell and tube arrangement used as the model for all the equations is shown in Figure 2-2.

TABLE 1

INPUT AND OUTPUT OF THE COMPUTER PROGRAM USED IN THE LOOP DESIGN

Duplex tube ID = 0.435 inch

Duplex tube OD = 0.825 inch

Heat Exchanger Length = 2 ft

Shell Fluid Temp. = 900°F

Tube Fluid Inlet Temp. = 300°F

Tube Fluid Outlet Temp. = 359°F

Tube Side Reynolds Number = 23,090

Tube Flow = 4.5 gpm

Duplex Tube ID Temp. = 709°F

Duplex Tube OD Temp. = 900°F

Average Tube Side Resistance = 0.003 hr-ft^2-°F/BTU

Average Wall Resistance = 0.001

Heat Transfer in the Test Section = 58,379 BTU/hr = 17.1 kilowatts

The energy balance on the test section is:

$$Q = M_c \; C_{p_c} \; (T_{c\ out} - T_{c\ in}) \tag{1}$$

The subscript c refers to the cold fluid. The hot fluid, liquid Pb-Bi, is stationary and at constant temperature.

The rate of heat transfer between the two fluids in terms of heat transfer coefficients can be written as:

$$Q = \frac{\pi D_4 L \; \overline{\Delta T_L}}{\frac{D_4}{D_1 h_i} + \frac{D_4 \ln (D_2/D_1)}{2K_1} + \frac{D_4 \ln (D_3/D_2)}{2K_g} + \frac{D_4 \ln(D_4/D_3)}{2K_2}} = U_o A_o \quad \overline{\Delta T_L} \tag{2}$$

h_i can be found from a modification of Sieder and Tate equation suggested by the heat transfer fluid manufacturer:

$$h_i = 0.022 \; \frac{K}{D/12} \; \left(\frac{\rho \upsilon D}{\mu}\right)_b^{0.3} \; \left(\frac{C_p \mu}{K}\right)^{0.4} \; \left(\frac{\mu b}{\mu_w}\right)^{0.16} \tag{3}$$

The subscript b refers to bulk fluid temperature and w to the tube wall temperature. Substituting the known values and the values from equation (1) and (3) into equation (2), the gap conducitivity Kg will be determined. From equation (2):

$$U_o = \frac{1}{\frac{D_4}{D_1 h_i} + \frac{D_4 \text{ In } (D_2/D_3)}{2K_1} + \frac{D_4 \text{ In } (D_3/D_2)}{2K_g} + \frac{D_4 \text{ In } (D_4/D_3)}{2K_2}} \tag{4}$$

$$= \frac{1}{R_1 + R_2 + R_3 + R_4}$$

From equation (4) the gap resistance R_3 is found.

LOOP DESIGN

In order to facilitate the calculations for the loop design, a computer program has been prepared in the BASIC language. A copy of this program is attached to this report. The tube inlet temperature and the constant outside tube temperature are given; from these the outlet temperatures are found by trial and error calculations. Using this program, a series of runs with various parameters were made. A run with the average tube I.D. and O.D. temperature difference of 191°F appeared to be the optimum design and was used as the design basis. The result of this run is shown in Table 1.

COMPUTER PROGRAM FOR THE LOOP DESIGN

```
10 READ T3, L, R5, T7
12 FOR M1 = 2000 TO 8000 STEP 500
20 T4 = 315
30 PRINT T3,L,R5,T7
32 PRINT
34 PRINT T4,M1
40 PRINT
50 T5 = (T3+T4)/2
60 C1 = 0.0005*T5+0.33
70 R1 = (-0.0005*T5+1.06)*62.43
80 V1 = 5468049.776/(T5↑2.484062)
90 K1 = -0.000016*T5+0.0717
100 F1 = (M1/(R1*60))*7.48
110 Q = (M1*C1)*(T4-T3)
120 PRINT T4,T5,C1,R1
130 PRINT
140 PRINT V1,K1,F1,Q
150 PRINT
160 D1 = 0.435
170 D2 = 0.825
180 V3 = M1/(3600*R1*(3.1416/4)*(D1/12)↑2)
190 N1 = 4*M1/(3.1416*(D1/12)*V1)
200 P1 = (C1*V1)/K1
210 K5 = ((0.875/(12*2))*LOG(0.875/0.571))/R5
220 T8 = T7-Q*LOG(D2/D1)/(2*3.1416*K5*L)
230 V8 = 5468049.776/(T8↑2.484062)
240 H1 = 0.022*(K1*12/D1)*(N1↑0.8)*(P1↑0.4)*((V1/V8)↑0.16)
250 R4 = D2/(D1*H1)
260 PRINT V3, N1, P1, K5
270 PRINT
280 PRINT T8, V8, H1, R4
290 PRINT
300 U0 = 1/(R5+R4)
310 L1 = ((T7-T3)-(T7-T4))/(LOG((T7-T3)/(T7-T4)))
320 Q1 = U0*3.1416*(D2/12)*L*L1
330 L4 = Q1/(M1*C1)+T3
340 PRINT U0,L1,Q1,L4
350 PRINT
360 PRINT
370 PRINT
380 IF ABS (T4-L4)<=0.1 THEN 410
390 T4=L4
400 GO TO 30
410 NEXT M1
420 DATA 300,2,0.001,900
430 END
```

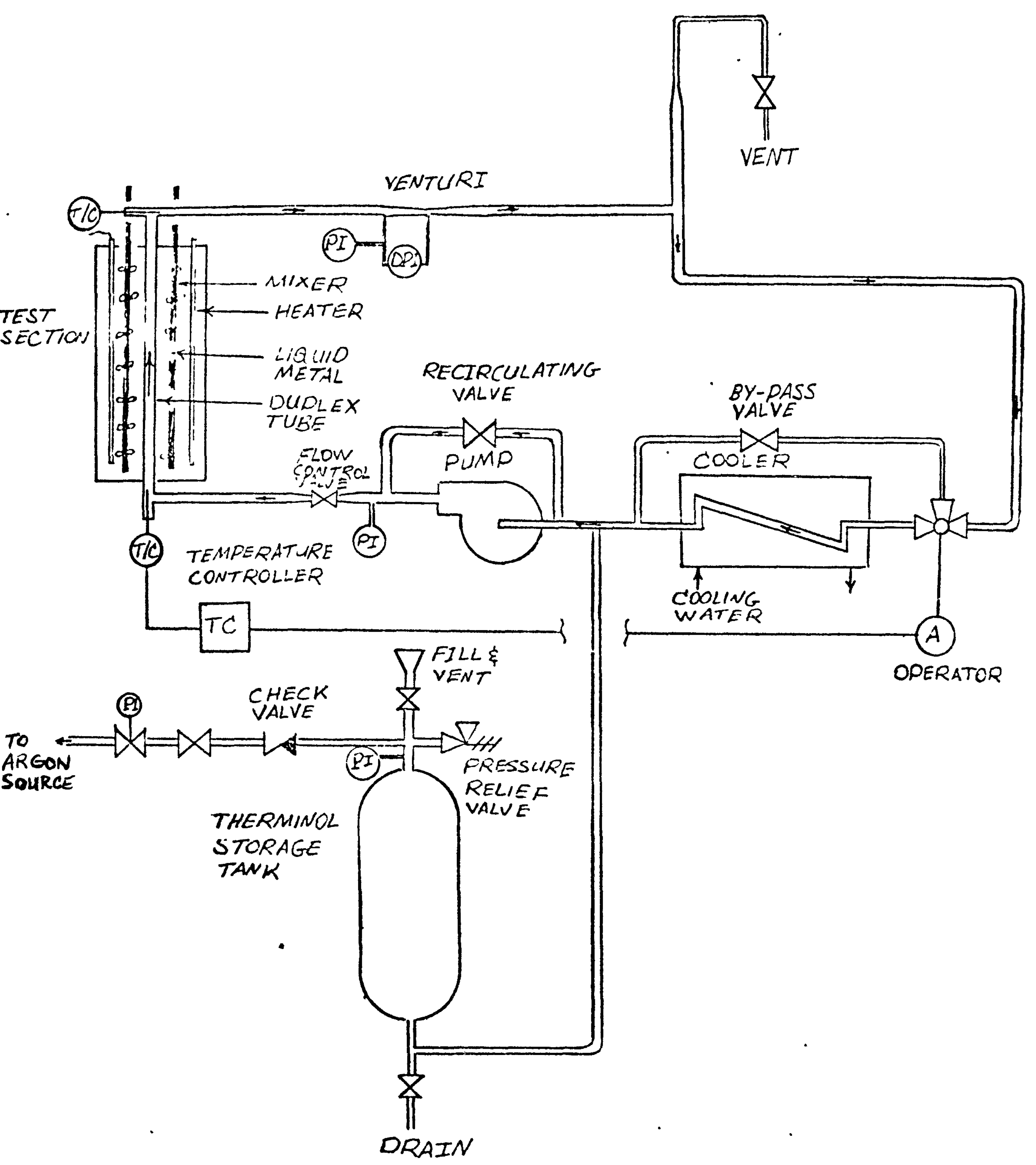


FIGURE 2-1 HEAT TRANSFER FLOW SYSTEM

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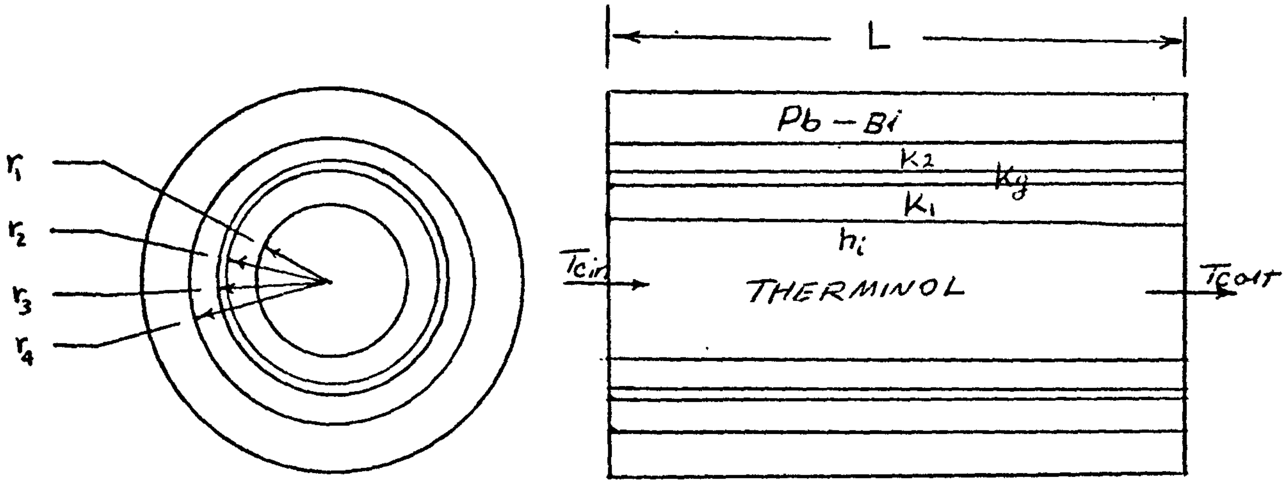

Figure 2-2 Duplex Tube and Shell Arrangement

APPENDIX III

HYDROGEN PENETRATION IN DUPLEX TUBE

INTRODUCTION

The phenomenon of hydrogen pressure buildup in the gap between two tubes was demonstrated by E. A. Wright and H. E. Honkala.* They have shown that when a brass rod was press-fitted inside a steel tube and exposed to water saturated with hydrogen sulfide, hydrogen will buildup in the gap between the two metals. Hydrogen sulfide reacts with the steel according to the following chemical reaction:

$$Fe + H_2S \rightarrow FeS + 2H$$

It is believed that a portion of the atomic hydrogen permeates through the steel wall and when a discontinuity occurs at the gap between the two metals it combines to form the hydrogen molecule. The permeation rate of molecular hydrogen is much slower than that of the atomic hydrogen, consequently, the hydrogen pressure builds up in the gap.

A similar hydrogen-generating chemical reaction occurs in the steam generating system of the nuclear reactors:

$$3Fe + 4H_2O \rightarrow Fe_3O4 + 8H$$

The atomic hydrogen will permeate through the inner tube - the water side of the duplex tube and combine to form molecular hydrogen in the gap of the duplex tube. However, theoretical analysis shows that at the temperatures of the boiler and superheater (300 - 500°C, 572 - 932°F), the molecular hydrogen will dissociate to an atomic form at a rate considerably faster than that of the corrosion rate and permeates back to the water or sodium side. This will prevent the hydrogen from building up in the gap. Therefore, it appears that the hydrogen accumulation only occurs at lower temperatures.

---

*A paper presented at the Thirteenth Annual Conference, National Association of Corrosion Engineers, St. Louis, Missouri, March 11-15, 1957.

The following experiments were conducted to verify: (1) the hydrogen buildup in the duplex tube at the lower temperatures, and (2) the hydrogen dissociation at the higher temperatures.

EXPERIMENTAL PROCEDURE

1. Hydrogen Buildup

A pressure transducer, contacting the gap between the two tubes was welded to the outside of a 19 inch (48.26 cm) long duplex tube (See Figure 1). The inside and outside diameter of the tube were 0.435 inch (1.105 cm) and 0.825 inch (2.096 cm), respectively.

The test assembly is shown in Figures 2. Hydrogen sulfide was bubbled into a glass beaker containing the duplex tube and thermometer. Later in the test a heating tape was attached to the outside of the glass jar to maintain a uniform temperature throughout the day, because of the large temperature difference between the hot days and colder nights.

2. Hydrogen Dissociation

In this test the duplex tube was initially leak checked and then charged with hydrogen to a pressure of 2000 psig (13.79×10^6 pa gage). The tube was then inserted into a furnace and maintained at a constant testing temperature. The pressure decrease with time was then recorded.

The volume associated with the hydrogen buildup test was very small. It consisted of the duplex tube gap and the very small space between the tube and the pressure transducer. On the other hand, the metal volume of the hydrogen dissociation test was quite large, 22.7 cm^3, consisting of the duplex tube gap, some 1/8 inch (0.3175 cm) tubing and a large pressure gage.

RESULT

The buildup rate varied appreciably with different corrosive environments and the exposure temperatures. The results are shown in Figures 3. For water saturated with H_2S and the temperature maintained between (32.2 - 37.8°C, 90 - 100°F) a pressure buildup rate of 9.2 psi/hr (6.34×10^4 pa/hr) was achieved. When 2.5 percent hydrochloric and 1 percent sulfuric acid was added to the water that was continuously saturated with H_2S the buildup rate was increased to 370 psi/hr (2.55 x 10^6 pa/hr). Due to severe corrosion of the duplex tube in the acid environment a leak was developed and the test was discontinued.

The hydrogen association and permeation as a function of time at temperatures of 400°F (204°C), 500°F (260°C), and 600°F (316°C) is plotted in Figures 4 and 5.

The curves in Figures 4 and 5 are interchangeable, one showing the rate of hydrogen pressure decrease and the other the rate of hydrogen mole decrease as a function of temperature. It is seen that the dissociation rate increases rapidly with temperature.

CONCLUSION

The phenomenon of hydrogen buildup in the gap of the duplex tube was demonstrated. The buildup rate was found to be proportional to the rate of tube corrosion and the gap volume. The buildup, however, occurs at lower temperatures. Above a certain temperature, which is estimated to be 350°F (177°C), the hydrogen begins to dissociate and permeate out of the gap. Above this temperature the permeation rate appears to be much faster than that of the buildup rate.

The highest degree of corrosion for steam generating tubes is estimated at 1.5 mil/yr (0.0038 mm/yr). The hydrogen generated at this corrosion rate is 1.67 x 10^{-4} lb mole/yr (0.757 x 10^{-4} kg mole/yr). Assuming all the hydrogen is diffused through the tube and comparing this quantity with hydrogen dissociation rate of Figure 5 it appears that there will be no hydrogen buildup problem in the gap of the duplex tube at temperatures above 400°F. At conditions of lower temperature such as wet layup, storage, hydrotest, etc. where corrosion may be occuring, it is still uncertain whether hydrogen buildup will be a problem.

RECOMMENDATION

It was not intended to obtain accurate quantitative results in these tests. The volume for dissociation rate, Figures 4 and 5, is known to be 22.6 cm^3. But the volume for buildup rate, Figure 3, was very small and difficult to measure. Although as a result of these tests, one can intuitively conclude that at the operating temperature of the steam generator system hydrogen will not buildup in the gap, the dissociation and buildup rate is not accurately known. Therefore, it is recommended that a test be made at the steam generating system conditions to assure that this problem does not exist. In addition, it is recommended that hydrogen buildup tests be performed on duplex tubes under low temperature (∿400°F) conditions involving possible corrosion (such as wet layup, storage, hydrotest, etc.).

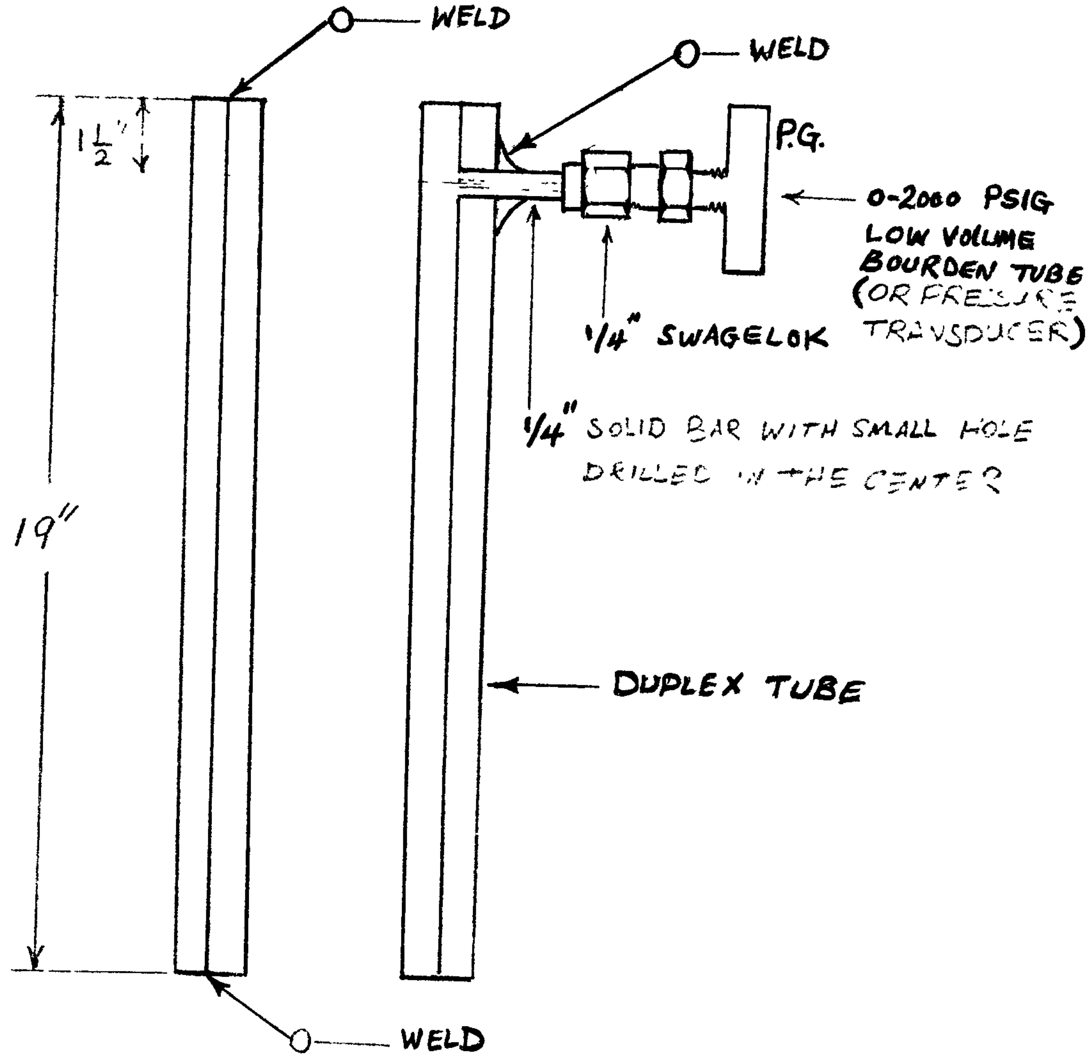

FIGURE 3-1 DUPLEX TUBE - PRESSURE GAGE ASSEMBLY

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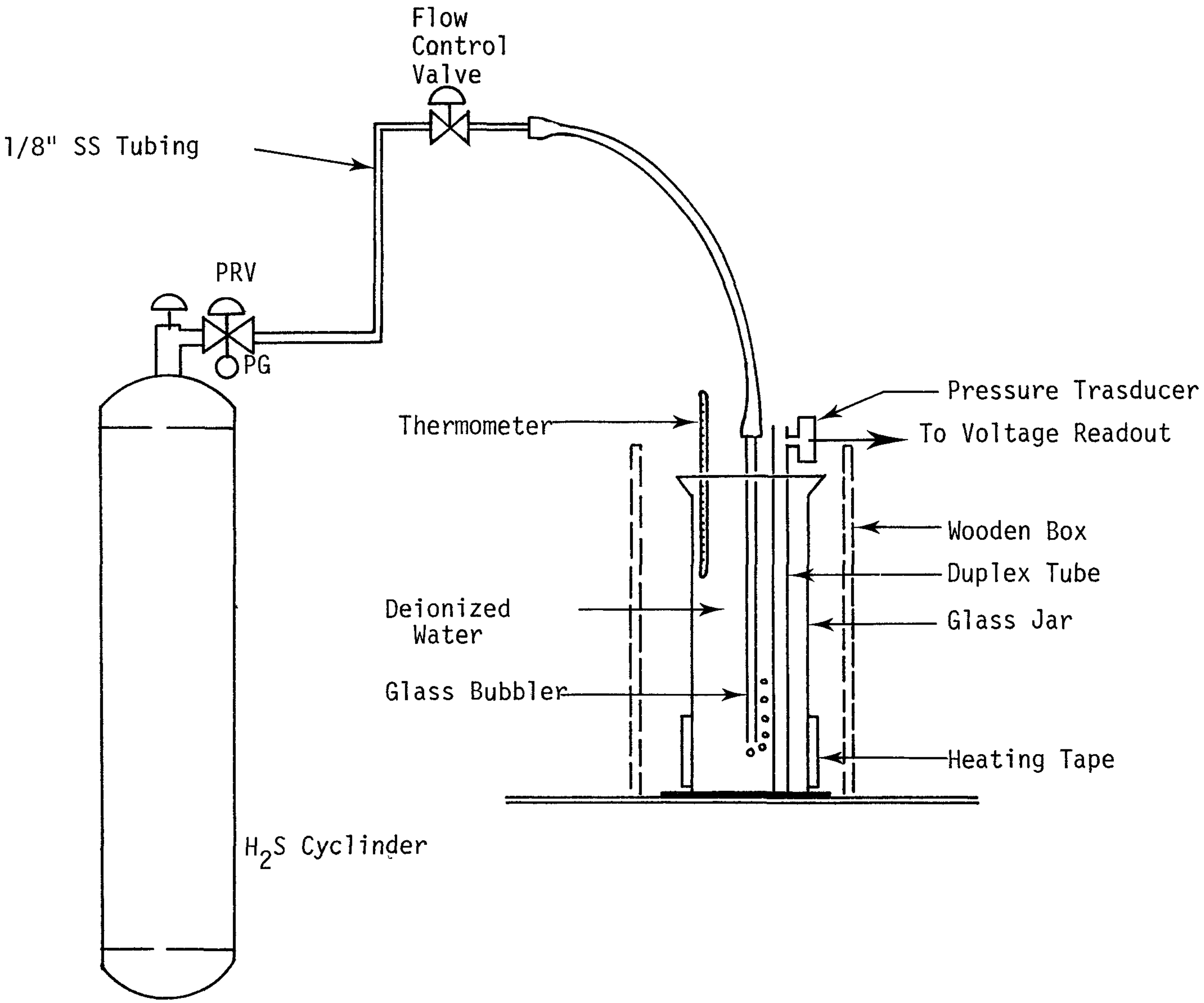

Figure 3-2 Duplex Tube H_2 Penetration Test Assembly

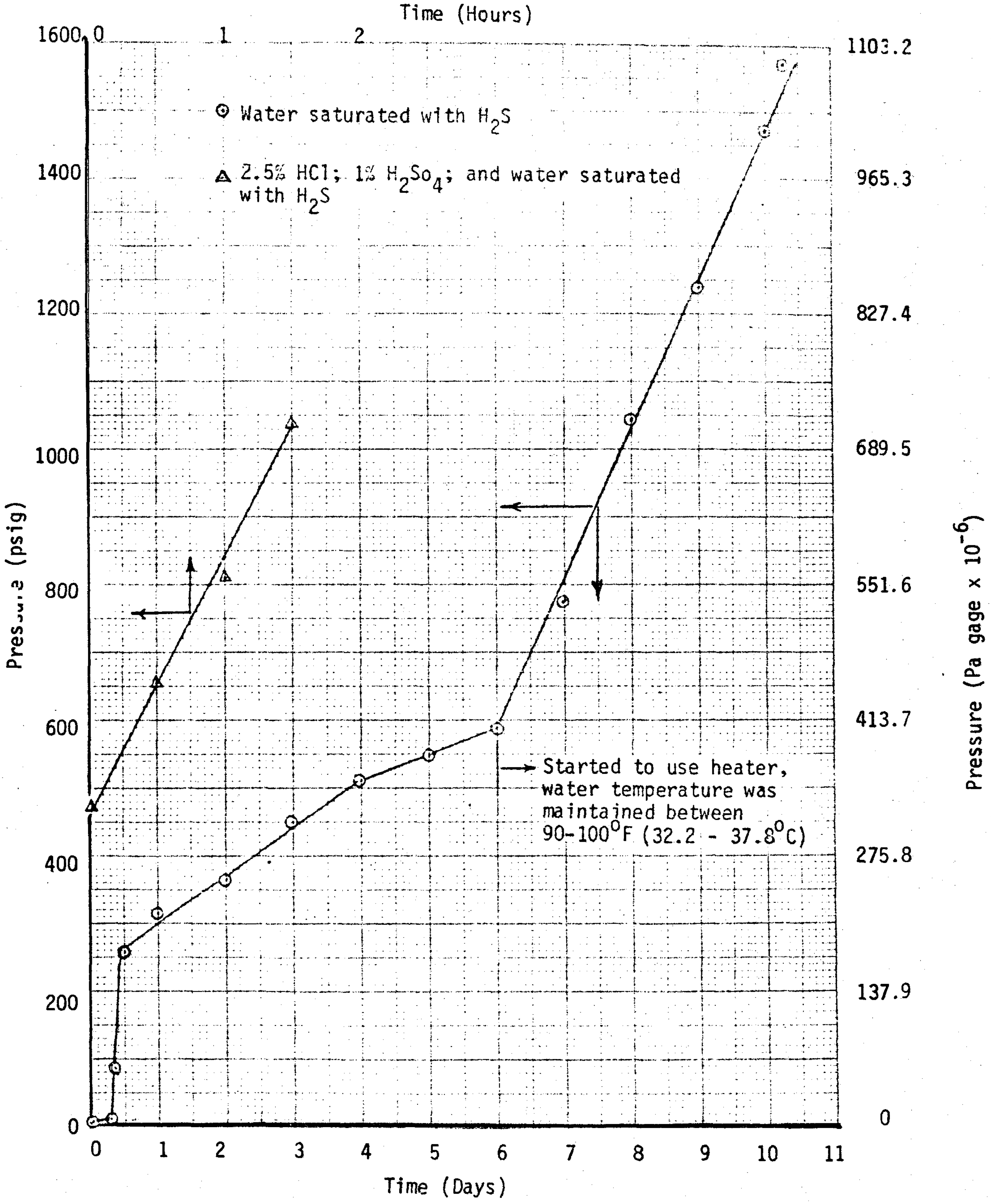

Figure 3-3 Hydrogen Pressure Build-Up for 2¼Cr-1Mo Duplex Tube RAK 8/28/75

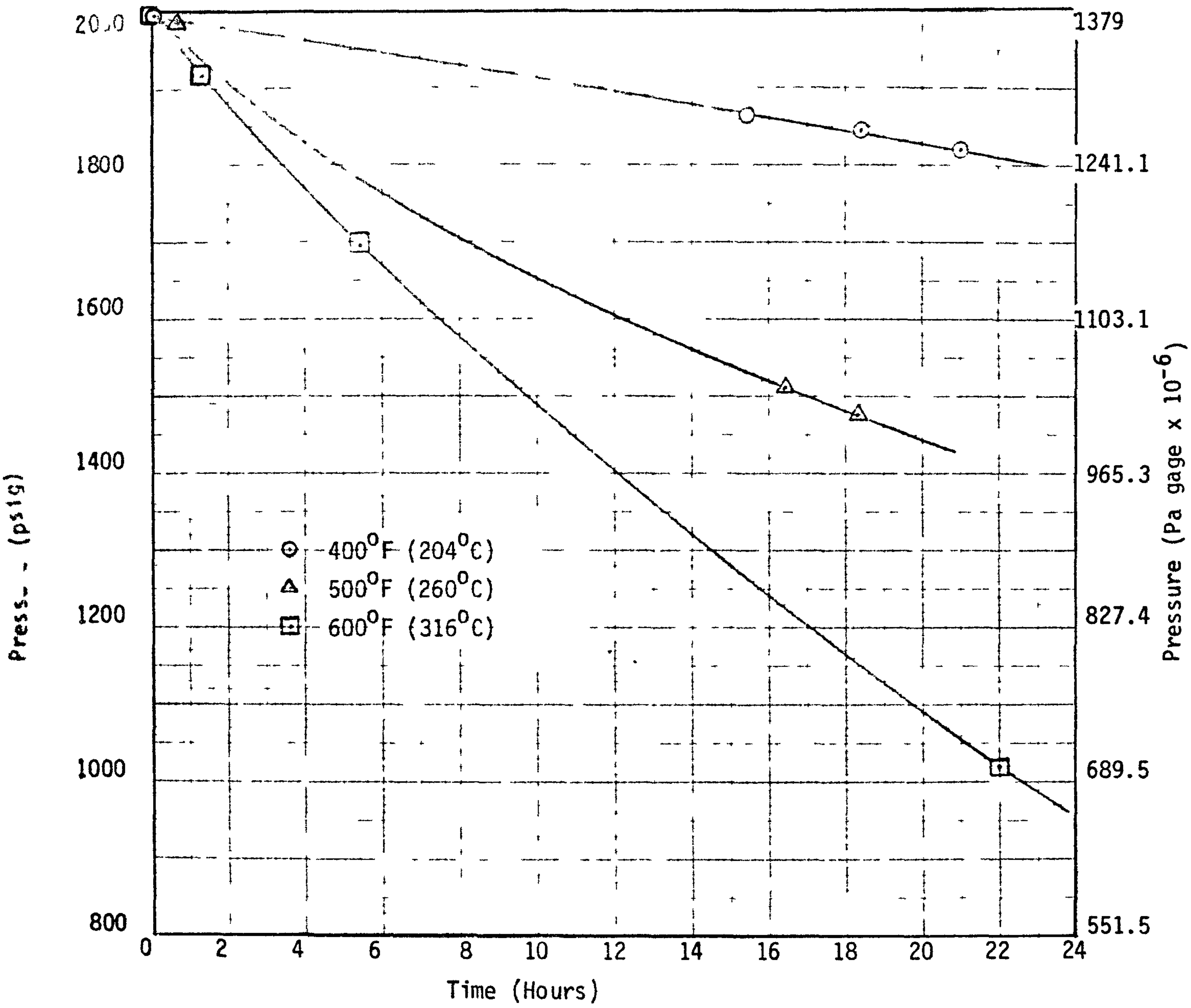

Figure 3-4 Hydrogen Dissociation at Various Temperatures (pressure vs. time)

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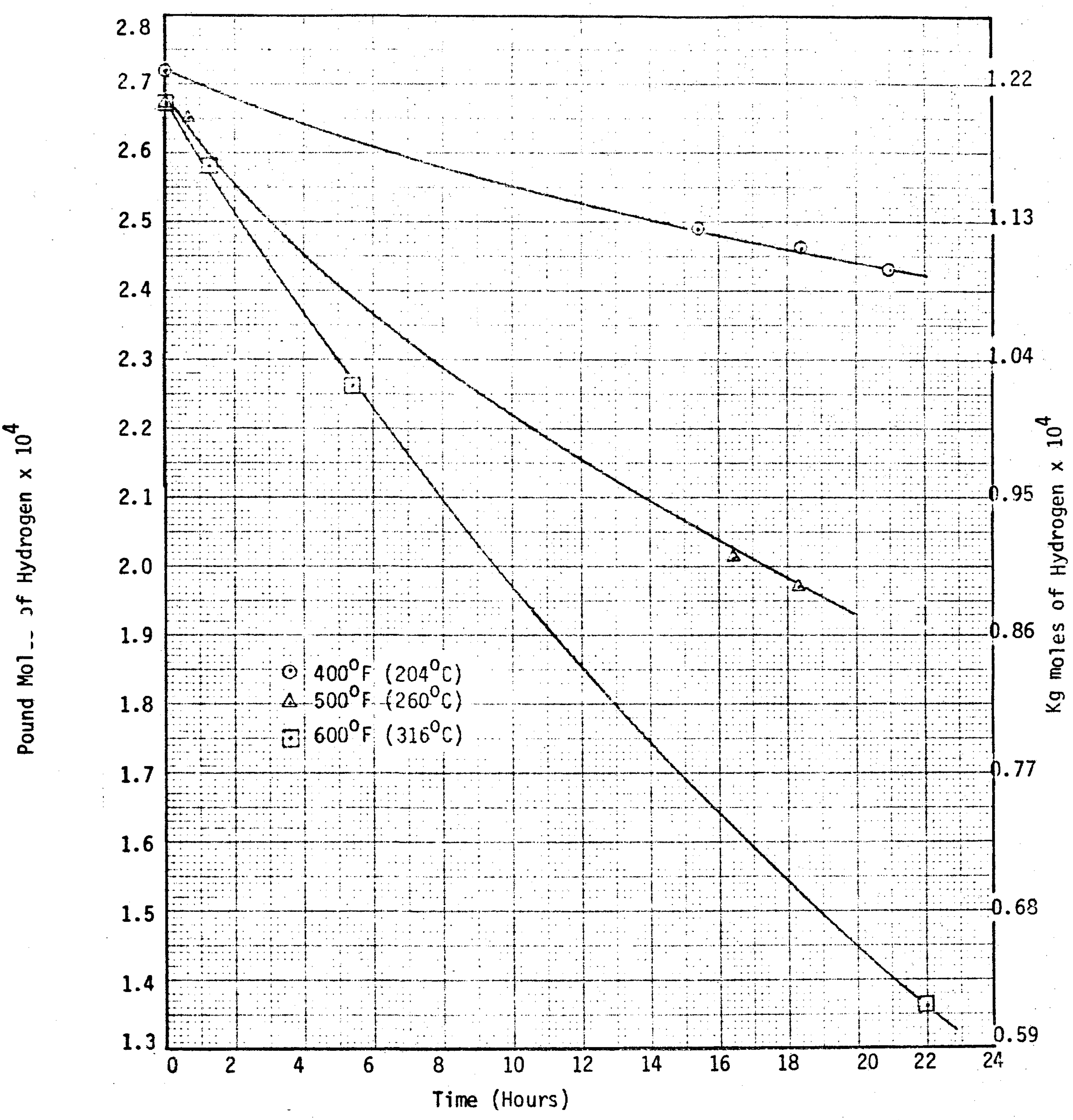

Figure 3-5 Hydrogen Dissociation at Various Temperatures (moles vs. time)

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