THE UNIVERSITY OF MICHIGAN

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THE EFFECT OF THERMAL CYCLING TO 350°F AND 600°F ON THE HEAT TRANSFER PERFORMANCE OF INTEGRAL FINNED DUPLEX TUBES

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INTRODUCTION

Duplex helical-finned tubes such as shown in Figure 1 have found wide usage in a variety of heat transfer applications. These tubes are generally fabricated with aluminum fins and utilize corrosion resistant liners, such as copper, admiralty brass, steel, stainless steel, cupro-nickel, etc. The metallic contact inherent in bi-metal tubes is not perfect and may cause a significant additional resistance to heat transfer, which is usually referred to as "bond resistance." The presence of traces of any foreign poorly conducting materials between the tube metals, such as air or metal oxides, generally tends to decrease the inter-face metal contact area, and thus increase the bond resistance. A schematic representation of heat flow at the interface of two metals is shown in Figure 2.

The thermal resistance of metallic contacts has been under investigation for some time(1-9). Several investigators have studied the effect of pressure on the contact surface area and on the heat transfer rate(1-6,8). The mathematical theory of elasticity and plasticity has been used to explain some of the heat transfer phenomena resulting from pressing the surfaces together(1,5).

Weills and Ryder(1) studied the thermal resistance of dry and oil-filled interfaces between flat surfaces of various metals. The experimental apparatus used consisted of two test blocks 3 inches in diameter by 3 inches long, stacked axially one on another between the platens of a hydraulic press. The upper block was inductively heated and the lower block watercooled. The thermal conductance was obtained from measurements of heat flow and temperature gradient through the blocks. The effects of temperature, pressure, and surface finish were studied. The investigators found that the thermal resistance at the interface is decreased by increasing the temperature and pressure, by the inclusion of oil, or by plating the surfaces with a soft metal. As a result of their experiments, Weills and Ryder made the following conclusions:

1. The thermal conductance of a dry joint increases with pressure, linearly for steel, and generally exponentially for aluminum and bronze.

2. The thermal resistance of both dry and oil-filled joints decreases with a decrease in roughness of the surfaces.

3. At a given temperature, pressure, and roughness, the thermal resistance of both dry and oil-filled joints decreases in the order of steel, bronze, and aluminum.

4. The thermal resistance of a dry joint decreases as the temperature increases. For oil-filled joints, no consistent relationship was found.

5. The thermal resistance is about one-half as great for oil-filled joints as for dry joints at 10 psi. The effect of the oil decreases at higher pressures. The thermal resistance is decreased by copper plating one surface of a steel joint.

6. A hysteresis-like loop in the thermal conductance-pressure relation is obtained when the pressure is decreased following an increase in pressure.

7. The presence of a film of oxide or other foreign material of low thermal conductivity could contribute to the thermal

> resistance of a joint. However, except for very low interface pressure, the oxide resistance appears to account for only a small part of the total resistance.

The investigators also indicated that they believe that the area in metallic contact is directly proportional to the load during plastic deformation and to the two-thirds power of the load during elastic deformation. This opinion is based on the mathematical theory of elasticity.

Kouwenhoven and Potter(8) studied the thermal conductance of steel-to-steel contacts under various conditions. The effects of pressure, temperature, and surface roughness were explored. The investigators assumed that the surface consisted of a series of parallel isosceles trapezoid ridges "like a plowed field." As the pressure at the interface is increased, the trapezoids are assumed to crush, increasing the contact area. The influence of pressure was found to be greater for rough surfaces. In general, Kouwenhoven and Potter's results agreed with those of Weills and Ryder(1).

Centinkale and Fishenden(5) considered the plastic flow of the metal at the interface when the surfaces are pressed together. These investigators concluded that when pressure is applied to the contact, the softer of the two metals will plastically flow until the average pressure at the contact interface is equal to the average resistance per unit area against indentation (Meyer hardness). If the pressure is subsequently reduced, the metallic flow is elastic and the area of contact is a function of the pressure to the two-thirds power.

Brunot and Buckland(9) investigated the thermal conductance of blocks of laminated steel. They also found that the effect of pressure was considerably greater in the case of rough surfaces and concluded that contact resistances vary widely depending on smoothness, contact pressure, thermal conductivity of the metal, and thermal conductivity of the material between the metal surfaces.

The bond-resistance of bi-metal duplex tubes has been under investigation since 1951 as a part of heat transfer investigations sponsored by The Wolverine Tube Division of Calumet and Hecla, Inc., at the University of Michigan Research Institute (formerly the Engineering Research Institute).

Bond Resistance Measurement Theory

The overall heat transfer obtainable from a tube is given by

$$Q = U_o A_o (\Delta t)_m \tag{1}$$

where Q = heat transfer rate, Btu/hr

U_o = overall heat transfer coefficient, Btu/hr °F ft^2

A_o = tube outside area, ft^2

$(\Delta t)_m$ = mean temperature difference driving force, °F

The overall heat transfer coefficient for a clean (non-fouled) duplex finned tube is related to the individual heat transfer coefficients by:

$$\frac{1}{U_o} = \frac{1}{h_o'} + \frac{A_o}{A_i\,h_i} + \frac{A_o}{A_m}\,rm + \frac{A_o}{A_\ell}\,r_b + r_f \tag{2}$$

where h_o' = actual outside film heat transfer coefficient, Btu/hr ft^2 °F

h_i = inside film heat transfer coefficient, Btu/hr ft^2 °F

r_m = root metal heat transfer resistance, hr °F ft^2/Btu

r_b = bond heat transfer resistance, hr °F ft^2/Btu

A_o = outside heat transfer area, ft^2

A_i = inside heat transfer area, ft^2

A_m = mean metal heat transfer area, $ft^2 = (D_r - D_i)/\ell n(D_r/D_i)$

A_ℓ = outside heat transfer area of the liner tube, ft^2

r_f = fin resistance in hr ft^2 °F/Btu.(10)

The accuracy of a bond resistance measurement by direct heat transfer measurements is dependent on both the accuracy of measurement of U_o and the relative magnitudes of the individual resistance terms. Figure 3 indicates the per cent of the overall heat transfer resistance due to bond resistance for a high-fin duplex tube with an A_o/A_{liner} of 13.7. The figure clearly indicates that a high value of U_o is required to accurately measure low values of bond resistance.

The metal resistance and fin resistance of a given tube are essentially constant, and are small for most commercial tubes. The variables present in designing a measurement apparatus are thus the inside and outside heat transfer coefficients. Maximum bond resistance measurement accuracy calls for maximizing these coefficients.

An apparatus capable of measuring bond resistances, utilizing a five-foot long concentric pipe heat exchanger with high velocity water both inside the tube and in the annulus (in countercurrent flow) has been developed and calibrated. The water flow rates on the tube side and on the shell side of the heat exchanger were standardized at 12,000 pounds per hour. For these flow rates the dotted line on Figure 3 indicates the percentage of the overall resistance to heat transfer due to the bond resistance. For example, with a measured U_o of 52 the bond resistance is 0.0005 based on the liner area and constitutes 36% of the overall resistance to heat transfer.

Description of Apparatus

Figure 4 shows the concentric pipe heat exchanger used for measuring bond resistances. A 9 fin-per-inch high fin duplex tube can be seen extending out of both ends of the exchanger. One of the two rotameters used for measuring the water flow rates is shown at the left end of the heat exchanger. Three of the four mercury-in-glass thermometers used for measuring the inlet and exit temperatures of the two water streams can be seen in the figure. The fourth thermometer is to the right of the photograph just outside of the picture. One of the four insulated mixing chambers is shown just above the two flanges on the right end of the exchanger. The mixing chambers are necessary for accurate stream temperature measurements and must be located upstream from all thermometers. Figure 5 shows the auxiliary hot water supply system used in conjunction with the heat exchanger.

Figure 6 presents a line diagram of the entire flow system. The piping system as indicated permitted the passage of hot or cold water through either the tube side or the shell side of the system so as to reverse the heat flux direction. The cold water entered the system from the city water mains and flowed to the assembly through a booster pump in the basement of the building. The inlet pressure to the test equipment was approximately 60 psig. The cold water passed through an auxiliary heat exchanger where its temperature was controlled.

The cold water could be sent to either the tube inlet or the shell inlet. In either case, the water inlet and exit temperatures were measured by -1°C to 101°C mercury-in-glass thermometers having 0.1°C graduations, which were calibrated against a Bureau of Standards thermometer. The volumetric flow rates were measured by Fisher and Porter rotameters. After passing through the test heat exchanger, the cold water was discharged to the municipal sewer.

The hot water system was operated as a closed loop as indicated in Figure 6. The water was pumped from a 42-gallon tank through the heat exchanger. Part of the water was by-passed from the discharge side of the heat exchanger back into the surge tank. The remainder of the hot water could be passed to the tube or shell inlet side of the test heat exchanger. The inlet and exit water temperatures and flow rates were measured. The hot water was returned to the surge tank after leaving the test heat exchanger.

The test data were obtained by measuring the hot and cold water inlet and exit temperatures and water flow rates.

The two rotameters used for measuring the volumetric flow rates of the two water streams have 42.5 gpm maximum capacity and are provided with scales reading from 8 to 100% of maximum flow capacity. For this investigation the rotameters were calibrated by collecting a specified quantity of water in a weigh barrel and timing the collection period with a stop watch. The calibration curves enabled the operator to rapidly set the water flow rates to any desired level.

The test section was fabricated from a five-foot length of standard 3-inch schedule 40 steel pipe. The ends of the pipe were threaded and standard threaded flanges were attached. The shell was drilled for entering and leaving water lines and for vents which were necessary to release trapped air. The entire heat exchanger assembly was insulated to reduce heat losses.

In order to test the various high fin tubes, it was necessary to devise some simple, nondestructive means of sealing the tubes in the shell. A simple and satisfactory sealing method was developed by using a combination of natural rubber and sponge rubber gaskets. Figure 7 shows the gasketing method used.

A photograph of the steam cycling apparatus is shown in Figure 8; a line diagram of the apparatus appears in Figure 9. This apparatus was designed to cycle up to four tubes simultaneously and automatically. The cycles consisted of heating the entire tube to approximately 350°F for three minutes using 120 psig saturated steam inside the tube, followed by cooling the entire tube to less than 70°F for three minutes using mains water at about 5 feet per second inside the tubes. When running automatically, a complete thermal cycle was obtained every eight minutes.

The equipment consisted primarily of inlet and outlet header arrangements, each supported by an A-frame. In addition, a third A-frame was used to support the center of the tubes. The outlet header was adjustable both vertically and horizontally and was maintained at a level approximately two inches lower than the inlet header to facilitate drainage.

Steam at 120 psig and water at about 60°F were piped into the inlet header. The intermittent flow of these fluids was controlled using an electric timer mechanism in conjunction with two 1-inch solenoid valves. An electric counter was also connected to the timer to record the number of cycles completed. Provision was made for manual operation when desired. The tubes were connected to the headers using standard 1-inch unions. Gate valves were placed in the header system to allow any tube to be isolated from the cycling process. Condensate and water were removed from the system through a high-capacity bucket-type steam trap.

Photographs of the oil cycling apparatus are shown in Figures 10, 11, and 12. A line diagram of the apparatus appears in Figure 13. This apparatus was designed to thermally cycle four tubes simultaneously. The cycles consisted of heating the entire tube to 600°F using hot heat-transfer oil inside the tubes, followed by cooling the tubes to less than 150°F using compressed air in axial flow between the tube and an annular shell. The oil present in the tubes at the end of the heating part of the cycle was also cooled to less than 150°F.

The time required for a complete thermal cycle was found to be about two hours, using the multipoint temperature recorder shown in Figure 10. Of this time, approximately 45 minutes are required for heating the tubes and the cold oil in the tubes to 600°F. The remaining 75 minutes are required for the air cooling part of the cycle.

The cycling apparatus was constructed of 3-inch standard pipe supported on both ends by A-frames as shown in Figure 10. The tubes were sealed in the apparatus using blind flanges in which holes approximately 0.001 inch larger than the tube outside diameter were drilled. No attempt was made to seal the tubes tightly since moderate air leakage could be tolerated. The hot oil entered and left the tubes through 18-inch flexible steel hoses. The heat-transfer oil used was "Mobiltherm 600." The oil was heated in a 48 kw electric heater. A 3-horsepower pump was used to recirculate the oil. An oil by-pass was incorporated into the system to allow continuous oil circulation through the heater, and thus minimize fouling.

A total of eighteen integral finned duplex tubes ten feet long provided by Wolverine Tube have been cyclic tested to date. Of these tubes, fourteen had admiralty liners and four had copper liners. The characteristics of the tubes tested are presented in Table I. Ten of the fourteen admiralty liner tubes and all four of the copper liner tubes were stripped approximately three inches on both ends. The stripping operation exposes the liner tube as shown in Figure 1. It was found that the amount of bare liner tube exposed between the aluminum finned section and the end pieces used for testing had a pronounced effect on the cyclic characteristics of the tube. This effect is discussed in the next section.

All of the bond resistances reported were obtained using hot water inside the tubes and cold water in the annulus of the measurement apparatus. The inside of the tubes cycled with steam was cleaned periodically. This cleaning was found to have a negligible effect on the measured bond resistance. The tubes cycled with hot oil were thoroughly cleaned on the inside before each bond resistance measurement.

Results

A total of 216 bond resistance measurements were made on the eighteen tubes. The tubes were cycled between 55 and 9,527 cycles.

The effect of thermal cycling on the bond resistance of the tubes is presented in Figures 14, 15, 16, and 17.

Figure 14 presents the results obtained on thermal cycling four copper-liner duplex finned tubes with stripped ends to 350°F in the steam cycling apparatus. The bond resistances varied from values in the neighborhood of 0.00016 up to 0.00027 after three thousand cycles. The four tubes were cycled in two groups, tubes 121 and 122 together followed by tubes 124 and 125. Tubes 121 and 122 were carefully examined after 3,652 cycles. Several circumferential cracks or splits were observed in the aluminum root metal between some of the fins. It was not known exactly when these cracks started to appear. The 3,652 cycles is approximately equal to cycling three times a day for three and one-half years. The appearance of the cracks was not entirely unexpected since the thermal coefficient of expansion of aluminum is 42% greater than that of copper(11). Tubes 124 and 125 were then cycled to 350°F until cracks appeared in the aluminum, at which time the cycling was discontinued. Cracks appeared in the aluminum root portion of tube 124 at 2,084 cycles and in the aluminum root portion of tube 125 at 3,394 cycles. The final bond resistances were 0.00014 for tube 124 and 0.00020 for tube 125. No elongation measurements on the aluminum portion of these duplex finned tubes were made. The question arises as to whether or not the cycling from steam at 350°F to water at about 70°F is in effect thermal shocking the liner and shrinking the liner before the aluminum finned portion has a chance to cool, thereby contributing to the cracking of the aluminum. External air cooling of the duplex tube with a longer cycle period, as in the hot oil cycling, may not crack the aluminum. This will be experimentally verified in the continuation of this investigation.

Figure 15 presents the results on six admiralty-liner duplex tubes with stripped ends that were thermally cycled to 350°F in the steam cycling apparatus. Four of the tubes were cycled 3,258 times and two of the tubes were cycled 9,527 times. No crack of any kind appeared in the aluminum or admiralty portion of these tubes. It should be noted that the thermal coefficient of expansion of aluminum is about 24.7% greater than that of the admiralty metal liner(11). This is believed to be significant in that the aluminum portion of the copper-liner duplex finned tubes cracked after 2,000 to 3,000 cycles under identical cycling conditions. The thermal coefficient of expansion of aluminum is 42% greater than that of the copper liner.

The plotted values on Figure 15 that lie between ± 0.00005 can be considered to be essentially zero due to the limits with which the bond resistance could be measured. Figure 3 indicates that a bond resistance of 0.00005 is 5% of the overall heat transfer resistance in the measurement apparatus. The bond resistances of the six tubes had not reached 0.0001 at 3,000 cycles. The maximum value reached was 0.00015 at 9,527 cycles.

Figure 16 presents the results of heating four admiralty-liner duplex finned tubes with stripped ends to 600°F with hot oil followed by air cooling for fifty-five cycles. The four tubes initially had essentially zero bond resistance. The changes in bond resistance obtained with the four tubes are such that the tubes seem to follow a pattern during the fifty-five cycles.

The maximum bond resistance obtained was 0.00034 after fifty-five cycles. The rate of increase in bond resistance per cycle is greater than that obtained with any of the duplex tubes that were cycled to 350°F. The increase in the length of the aluminum finned section of the duplex tubes was measured after 6, 22, 35, and 55 cycles. The average per cent increases were 0.4%, 0.9%, 1.2%, and 1.8%, respectively. The last value corresponds to an increase in length of the aluminum of approximately two inches after fifty-five cycles. This growth phenomena has been encountered in the thermal cycling of metal jacketed slugs of uranium. Considerable disagreement exists over the cause of this growth phenomena(12). Cycling of these tubes to 600°F results in annealing the tubes and liners.

The cycling system requires manual supervision and the cycle period is of such a length that only three cycles per day were obtained. The cycling of these tubes is being continued.

Figure 17 presents the results obtained on cycling four admiralty-liner duplex finned tubes with insufficiently stripped ends to 350°F in the steam cycling apparatus. These four tubes had threaded pipe fittings brazed on the admiralty liners close to but not touching the aluminum finned portion of the tubes. After 1,000 cycles the aluminum portion of the tubes had contacted the end fittings and was pushing against them. When this occurred the bond resistance of two of the tubes varied erratically as indicated in Figure 17. Tube 112 had two circumferential cracks in the aluminum root wall approximately eighteen inches from one end after 4,976 cycles. Tube 113 had developed three circumferential cracks by the time 7,276 cycles had been completed. Tube 115 also had developed several cracks by the time 7,033 cycles had been completed. The maximum bond resistance reached was 0.00054 and was obtained by tube 115. After reaching this value, the bond resistance of this tube fell off to one-half this value. Tube 113 behaved in a similar manner, reaching a maximum value of 0.00041 followed by a reduction to essentially zero. The other two tubes in this figure, 112 and 114, followed a pattern similar to that indicated by tubes 116 and 117 in Figure 15, except that they reached about 50% greater maximum values. Thus, the bond resistance of duplex integral-finned tubes with admiralty liners, in which the aluminum portion is permitted to push against stops fastened to the liner, results in cracking of the aluminum root wall and erratic bond resistance behavior at a larger resistance level than that which is obtained by adequately stripped admiralty-liner tubes. In addition, no cracking is observed if the admiralty-liner tubes are adequately stripped.

The effect of the indicated bond resistance variations on the performance of duplex finned tubes in air cooling applications can be directly ascertained by use of Equation (3).

$$\frac{1}{U_o} = \frac{1}{h_o'} + \frac{A_o}{A_i} r_i + \frac{A_o}{A_i h_i} + \frac{A_o}{A_m} r_m + \frac{A_o}{A_\ell} r_b + r_o + r_f \qquad (3)$$

Equation (3) is Equation (2) with the inside fouling factor, r_i, and outside fouling factor, r_o, added. This relationship is general and can be applied to any application.

Consider the case of a jacket water cooler which is fabricated of 2-inch O.D. aluminum integral-finned tubes with 1-inch admiralty liners. The tube specifications are assumed to be as follows:

diameter over the fin	2.00 inches
number of fins	9 fins per inch
fin height	0.460 inches
fin thickness	0.019 inches
root diameter	1.080 inches
aluminum root wall thickness	0.040 inches
O.D. of liner	1.00 inches
I.D. of liner	0.902 inches
liner wall thickness	0.049 inches
outside heat transfer area, A_o	3.62 sq. ft. per ft. length
A_o/A_i	15.3
A_o/A_ℓ	13.83

The water film coefficient is assumed to be 1,000 based on the inside area. The jacket water fouling factor, r_i, from TEMA(13) is 0.001 and the air fouling factor is assumed to be zero. Two air film coefficients will be considered, 8 and 11, based on the outside area. For these coefficients the fin efficiencies are computed to be 94% and 91% respectively(13). The corresponding fin resistances, r_f, are 0.00663 and 0.00662 respectively(15). The resistance of the aluminum root wall and of the admiralty liner can be readily calculated. The above information along with various assumed values of bond resistance can be substituted into Equation (3) and the overall coefficients computed. The results obtained for a series of calculation are tabulated in Table II for various values of bond resistance, r_b.

Table II gives a clear indication of how the bond resistance would affect this jacket water cooler application. The bond resistances indicated in Figure 15 for adequately stripped admiralty-liner integral-finned tubes cycled to 350°F over thousands of cycles reduces the overall coefficient about 1-1/2 per cent. The same type tubes cycled to 600°F for fifty-five cycles, Figure 16, will reduce the overall coefficient 2-1/2 to 3%. For non-cyclic applications the admiralty-liner tubes had essentially no bond resistance.

The results obtained in this investigation have raised a number of questions as to why the bond resistance curves presented in Figures 14 through 17 have the patterns indicated. Considerable further research will be required to unravel the answers.

TABLE I

DIMENSIONS OF DUPLEX FINNED TUBES

Tube No.	Cycl. Med.	Liner Material	D_o Inches	D_r Inches	D_i Inches	D_o liner Inches	Fins/ Inch	Fin Thick. Inches	A_o ft^2/ft	A_i ft^2/ft	A_{liner} ft^2/ft
112	Steam	Admiralty	2.000	1.102	0.902	1.000	9.17	0.019	3.624	0.236	0.262
113	Steam	Admiralty	2.000	1.102	0.902	0.997	9.17	0.019	3.624	0.236	0.260
114	Steam	Admiralty	2.000	1.102	0.902	0.999	9.17	0.019	3.624	0.236	0.261
115	Steam	Admiralty	2.000	1.102	0.902	0.997	9.17	0.019	3.624	0.236	0.260
116	Steam	Admiralty	1.979	1.078	0.899	1.000	8.75	0.013	3.432	0.235	0.262
117	Steam	Admiralty	1.987	1.078	0.898	1.000	8.67	0.013	3.447	0.235	0.262
121	Steam	Copper	2.014	1.078	0.901	1.002	8.75	0.013	3.599	0.236	0.262
122	Steam	Copper	2.016	1.078	0.899	1.003	8.83	0.013	3.645	0.236	0.263
124	Steam	Copper	2.015	1.069	0.893	1.002	8.75	0.013	3.622	0.236	0.262
125	Steam	Copper	2.007	1.086	0.899	0.999	8.83	0.013	3.579	0.236	0.262
126	Oil	Admiralty	2.000	1.092	0.897	0.995	8.97	0.014	3.583	0.235	0.260
128	Oil	Admiralty	2.000	1.092	0.899	1.000	8.96	0.014	3.579	0.236	0.262
129	Oil	Admiralty	1.993	1.086	0.897	0.998	8.95	0.014	3.563	0.235	0.261
136	Oil	Admiralty	1.991	1.086	0.898	1.000	8.93	0.014	3.540	0.235	0.262
127	Steam	Admiralty	2.000	1.086	0.900	1.000	8.97	0.014	3.595	0.236	0.262
130	Steam	Admiralty	1.994	1.088	0.897	0.997	8.93	0.014	3.542	0.235	0.261
131	Steam	Admiralty	2.004	1.086	0.899	1.000	8.93	0.014	3.600	0.236	0.262
132	Steam	Admiralty	1.997	1.086	0.897	0.998	8.93	0.014	3.570	0.235	0.261

TABLE II

COMPUTED EFFECT OF BOND RESISTANCE ON A JACKET WATER AIR COOLER APPLICATION

r_b	$h_o' = 8$		$h_o' = 11$	
	U_o	% Decrease	U_o	% Decrease
0	6.101	0	7.704	0
0.00001	6.096	0.08	7.696	0.10
0.00005	6.075	0.43	7.663	0.53
0.00010	6.050	0.83	7.622	1.06
0.00015	6.024	1.26	7.582	1.58
0.00030	5.952	2.44	7.468	3.06
0.00050	5.855	4.03	7.315	5.05
0.00080	5.718	6.27	7.102	7.81
0.00100	5.627	7.76	6.964	9.60

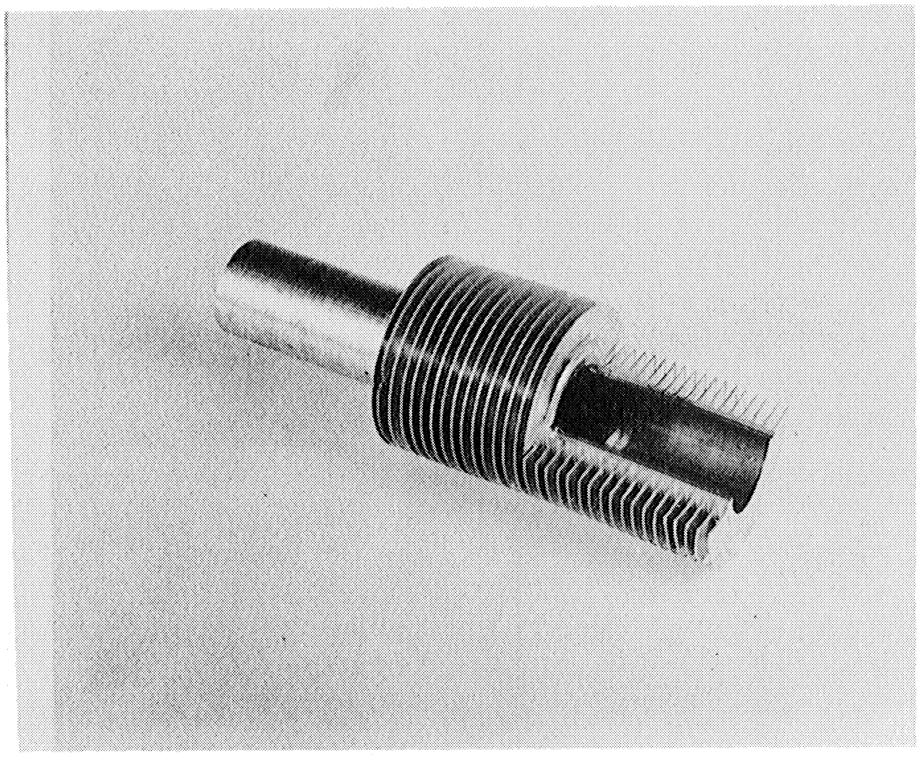

Figure 1. Section of a Stripped-End 2-In. O.D. Duplex Integral-Finned Tube with 1-In. Admiralty Liner

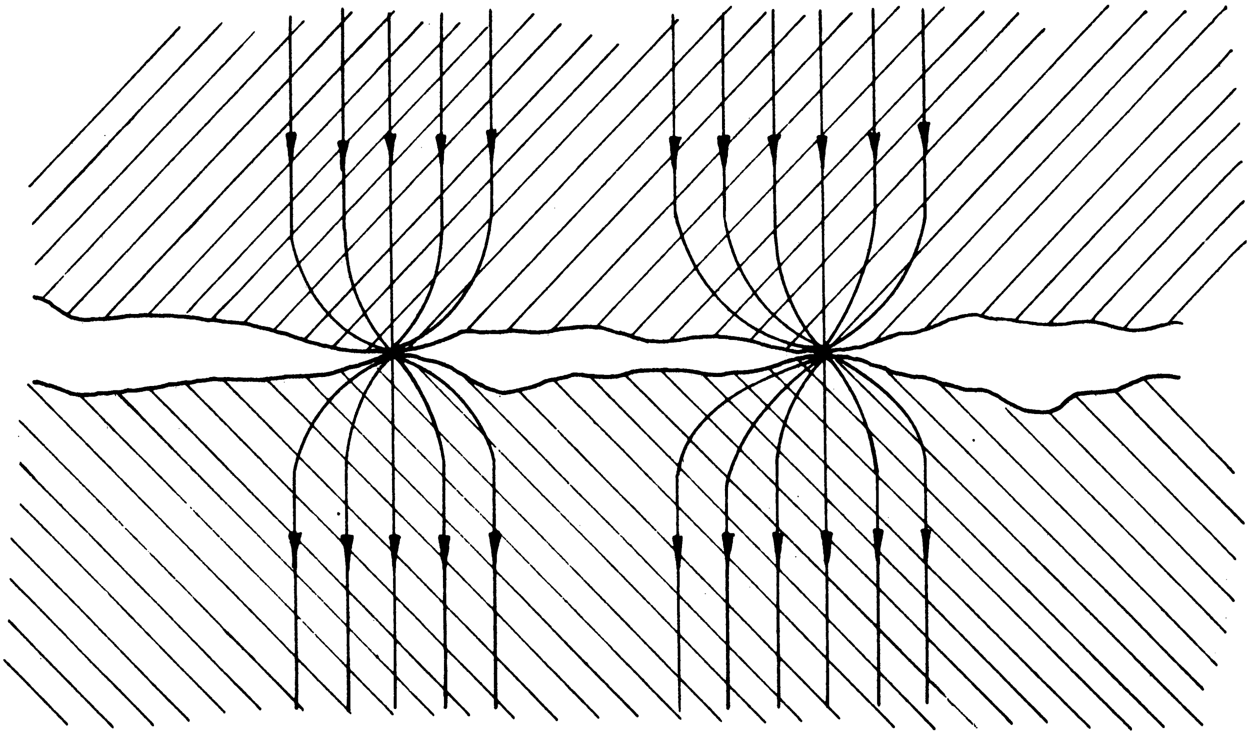

Figure 2. Schematic Representation of Heat Flow Across Metallic Contact Areas

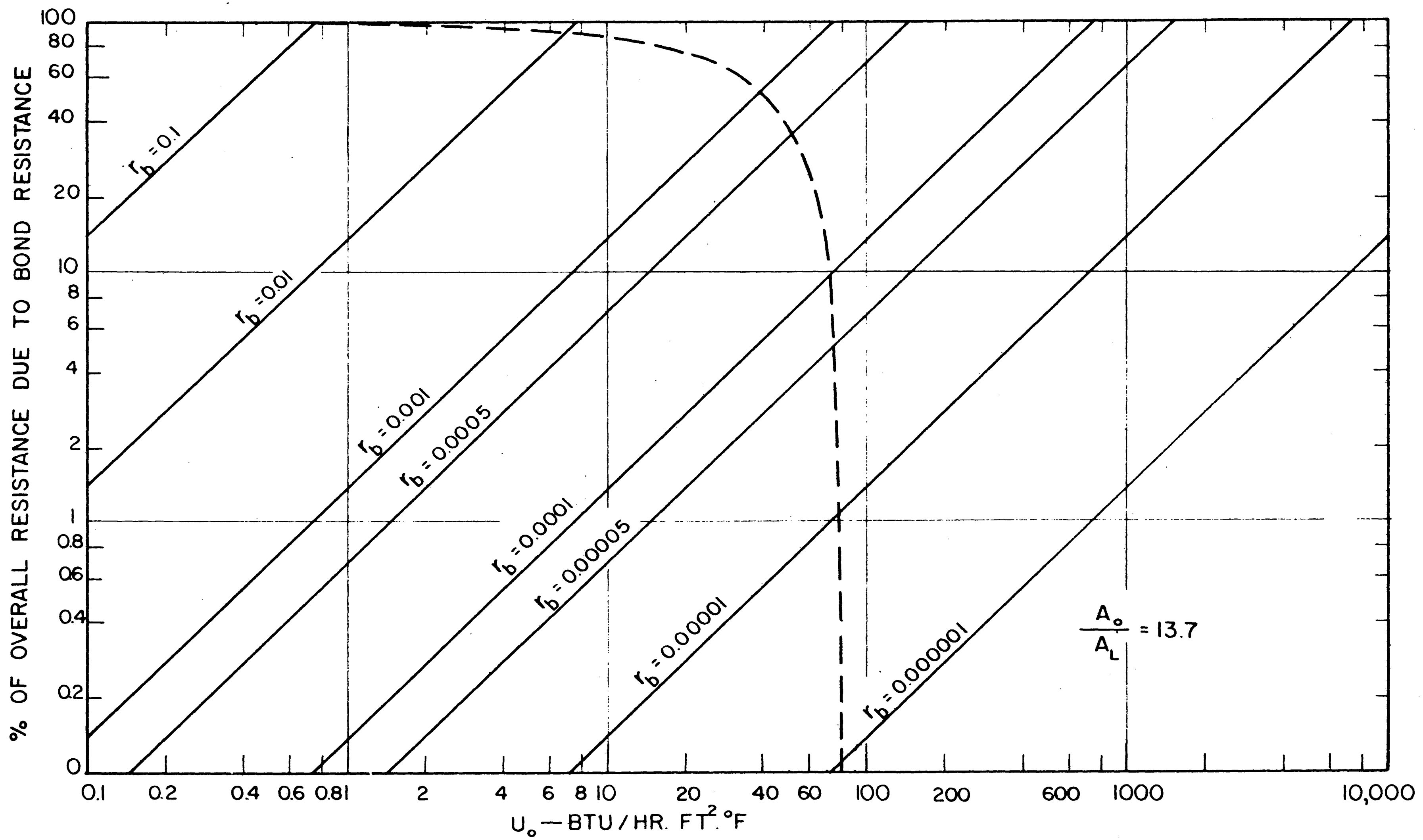

Figure 3. Percentage of Overall Heat Transfer Resistance Due to Bond Resistance

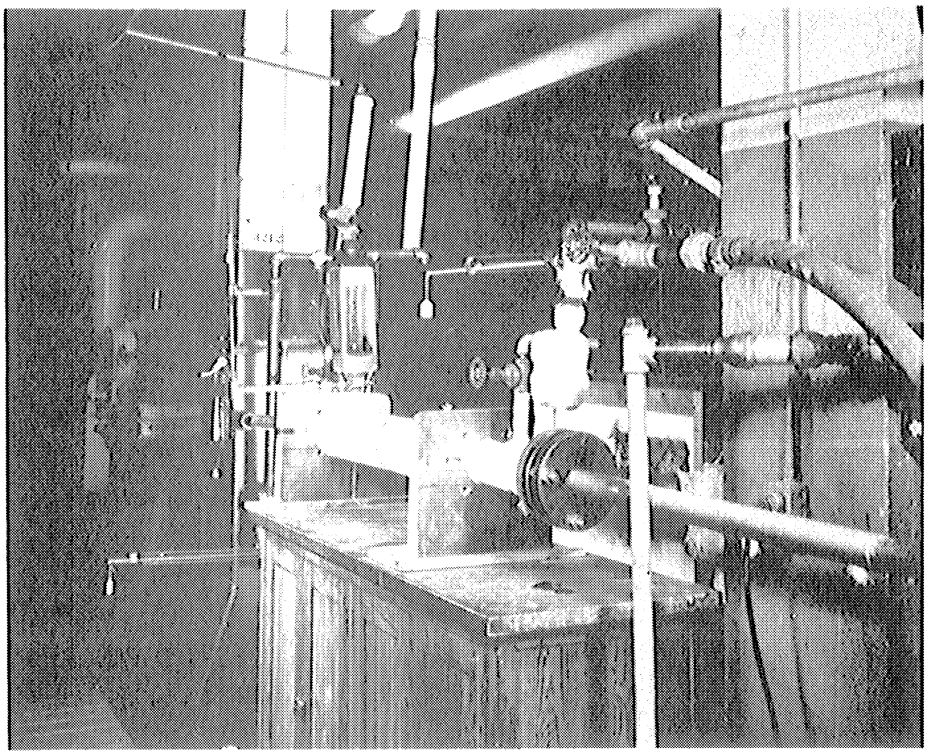

Figure 4. Bond Resistance Measurement Apparatus

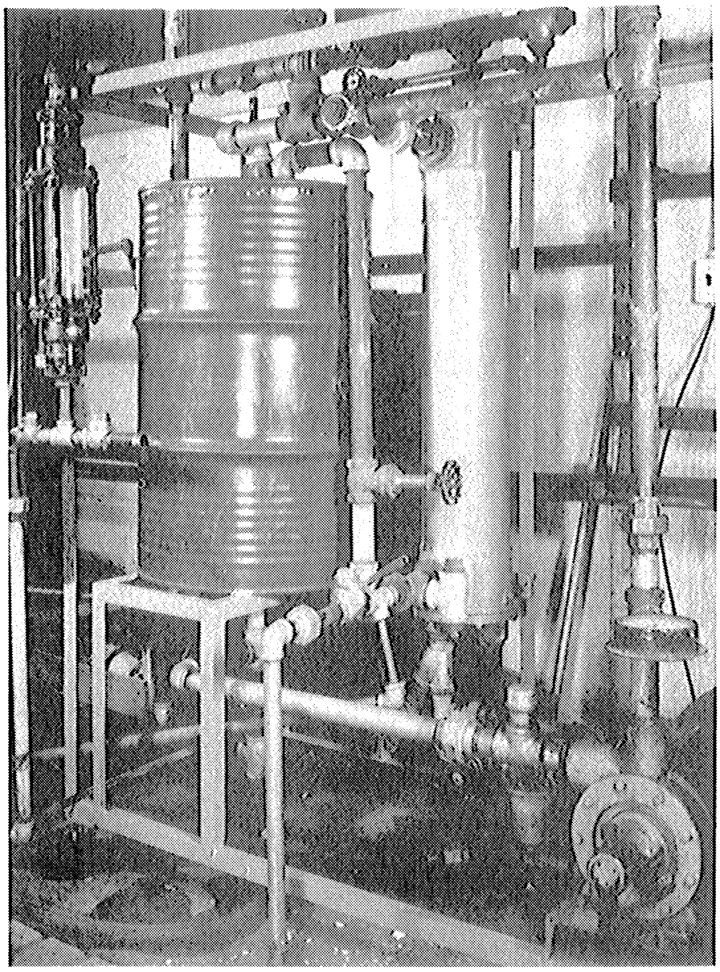

Figure 5. Auxiliary Hot Water Supply System

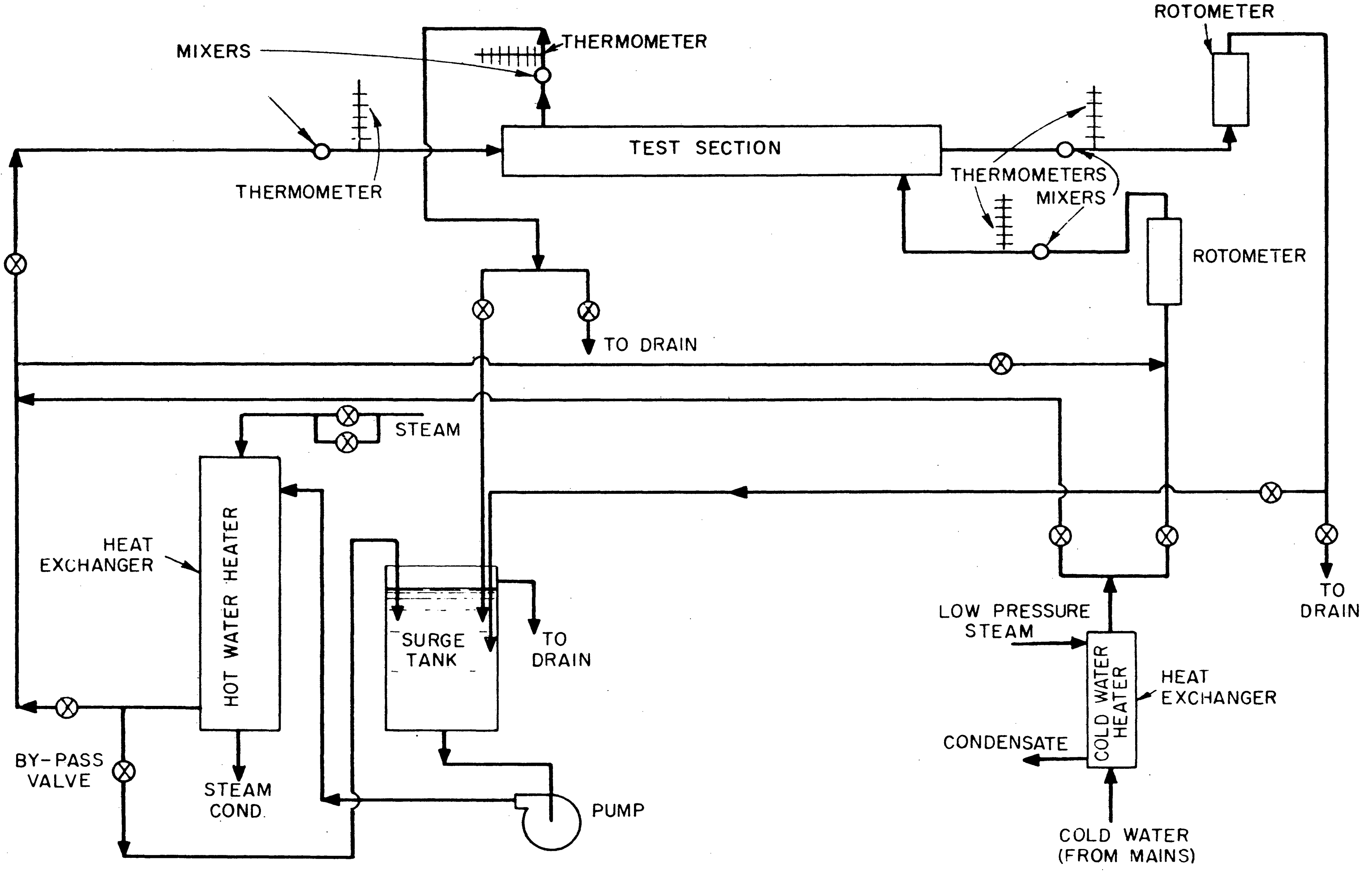

Figure 6. Line Diagram of Bond Resistance Measurement Apparatus Including Auxiliary Equipment

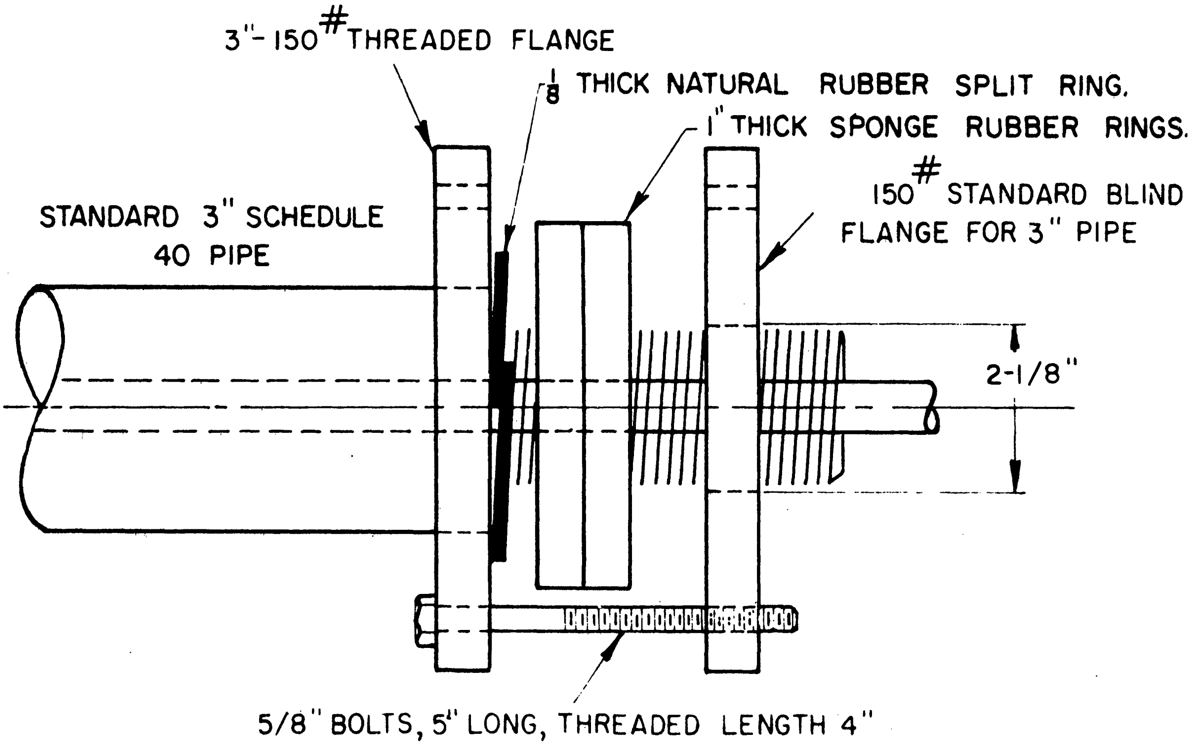

Figure 7. Method of Sealing High-Finned Tubes for Testing

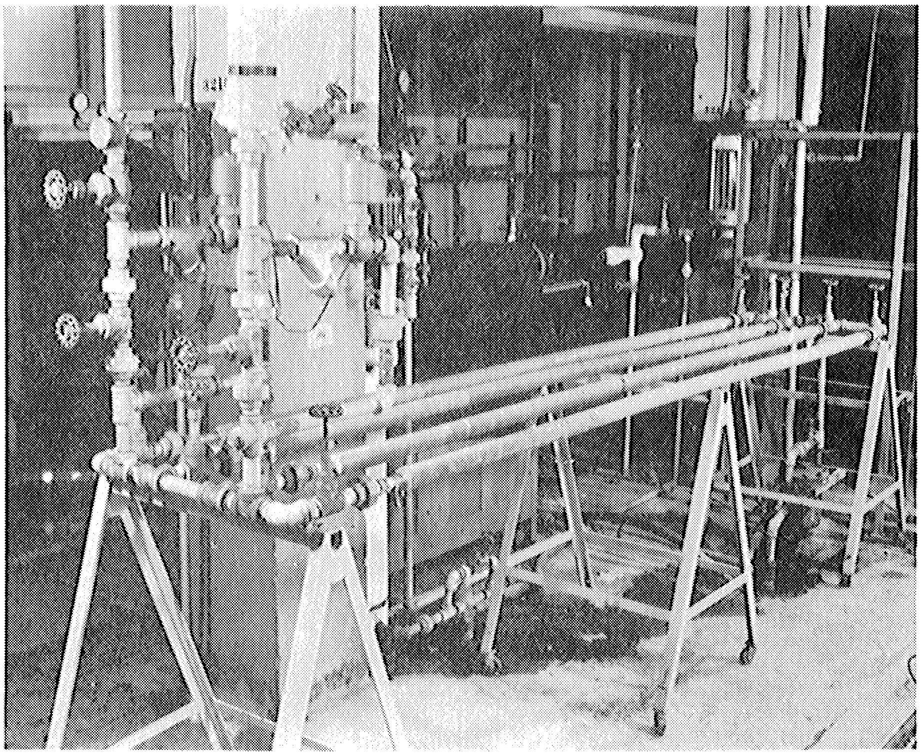

Figure 8. Steam Cycling Apparatus

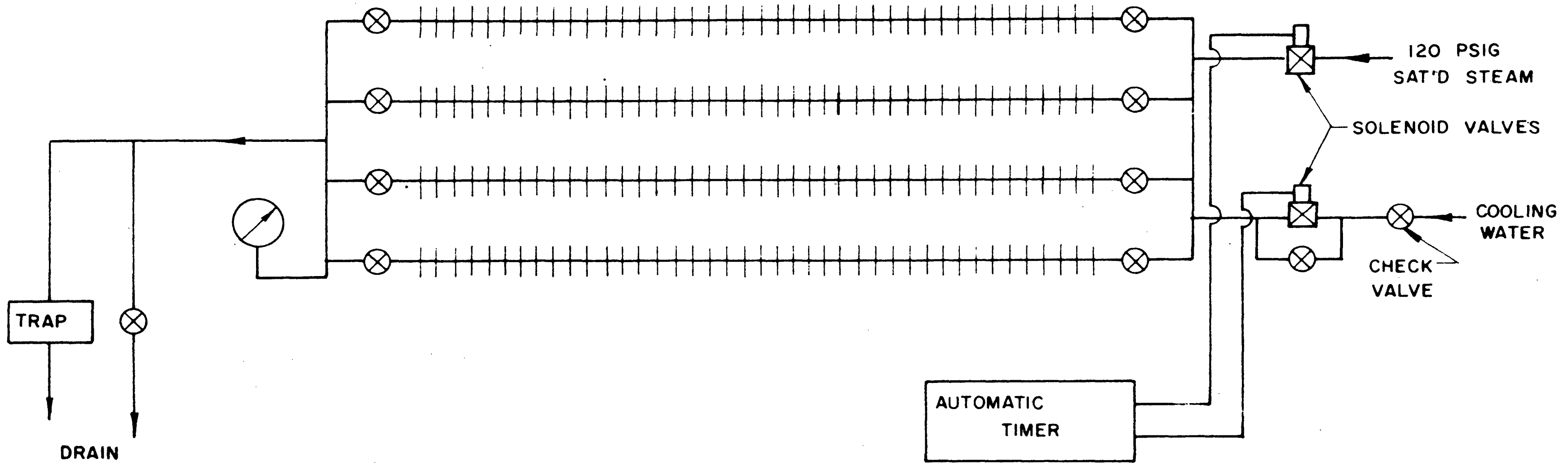

Figure 9. Line Diagram of Steam Cycling Apparatus

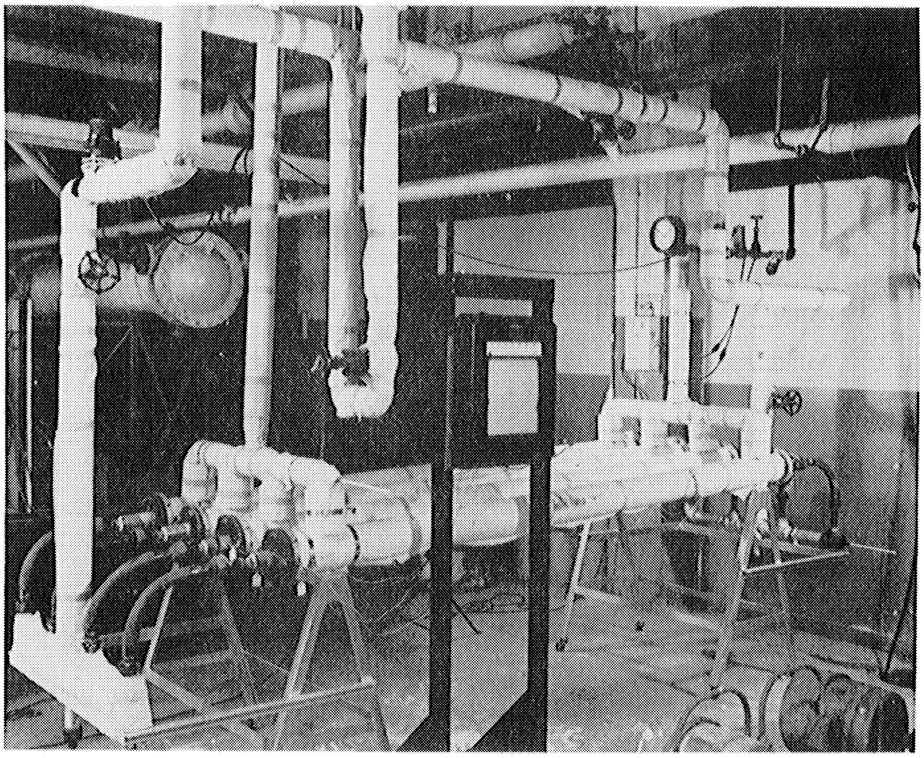

Figure 10. Hot Oil Cycling Apparatus and Temperature Recorder

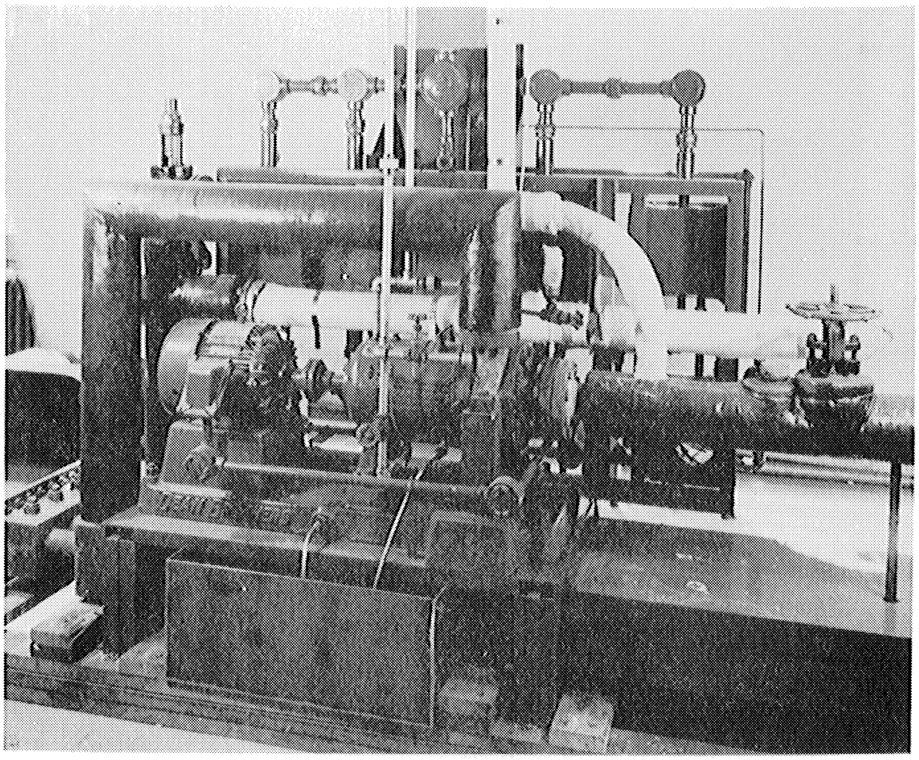

Figure 11. 48-kw Electric Heating System with Oil Circulating Pump

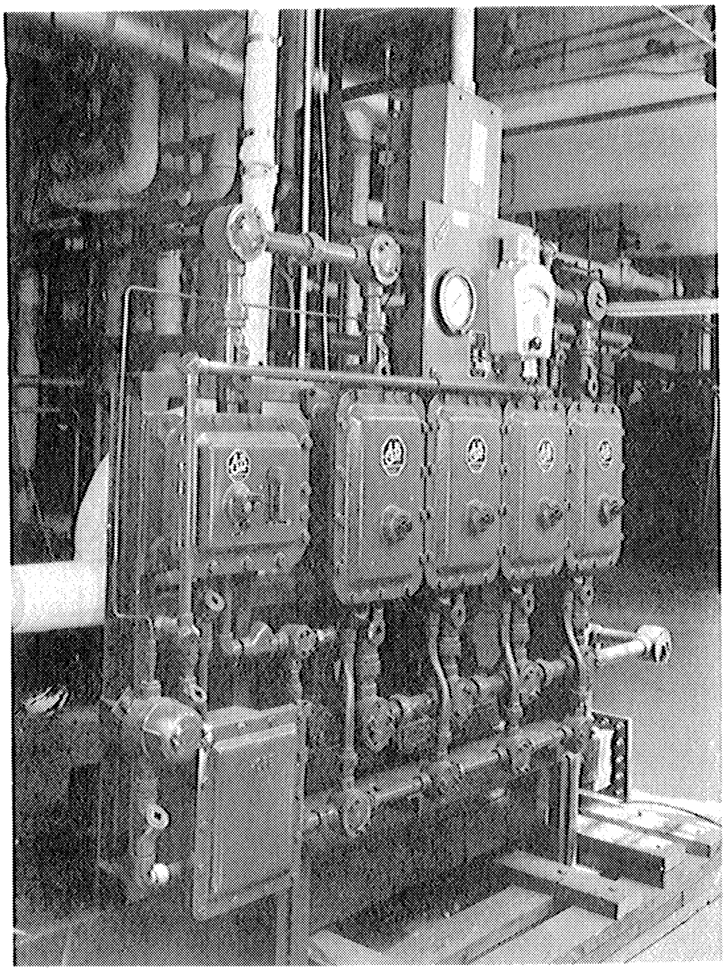

Figure 12. Control Panel for Electric Heating System

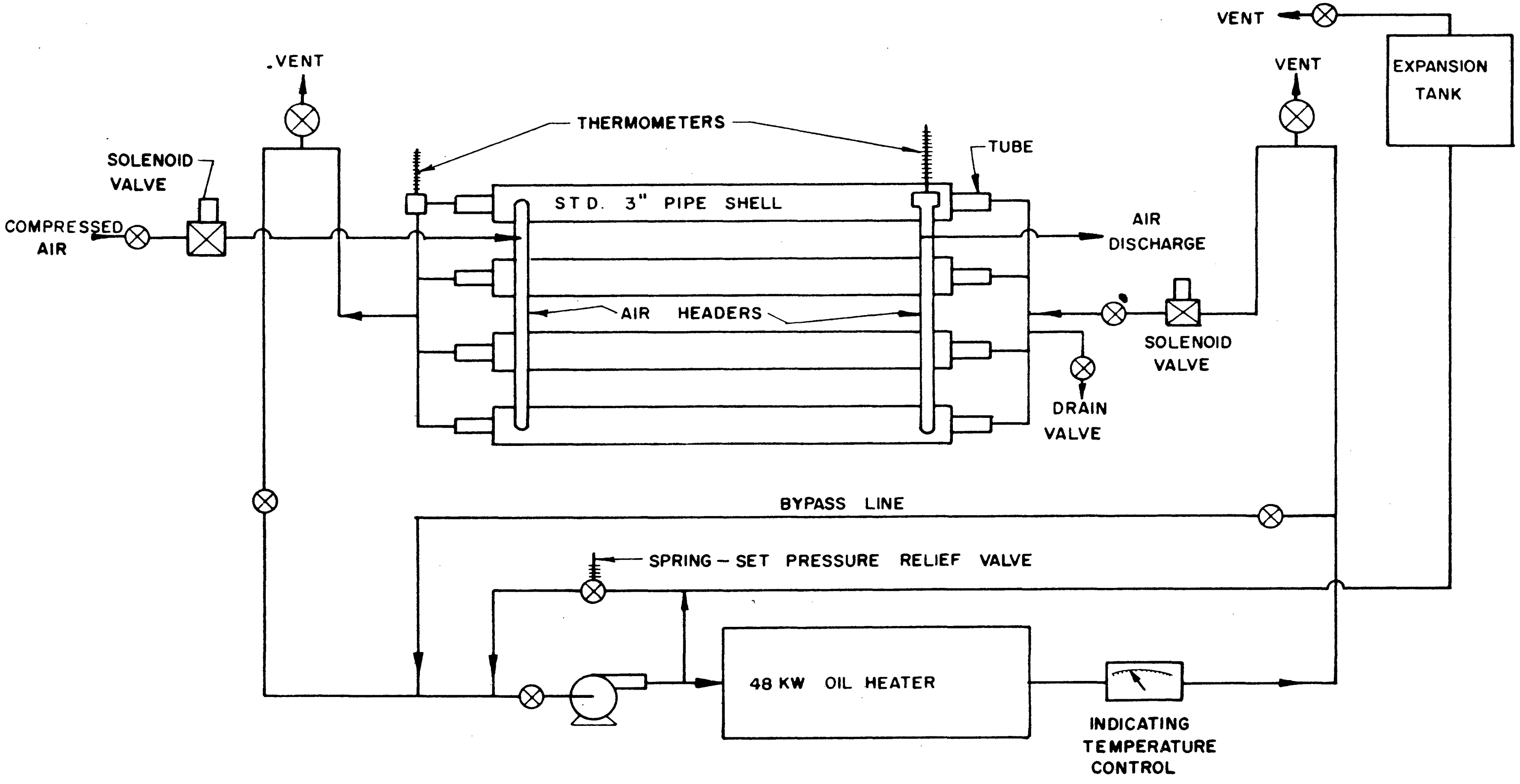

Figure 13. Line Diagram of Hot Oil Cycling Apparatus

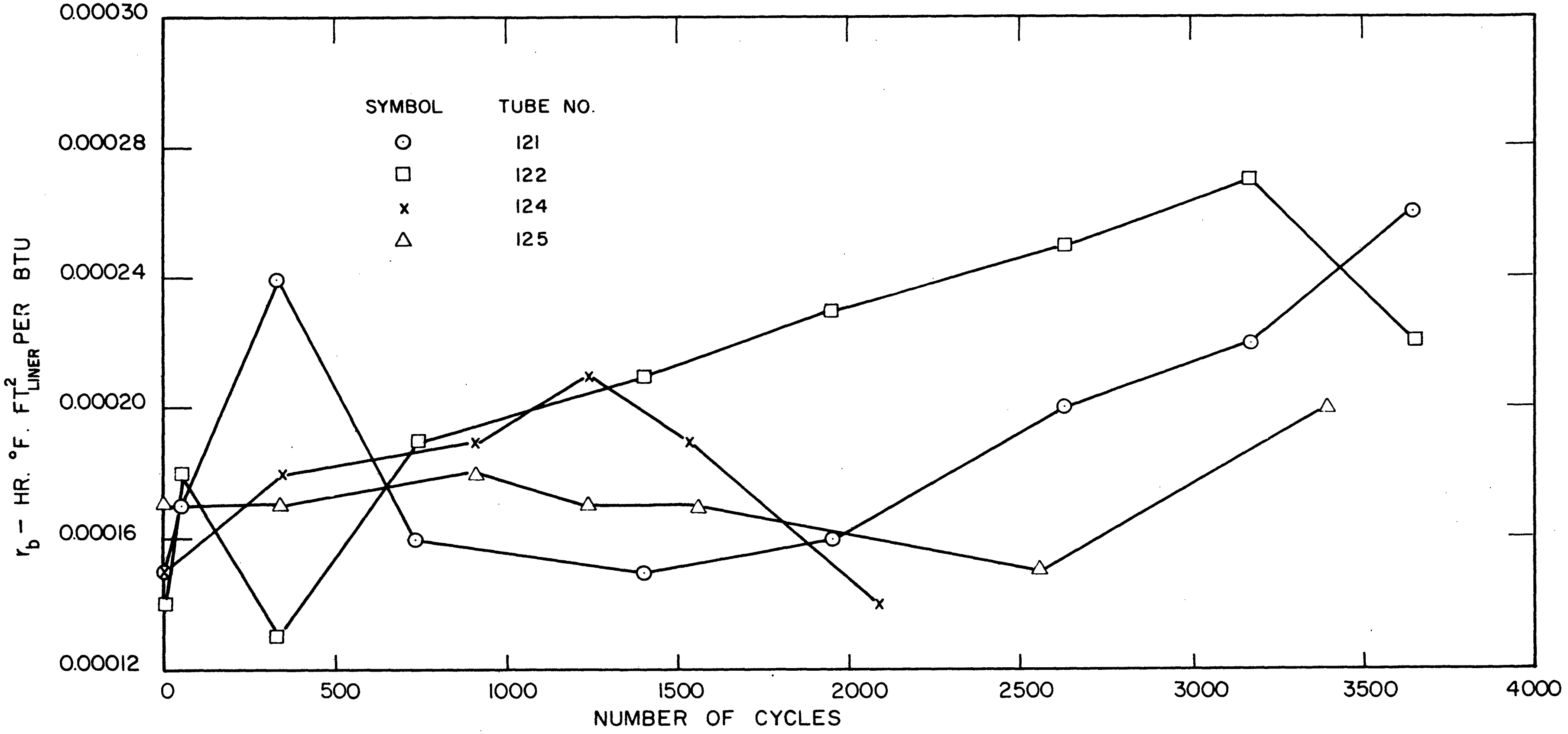

Figure 14. The Effect of Thermal Cycling to 350°F on the Bond Resistance of Four Copper-Liner Duplex Finned Tubes with Stripped Ends

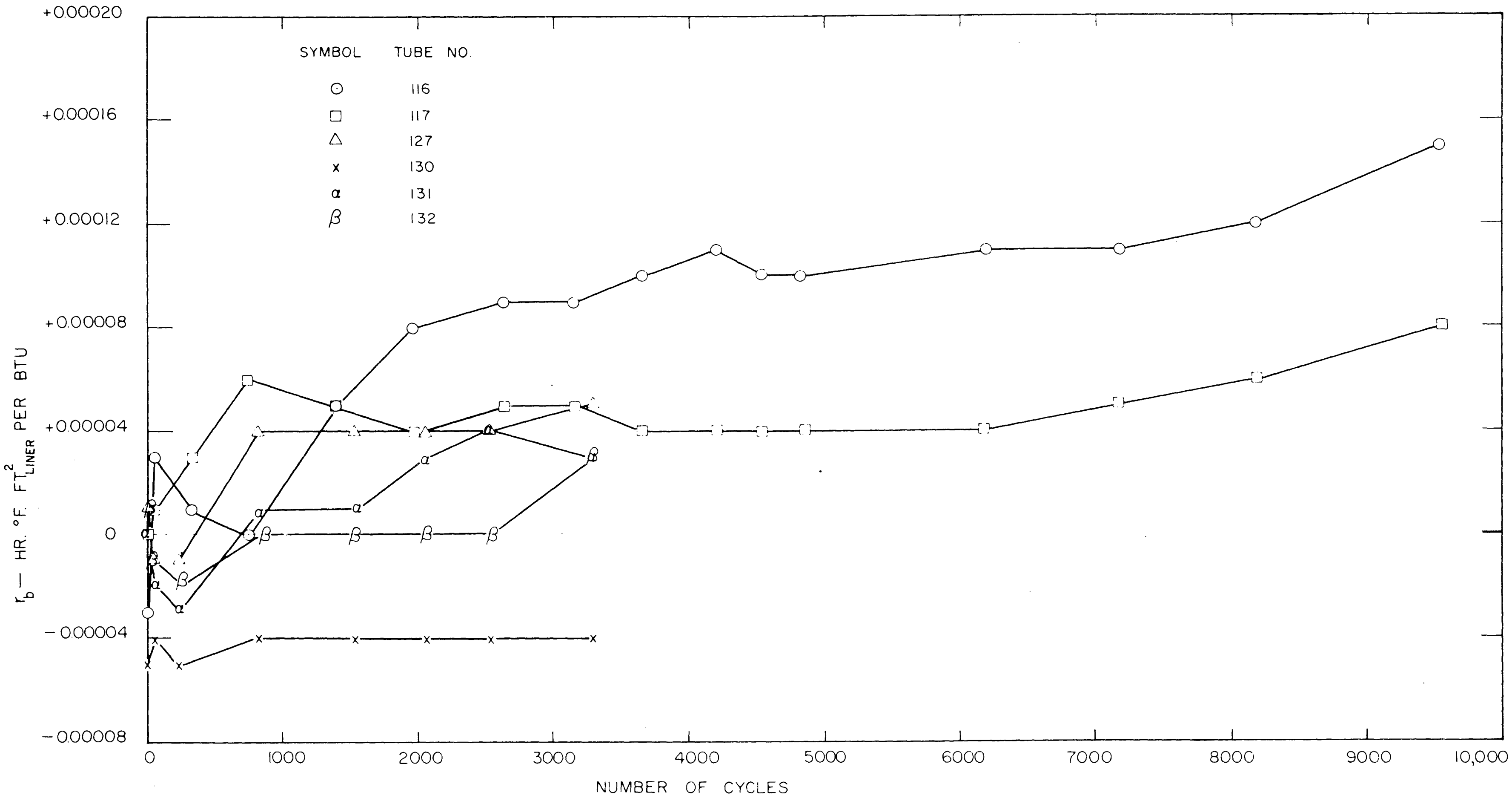

Figure 15. The Effect of Thermal Cycling to 350°F on the Bond Resistance of Six Admiralty-Liner Duplex Finned Tubes with Stripped Ends

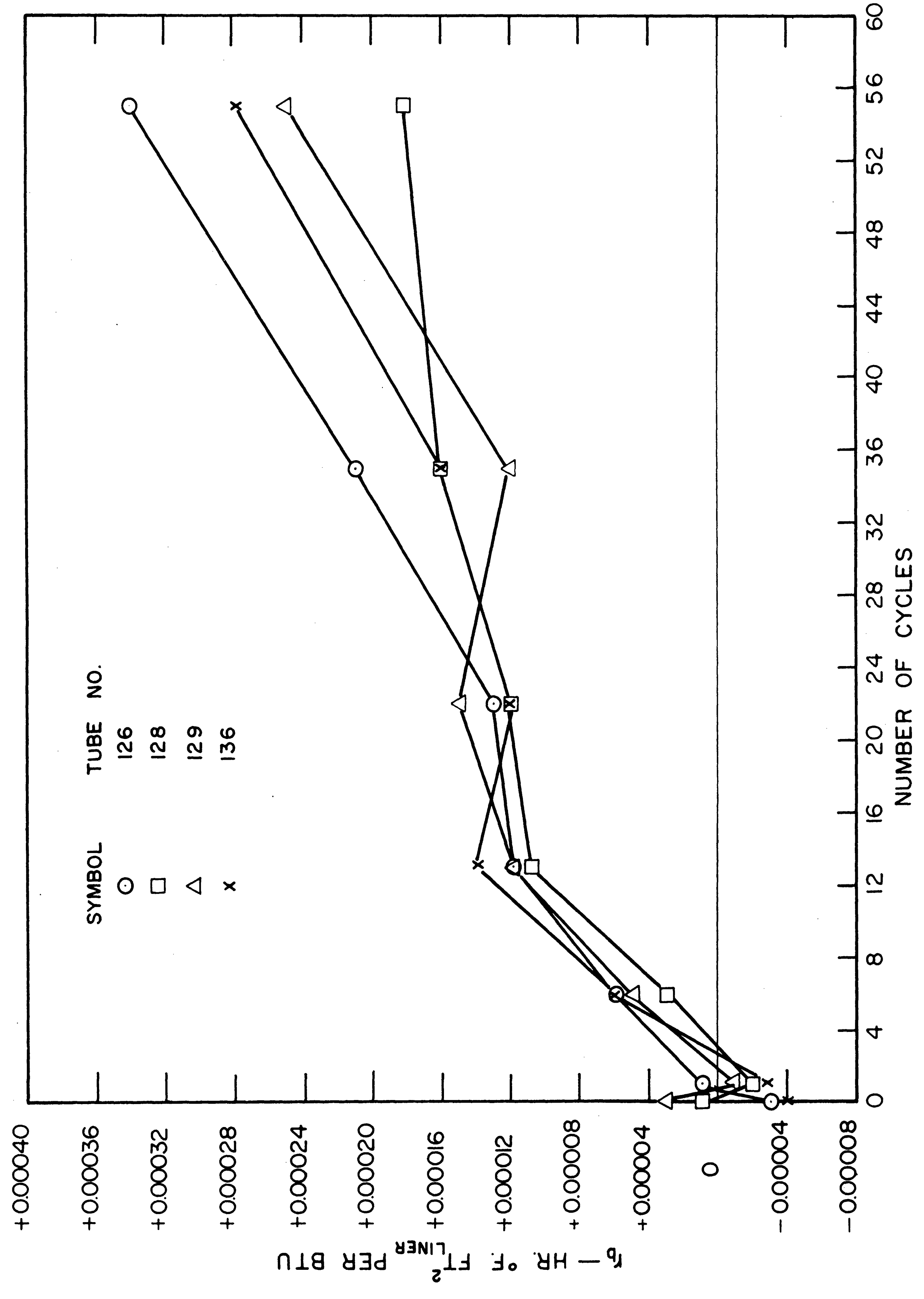

Figure 16. The Effect of Thermal Cycling to 600°F on the Bond Resistance of Four Admiralty-Liner Duplex Finned Tubes with Stripped Ends

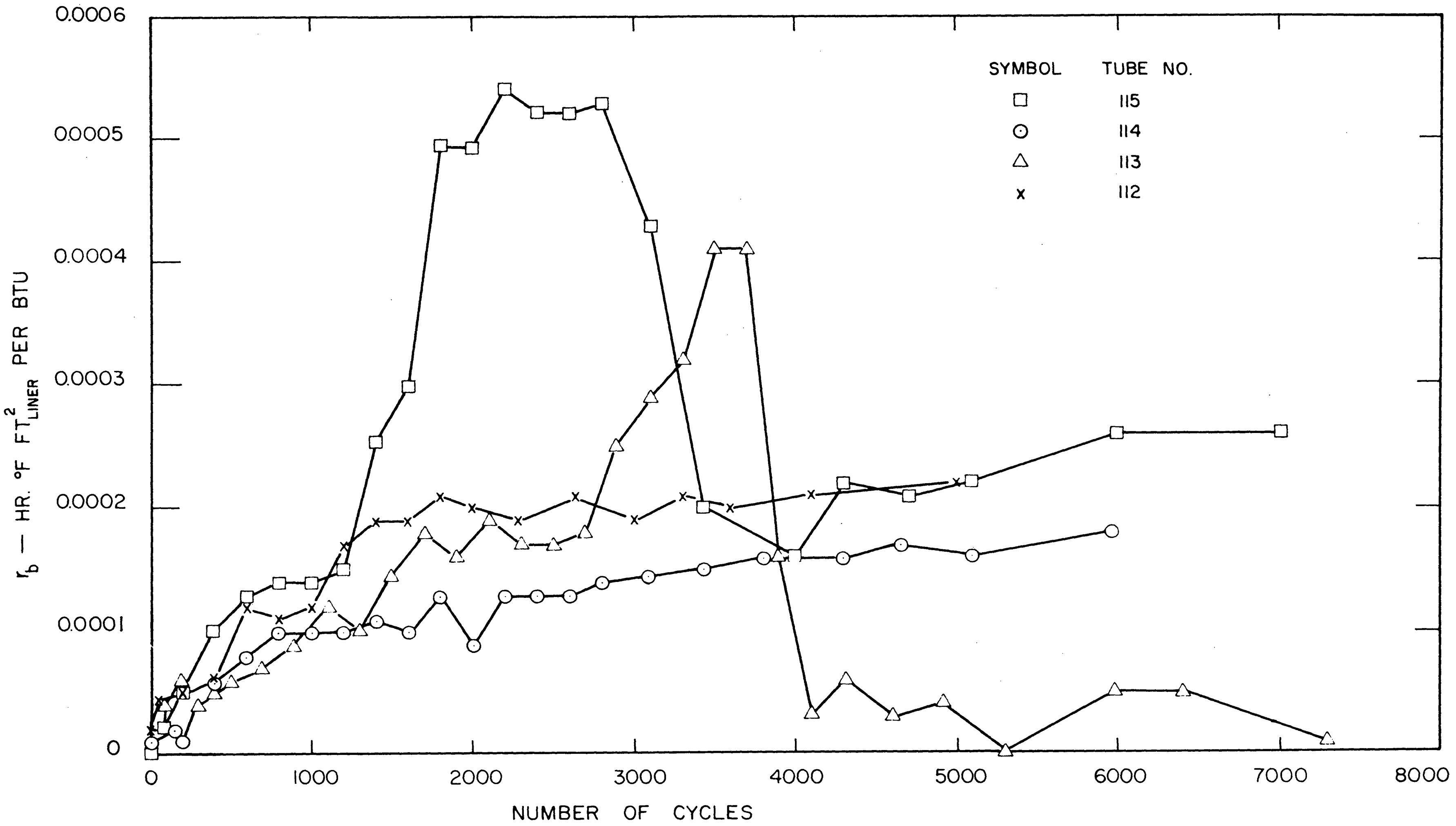

Figure 17. The Effect of Thermal Cycling to 350°F on the Bond Resistance of Four Admiralty-Liner Duplex Finned Tubes with Inadequately Stripped Ends

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