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"LIFE" TESTS ON INTERNALLY WATER-COOLED HOLLOW COPPER CONDUCTORS

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ABSTRACT

Tests have been conducted to determine whether a time limitation exists on the use of internally water-cooled hollow copper conductors operating at densities of up to 330,000 amps/in². Using demineralized water, having a specific resistivity of 4 to 9 x 10⁶ ohm-cm, no indication of a decrease in heat transfer coefficient as a function of time was observed. However, metallographic examination revealed that corrosion-erosion does occur at a slow rate. Using process water there was a time dependent decrease in heat transfer coefficient and a consequent rise in metal temperature. The subsequent use of demineralized water in the same conductor again produced stable heat transfer, over the time spans investigated, 192 hours. The maximum total time investigated was 873 hours for one conductor.

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"LIFE" TESTS ON INTERNALLY WATER-COOLED HOLLOW COPPER CONDUCTORS

INTRODUCTION

Hollow copper conductors are widely used for making magnet coils to produce strong magnetic fields. These conductors are cooled by water whose rate of flow is chosen so as to maintain a copper temperature within the allowable range for the insulation between conductors and, usually, so as to avoid boiling. At heat fluxes between 1 and 2×10^6 BTU/hr ft² it was found that under certain other conditions the heat transfer coefficient from aluminum to water decreased with time, leading to a steady increase in metal temperature.¹ The tests described here were conducted to determine whether a comparable effect takes place in hollow copper conductors and to determine the effects of water composition on stable heat transfer.

Other topics of interest on which information was sought were the following:

1. The influence of dissolved oxygen content on buildup of copper oxides on the interior walls of a copper conductor. It is an analogous buildup that caused the decreasing heat transfer from aluminum to water.¹
2. The effects of high flow velocities on erosion of the coolant passage surfaces. The generally used upper limits of flow velocity for fresh water in copper are between 6 and 10 feet per second.³ However, in hollow copper conductors flow velocities of up to 75 feet per second are contemplated.
3. The validity of a burnout heat flux prediction² for hollow copper conductors with circular cross section of cooling passages.

DESCRIPTION OF TESTS

Test Arrangement

The cross section and test configuration of the conductor used in the tests are shown in Fig. 1. Figure 2 is a photograph of one quarter of the cross section in the as-received condition at a magnification of 50x.

Figure 3 shows the test arrangement and the location of thermocouples used to measure the temperature of the outside surface of the conductor. It was assumed that this was the uniform temperature throughout the copper cross section since the heat flux to the outside of the conductor was negligible, as is shown later, and the thermal conductivity of copper is relatively high.

The conductor was insulated from ambient temperature by means of a layer of fiberglass tape and one to two inches of asbestos cement.

Current was supplied by a rectifier of 7000 amps, 12 volt capacity. Current was put into the conductor through two copper lugs to which the conductor was brazed over the entire width of the lug.

The current was measured with a 10,000 amp shunt. This, together with the voltage drop measured between midpoints of the lugs, provided a measure of power input. A thermometer at the inlet and outlet of the conductor provided the measurement of temperature rise of the water, and a rotameter provided the flow rate. Figure 4 shows a plot that compares the power removed by the water with the electrical indication of power input. The fact that points lie on both sides of the 45° line indicates that power lost to the air was negligible by comparison to sources of error in measurement.

Since water flow was interlocked with the power supply, the test could safely proceed unattended.

Test Data and Results

Table I shows the principal parameters of the main test runs. Readings of temperatures, flow and pressures, current, and voltage drop, were made at intervals of about 8 and 12 hours.

The difference between copper temperatures at the cold end of the conductor and at the hottest point downstream, divided by the square of the current, was plotted against running time in hours. This is shown in Fig. 5.

Figure 6 shows the actual heat flux across the inside surface of the conductor as a function of copper temperature. Using these curves it was possible to obtain the actual heat transfer coefficient in effect at the ends of the conductor, where the bulk water temperature was known. A plot of this coefficient versus time was made for Tests 2D, 3D and 4D, which were the only tests with wall temperatures below saturation. This is shown in Fig. 7. The slope and shape of the curves is analogous to the slope and shape of the curves of Fig. 5. The curves of temperature rise divided by the square of the current are therefore a good indication of changes in heat transfer to the cooling water.

A comparison of the heat transfer coefficients from the test data with the coefficients predicted by the Dittus-Boelter⁴ equation and the Sieder-Tate⁵ equation again shows the effects of scale formation from process water, as follows:

Test	Date	Test Coefficient	Dittus-Boelter Coefficient	Sieder-Tate Coefficient	Type of Cooling Water
B	12-14-61	10603	8220	9750	Demineralized
2D	4-24-62	3470	7100	8800	Process
4D	5-18-62	4740	7580	9400	Process

At the end of Test Run 4C the flow was decreased to a point that corresponded to burnout by the prediction in Ref. 2. After about an hour of operation with slowly rising metal temperatures, the tube burned out about one inch upstream of the hot end electrical lug, and the automatic pressure monitoring system shut down the test.

Metallographic Examination of Conductors

The Metallography Section of the Metals and Ceramics Division cut up and mounted the conductors of Tests C and D.

The photographs made of the inner surface of the conductors at several points along the length are shown in Figs. 9 through 18a. Figure 8 shows the locations of samples cut out of the two conductors.

DISCUSSION

It seems clear that within the limits of elapsed time investigated here, heat transfer in the nucleate boiling region, as well as the sub-cooled wall region, becomes stabilized when demineralized water is used as the coolant. However, the change of surface condition of the conductor's coolant passage suggests that corrosion-erosion is a factor that may become significant over longer elapsed times.

During the course of the tests a nitrogen blanket was placed over the head tank of the demineralized water system. This changed the dissolved oxygen content of the water from 8 ppm to 1.1 ppm between Tests 2C and 3C. No change in heat transfer characteristics was noted between the two tests. However, there may have been some effect on the corrosion-erosion rate, but this could not be detected in these tests.

It appears that under the conditions of Tests 1C, 2C, 3C and 4C, oxidation of copper does occur along the surface of the cooling passage. The photographs show that oxidation does not occur uniformly over the entire surface but takes the form of localized penetrations which are subsequently eroded away from the parent copper by the flowing water.

The maximum depth of corrosion-erosion for conductor "C" is about .002 inches. This indicates a maximum rate of about 4.8×10^{-6} inches per hour under the conditions of these tests.

The conductor used in Test B was also examined under a microscope and no oxidation or erosion was discovered. Only at the burned-out end of the conductor there was a thin layer of oxide. It has not been determined whether the difference between corrosion-erosion in Tests B and C is due to a temperature, heat flux, or velocity dependent threshold.

The conductor used in Tests D under metallographic examination shows the effects of both corrosion-erosion and scale deposition from the process water. It seems clear that in the straight sections of conductor, the scale confines the oxide of copper and prevents its erosion. The thickness of scale seems to increase toward the hot end of the conductor. At the joggle, however, scale was not able to deposit out onto the conductor walls and the erosion "craters" characteristic of conductor C are again in evidence here.

The velocity of Tests D was lower than the velocity of Tests C, and no determination has been made of the effects of velocity on scale deposition. However, one corrosion-erosion "crater" .004 inches deep appeared at the joggle of conductor D, indicating that even at the relatively low velocity erosion can reach dangerous values at changes in the flow path.

CONCLUSIONS

1. It appears from these tests that it is entirely feasible, from the heat transfer standpoint, to operate water-cooled copper conductors in the nucleate boiling region using demineralized water at pH 7, without incurring the gradual temperature rises of Ref. 1.
2. The life of conductors operating in this region of heat transfer appears to be unlimited by scale buildup considerations. However, the flow velocity should be kept as low as possible when demineralized water is used since corrosion-erosion does occur even in the case of demineralized water of low oxygen content. In the case of process water, higher velocities appear justified since deposition of scale retains oxide on the conductor's cooling passage walls.
3. The demineralized water presently used in Building 9201-2 is satisfactory for cooling hollow copper conductors and its oxygen content does not appear to be critical in determining operating life of such conductors.

ACKNOWLEDGMENTS

Mr. M. D. Allen, of Metals and Ceramics Division, carried out the metallographic examinations of the conductors and prepared the photographs used in this report.

Equipment, advice and assistance were provided by members of the Engineering Sciences Group of the Thermonuclear Division.

REFERENCES

1. Griess, J. C., et al., "Effect of Heat Flux on the Corrosion of Aluminum by Water" (ORNL-3230).
2. Gunther, F. C., "Photographic Study of Surface Boiling Heat Transfer to Water With Forced Convection", Transaction of ASME, February, 1951.
3. Lynes, Wilson, private communication.
4. Dittus, F. W. and L. M. K. Boelter, University of California, Pubs. Eng. 2, 443 (1930).
5. Sieder, E. N. and G. E. Tate, "Heat Transfer and Pressure Drop of Liquids in Tubes", Ind. Eng. Chem. 28, 1429-35 (1936).

APPENDIX

SOME EXPRESSIONS UTILIZED IN TESTS

Power Input:
$$P = EI = \frac{I^2}{A \cdot 2.54} \int_{L=0}^{L=L} \rho dL \quad \text{watts}$$

Power Removed by Coolant:
$$P = \frac{\Delta t_b G C_p}{3.413} \quad \text{watts}$$

Local Gross Heat Flux:
$$\frac{q}{a} = \frac{3.413 I^2 \rho \times 144}{2.54 A \pi D} \quad \frac{\text{BTU}}{\text{Hr Ft}^2}$$

Local Heat Flow to Coolant:
$$\frac{q}{a} = (t_w - t_b) h$$

Dittus-Boelter Coefficient:
$$h = \frac{k}{D} \cdot 0.023 [Re^{.8}] [Pr^{.4}] \quad \frac{\text{BTU}}{\text{Hr Ft}^2 \text{ } ^\circ\text{F}}$$

Sieder-Tate Coefficient:
$$h = \frac{k}{D} \cdot 0.027 [Re^{.8}] [Pr^{.33}] \left[\frac{\mu_b}{\mu_w} \right]^{.14} \quad \frac{\text{BTU}}{\text{Hr Ft}^2 \text{ } ^\circ\text{F}}$$

Burnout Flux:
$$\frac{q}{a} \text{ B.O.} = 0.0135 V^{0.5} \Delta t_{\text{bsc}} \quad \frac{\text{BTU}}{\text{Hr Ft}^2}$$

(Gunther's correlation, ref. 2)

- A = Copper cross section = $.02151 \text{ in}^2$.
- L = Length of conducting copper = 21 inches.
- ρ = Local resistivity of copper, ohm-cm.
- E = Voltage drop, volts.
- I = Current, amperes.
- G = Water flow rate, LB/Hr.
- C_p = Average heat capacity, BTU/LB $^\circ$ F.
- D = Diameter of cooling passage, .125 inches.
- q = Heat flow, BTU/Hr.
- a = Surface area for heat flow, Ft 2 .
- h = Local heat transfer coefficient, BTU/Hr Ft 2 $^\circ$ F.
- t_w = Temperature of wall surface.
- t_b = Bulk water temperature.
- Δt_b = Change in bulk water temperature, entrance to exit, $^\circ$ F.
- k = Conductivity of water, BTU/Hr Ft 2 $^\circ$ F/Ft.
- V = Bulk water velocity, Ft/Sec.
- Δt_{bsc} = Difference between saturation temperature and actual water temperature at given pressure.
- Re = Reynolds modulus.
- Pr = Prandtl number.
- μ_b = Viscosity of water at bulk temperature.
- μ_w = Viscosity of water at wall surface temperature.

Table 1 - Principal Test Parameters

	TEST B	TEST 1C	TEST 2C	TEST 3C	TEST 4C	TEST 1D	TEST 2D	TEST 3D	TEST 4D	TEST 4E
Current (amps)	4500	6250	7100	6850	5550	4400	3070	3110	3070	4500
Current density (amps/in ²)	209,200	290,560	330,080	318,456	258,020	204,556	142,800	144,580	142,800	209,200
Heat flux (BTU/hr ft ²)	1.08 x 10 ⁶	1.86 x 10 ⁶	2.51 x 10 ⁶	2.09 x 10 ⁶	1.68 x 10 ⁶	1.01 x 10 ⁶	42 x 10 ⁶	536,000	511,000	1,340,000
Flow velocity (ft/sec)	27.5	55.	75.	61.	35.	28	27.5	27.8	27.8	27.8
Max. copper temp. (°F)	284	302	302	320	330	644	302	257.	255.5	366
Bulk H ₂ O outlet temp. (°F)	160	160	155	170	220	187	105.	121	115	200
Bulk outlet sub-cooling (F°)	90	91	133	83	51	87	171.	156	157	72
Wall temp. superheat (F°)	34	51	14	67	59	370	-19 to 0	-20	-16	94
Duration of test (hours)	126	207	49	11	153	95	175	192	267	—
Total time on tube (hours)	126	207	256	267	420	95	270	606	873	873
Dissolved O ₂ content (ppm)	5.5 to 8.4	8.0	8.0	1.1?	1.1	10.8	10.8	1.1	11.15	11.5
Total solids content (ppm)	~2	~2	~2	1.9	1.9	80	80	8.3	96.4	96.4
Total hardness (ppm)	<1	<1	<1	<1	<1	87.5	87.5	1	90.6	90.6
Specific resistivity (ohm-cm)	8.9 x 10 ⁶	4.2 x 10 ⁶	4.2 x 10 ⁶	7.5 x 10 ⁶	7.5 x 10 ⁶	6 x 10 ³	6 x 10 ³	6 x 10 ⁶	6.27 x 10 ³	6.27 x 10 ³
pH	7.3	7.3	7.1	7.0	6.2	7.5	7.5	6.24	7.75	7.75
Non volatile matter (ppm)	~0.8	~0.8	~0.8	~0.8	0.8	56.1	56.1	5.8	57.9	57.9

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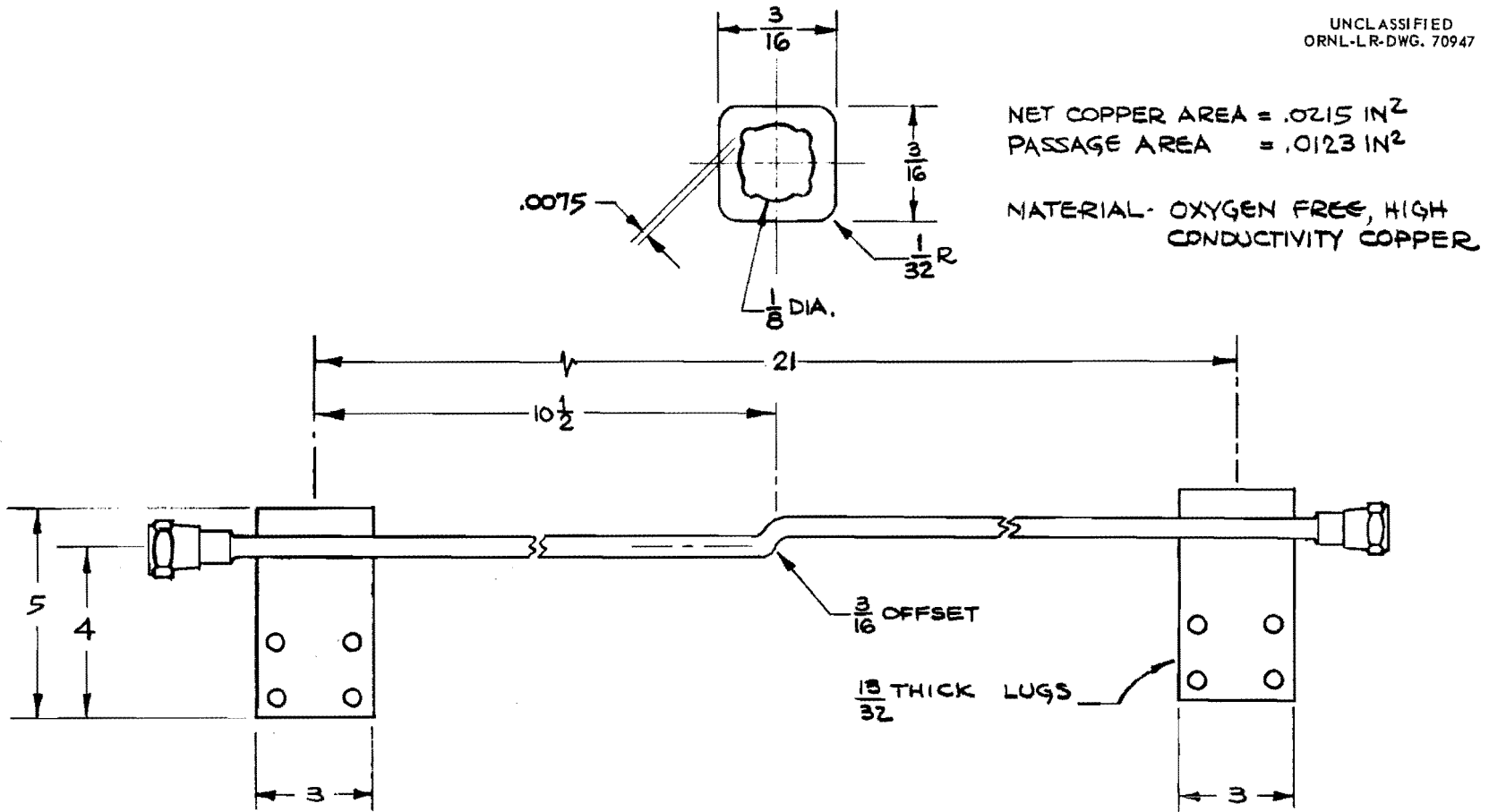


Fig. 1. Conductor Cross Section and Test Assembly.

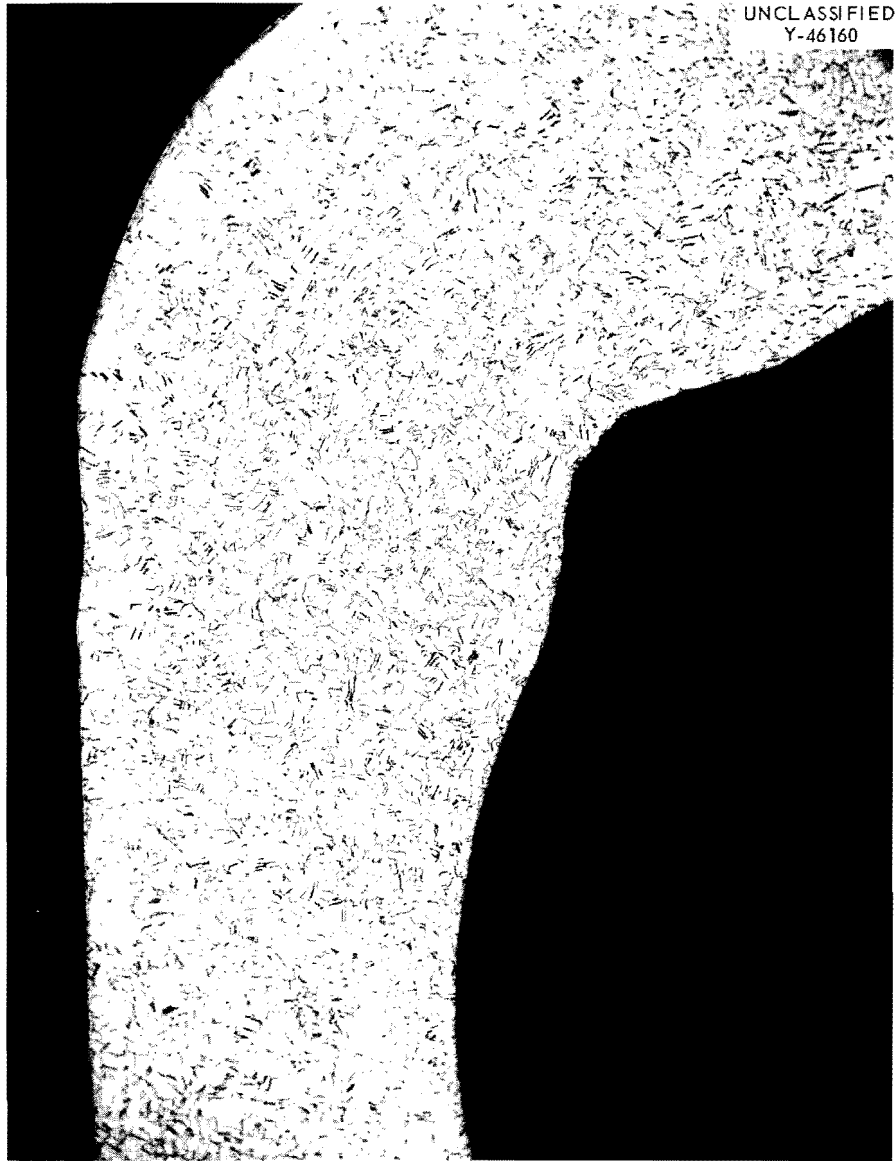


Fig. 2. Cross Section of Conductor - Polished and Etched.

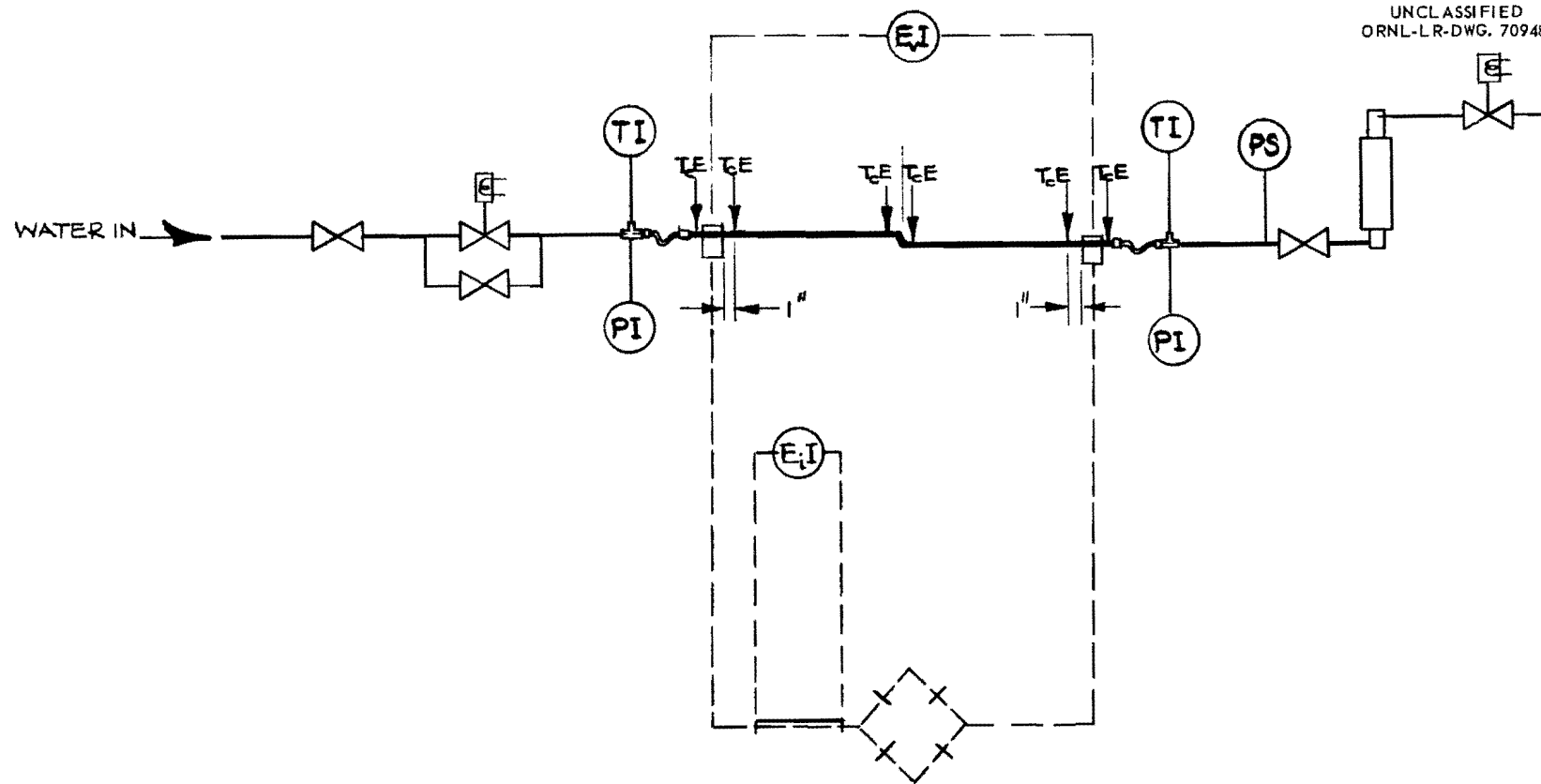


Fig. 3. Test Arrangement.

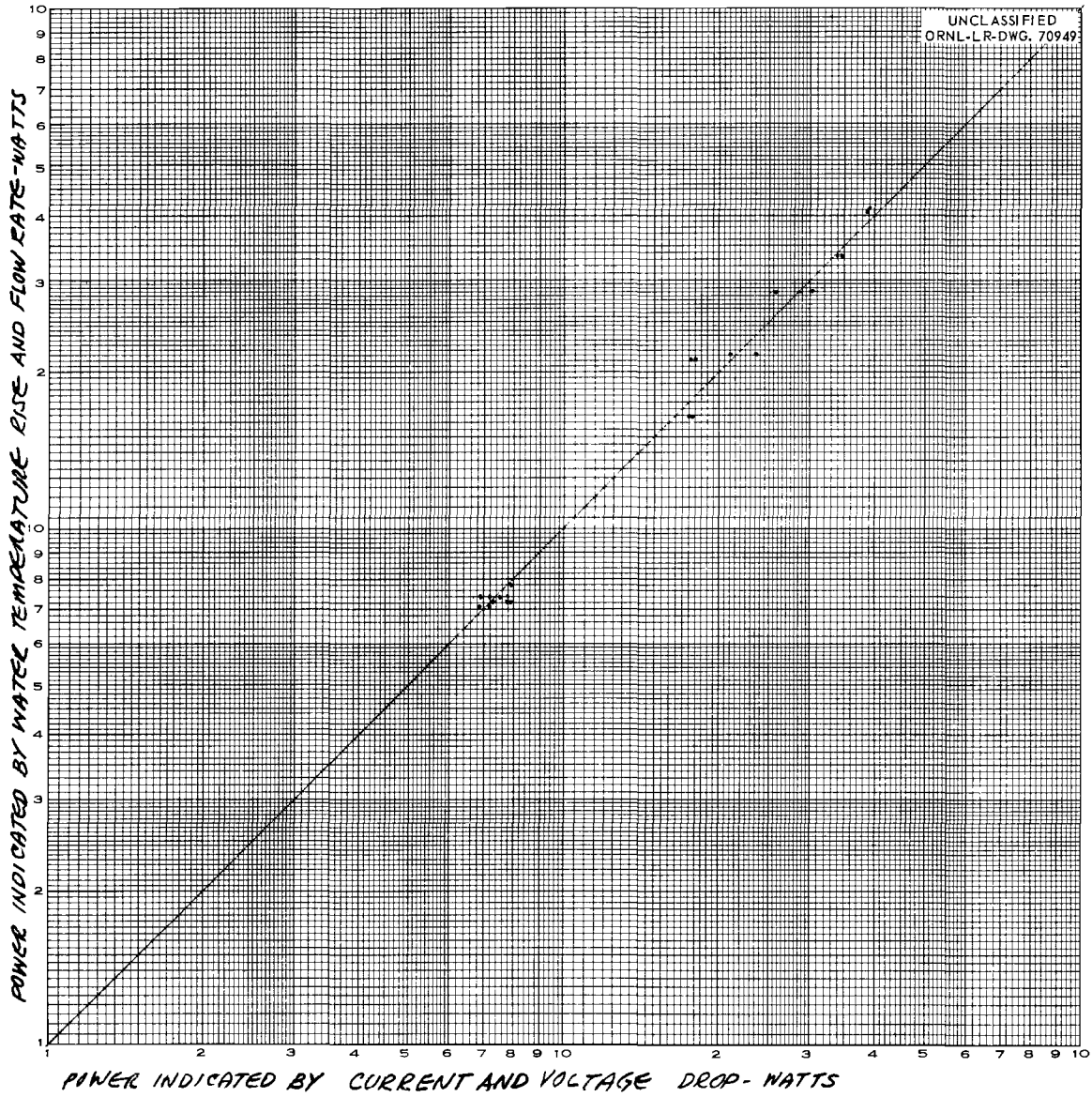


Fig. 4. Comparison of Power Removed by Water and Electrical Power Input.

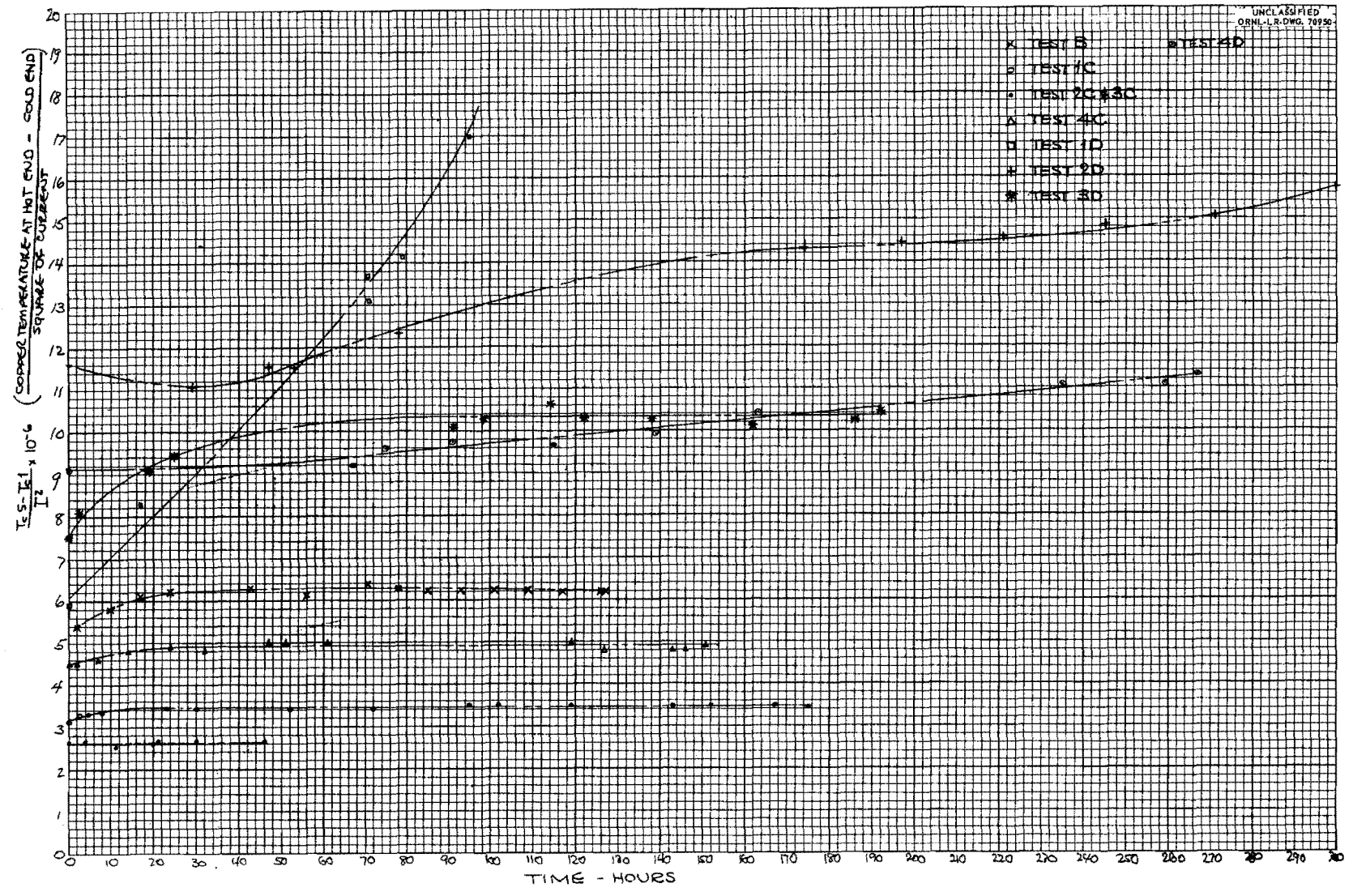


Fig. 5. Temperature Increase in Copper vs. Time.

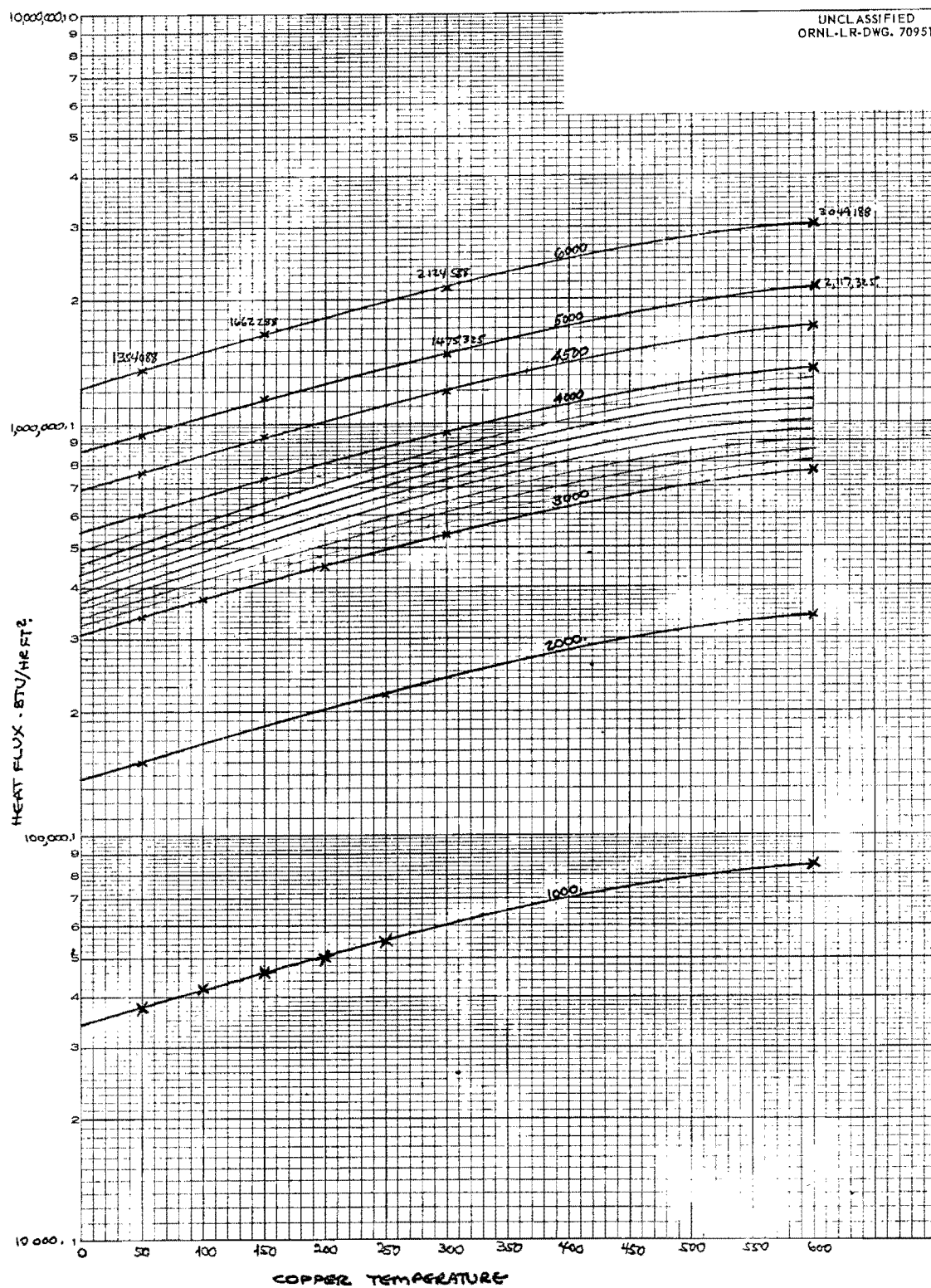


Fig. 6. Heat Flux vs. Copper Temperature for 3/16 x 3/16 Conductor at Various D.C. Current. (Flux refers to 1/8 circular internal passage.)

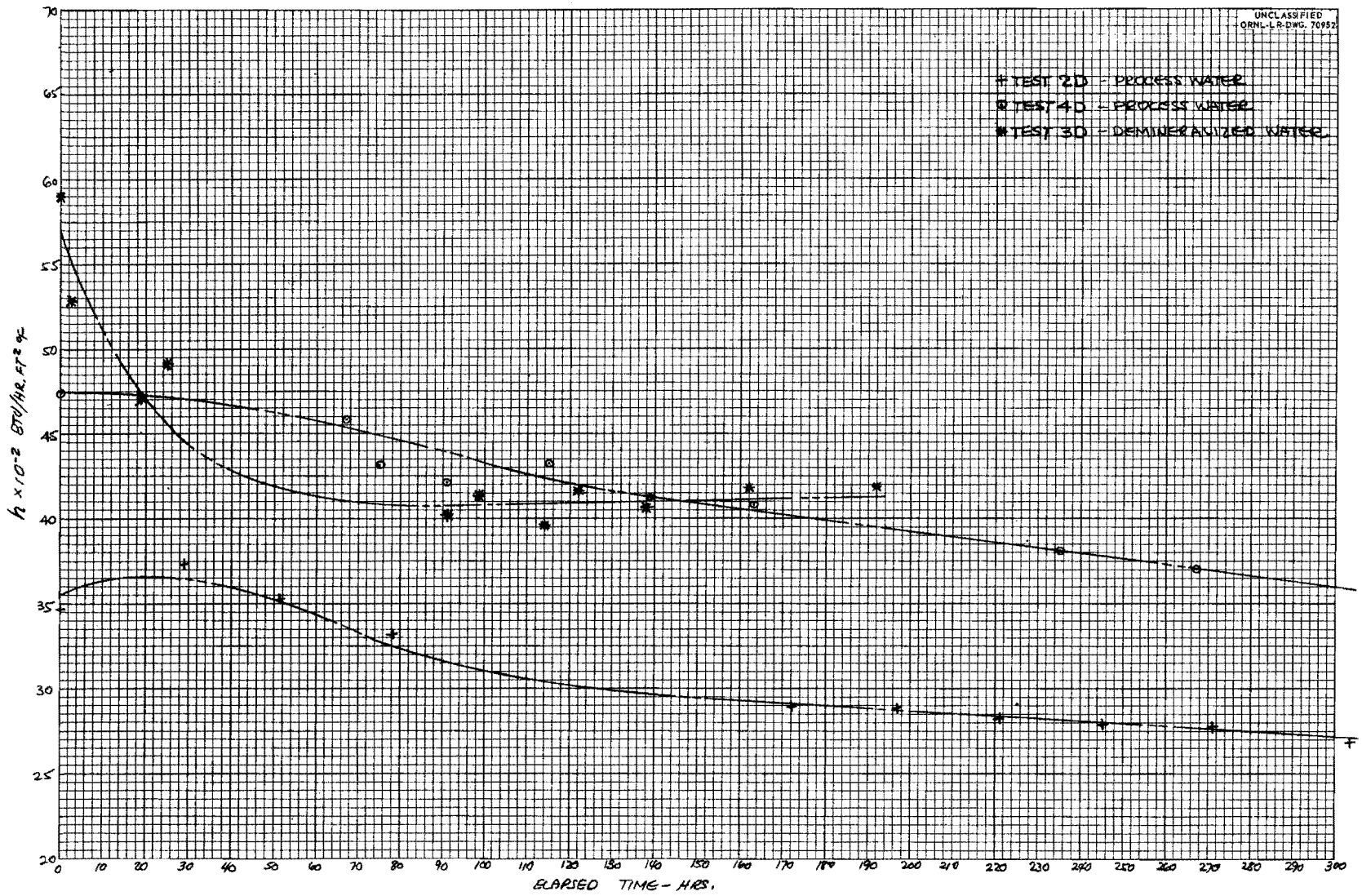
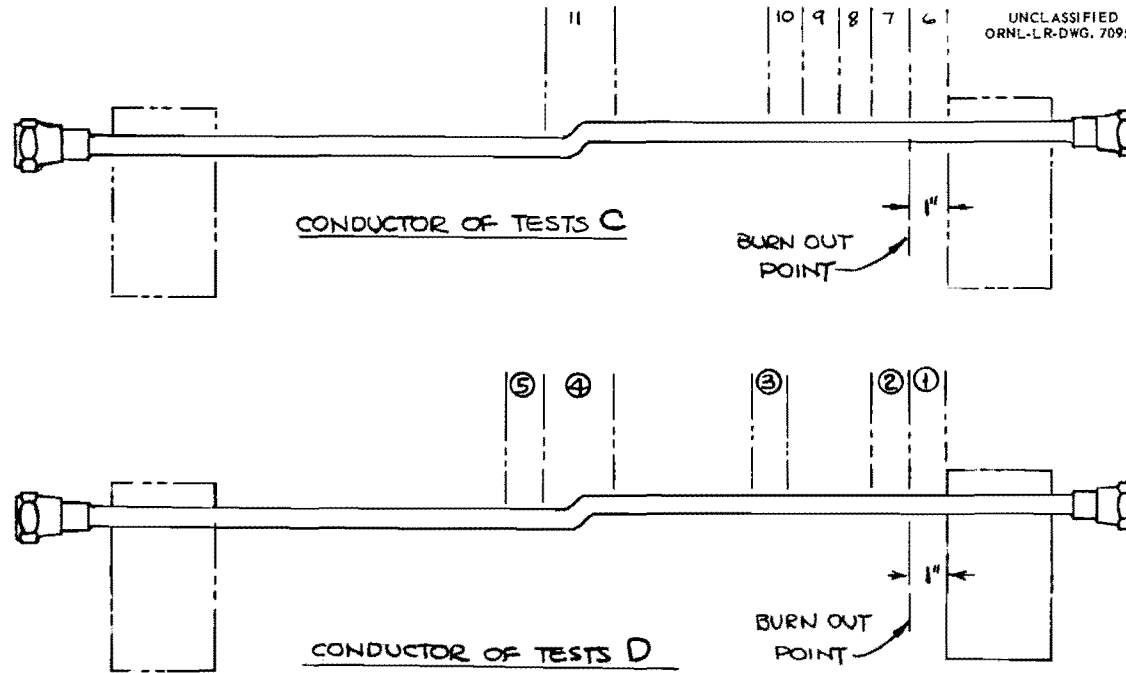


Fig. 7. Local Heat Transfer Coefficient vs. Elapsed Time.



TESTS D

- 1 - 31417
- 2 - 31418
- 3 - 31419
- 4 - 31420
- 5 - 31421

↑ SAMPLE NUMBER
↑ LOCATION

TESTS C

- 6 - 31002
- 7 - 31003
- 8 - 31004
- 9 - 31005
- 10 - 31006
- 11 - 31007

↑ SAMPLE NUMBER
↑ LOCATION

Fig. 8. Location of Samples for Metallographic Examination of Conductors C and D.

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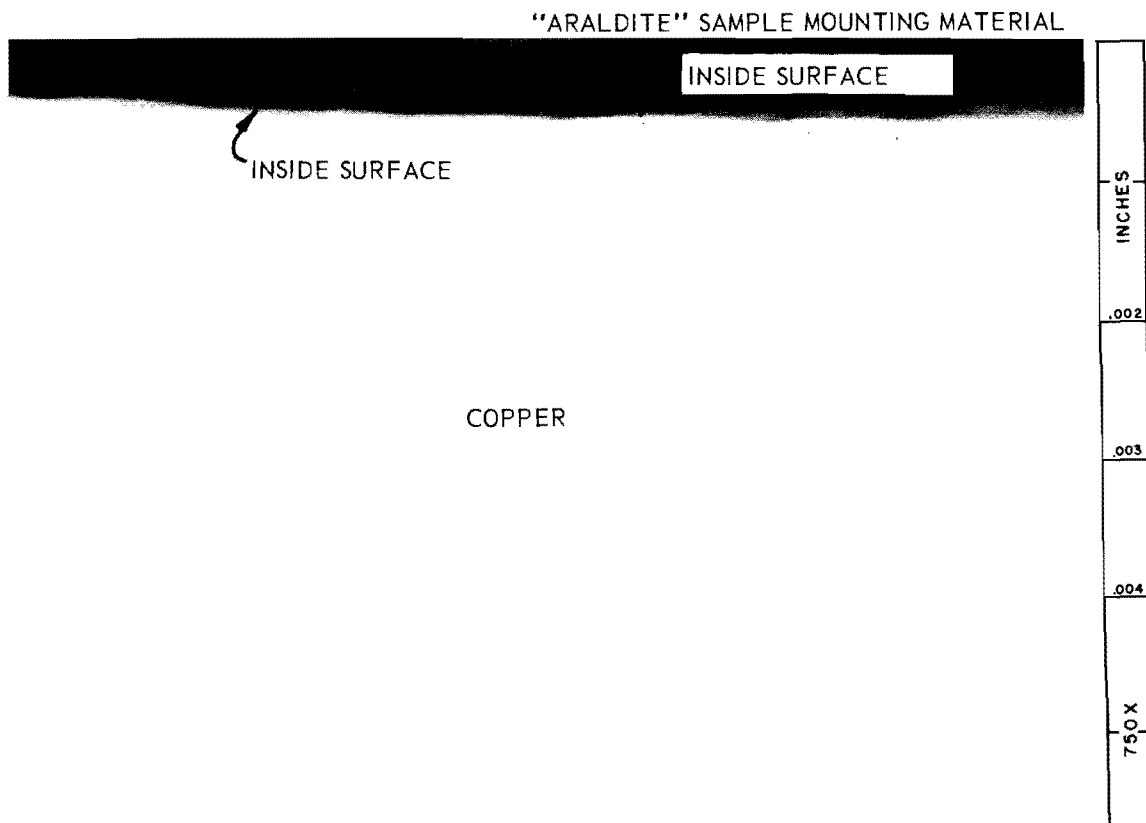


Fig. 9. Conductor As-Received. 750X. Reduced 6%.

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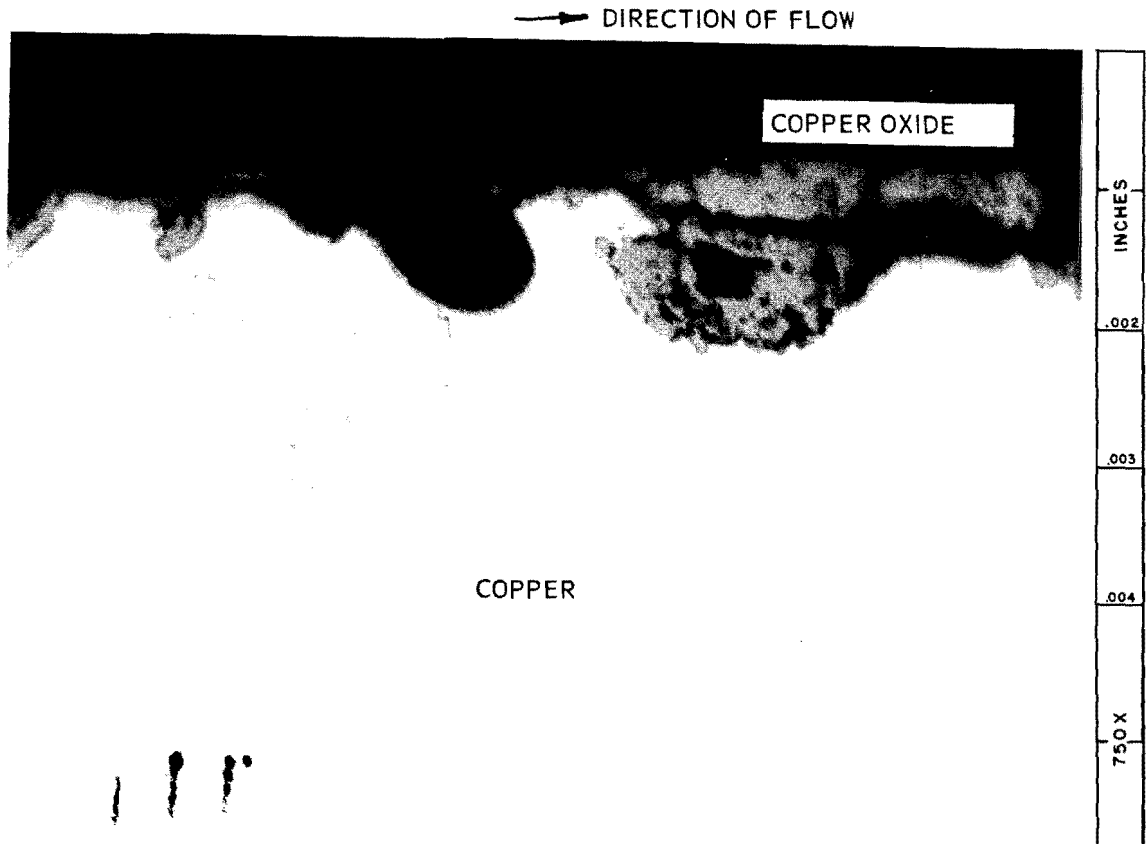


Fig. 10. Conductor C - Sample No. 31003. 750X. Reduced 6%.

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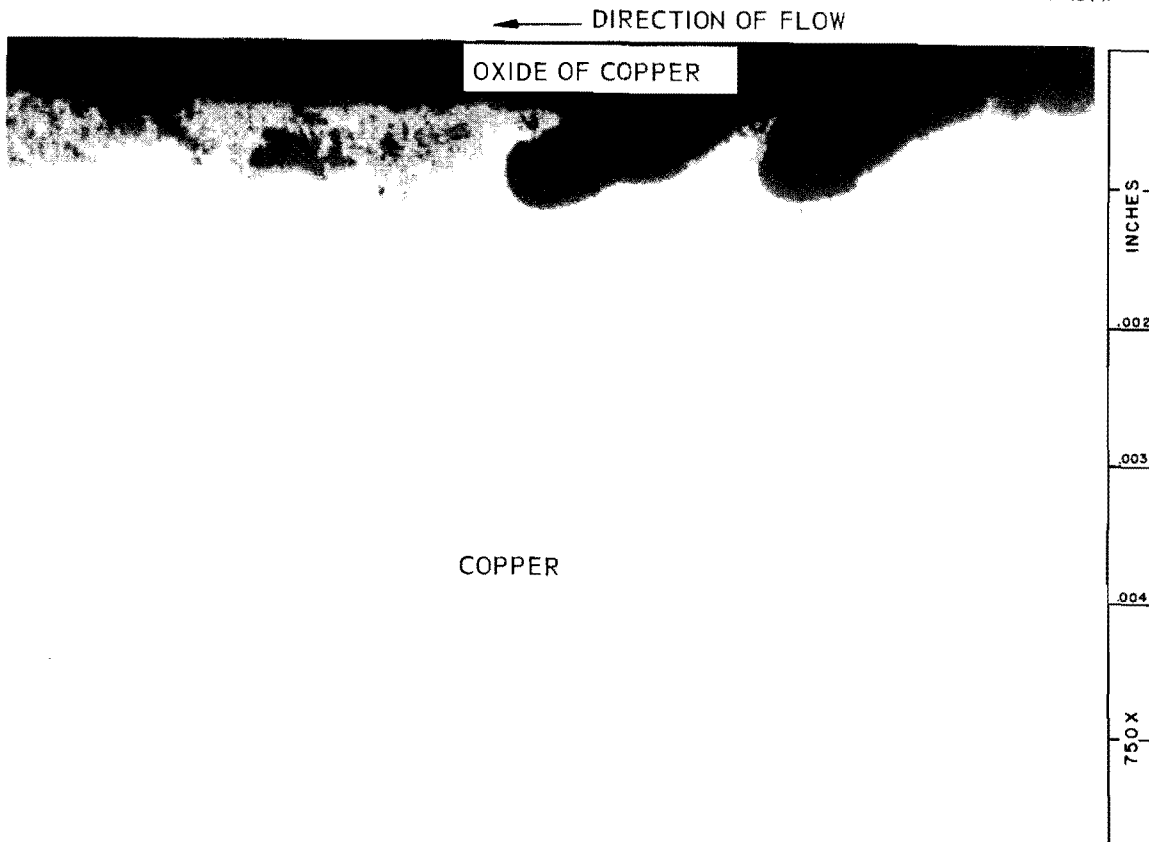


Fig. 11. Conductor C - Sample No. 31004. 750X. Reduced 6%.

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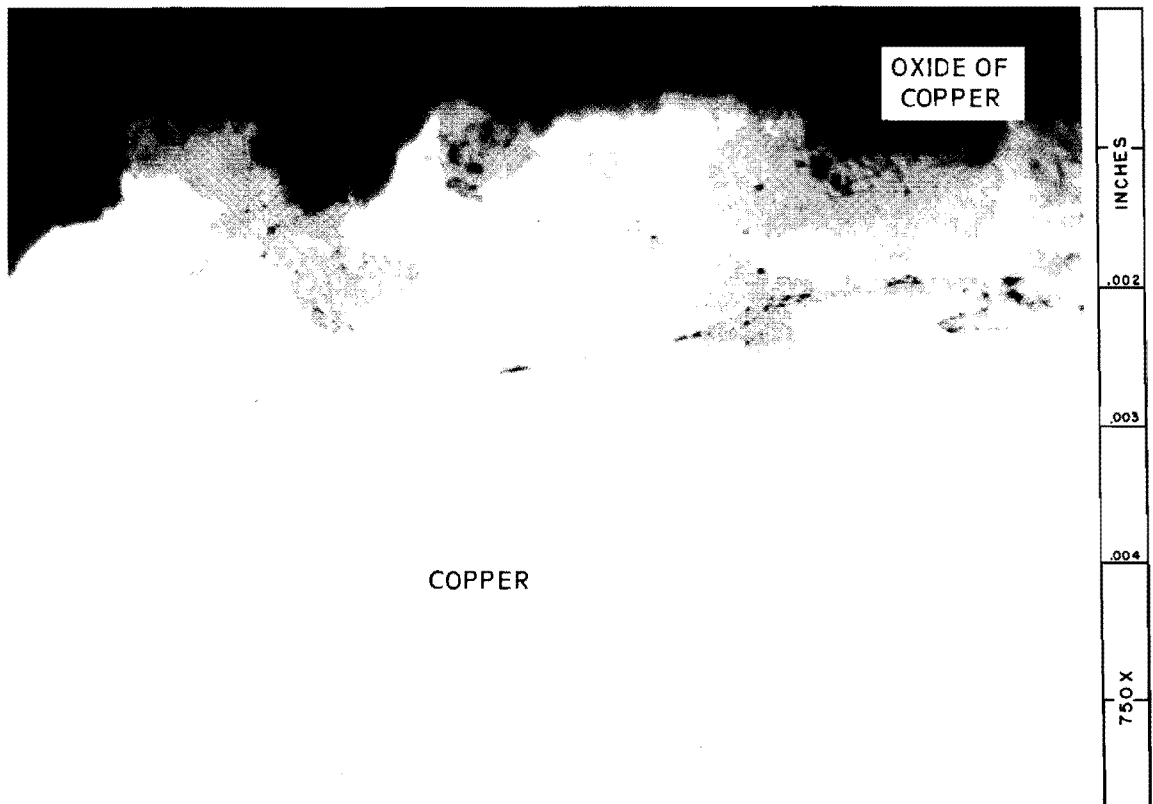


Fig. 12. Conductor C - Sample No. 31005. 750X. Reduced 6%.

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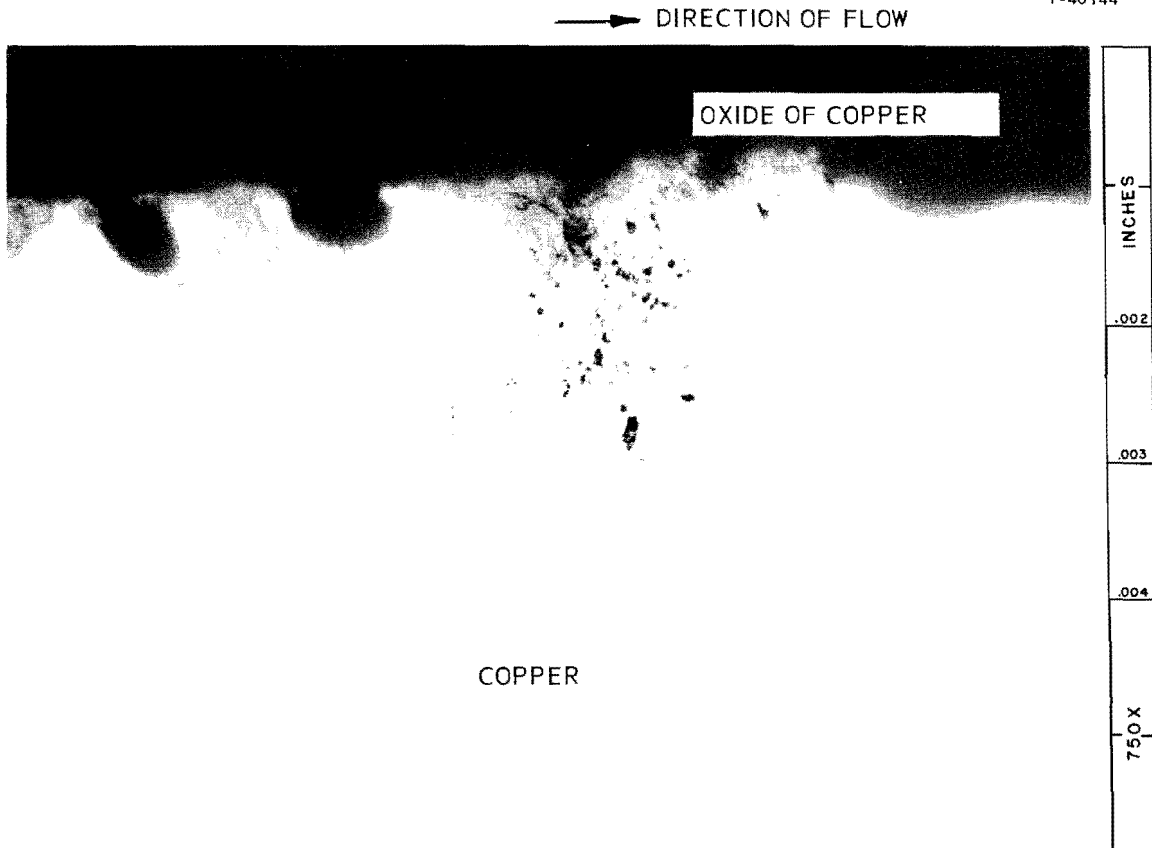


Fig. 13. Conductor C - Sample No. 31007. 750X. Reduced 6%.

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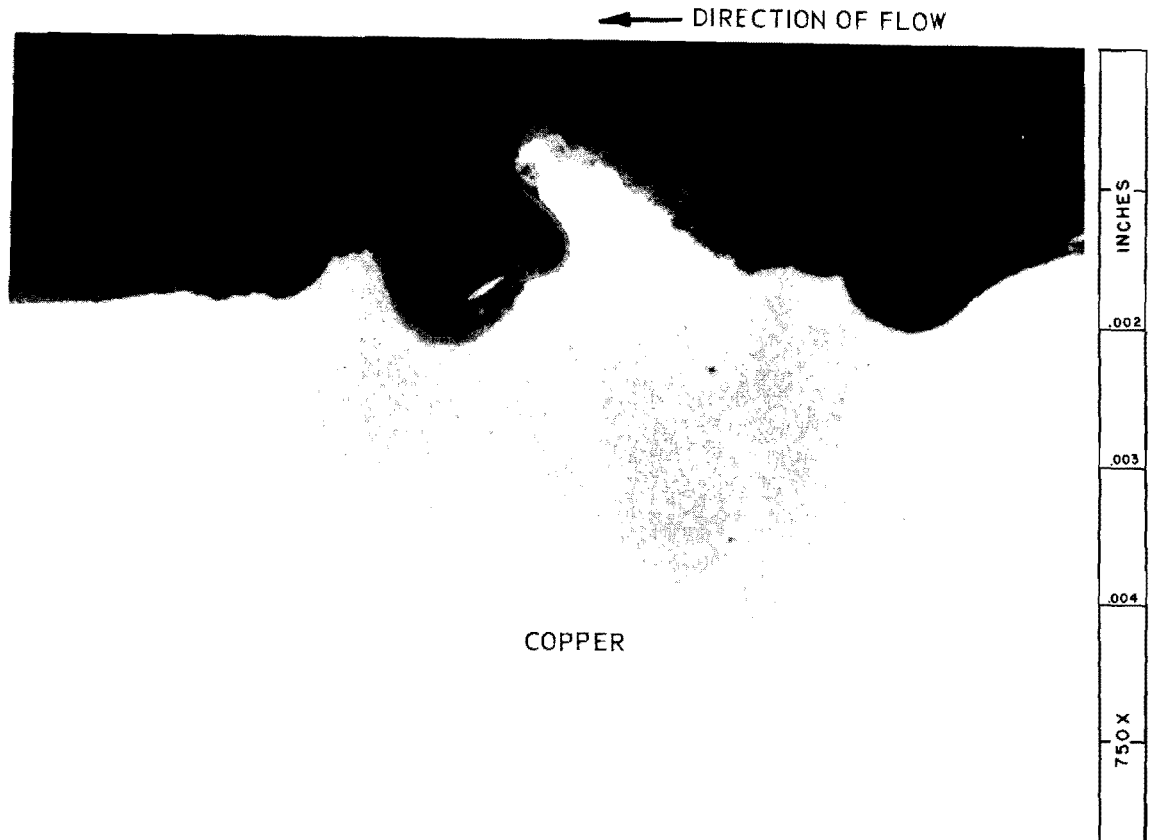
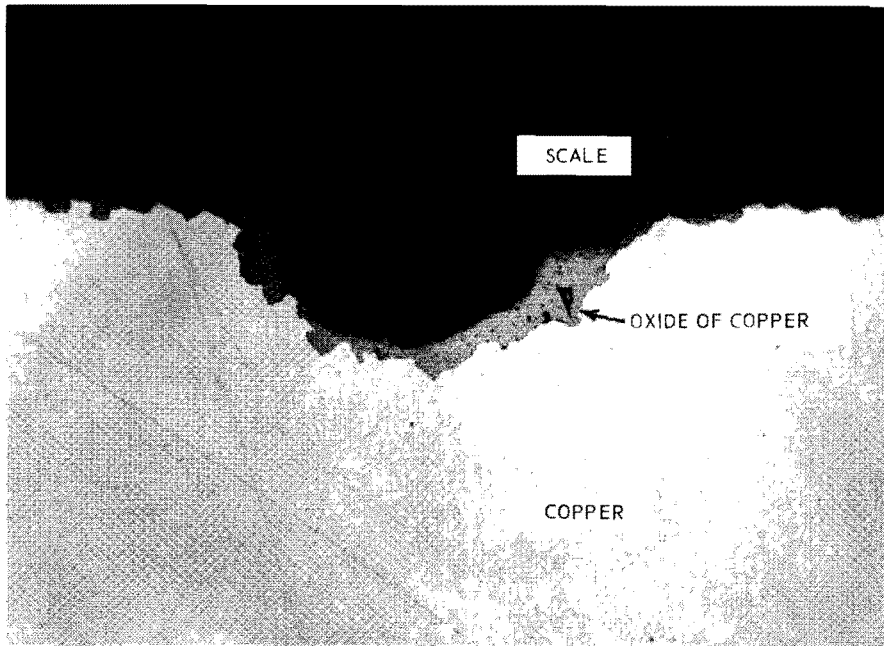


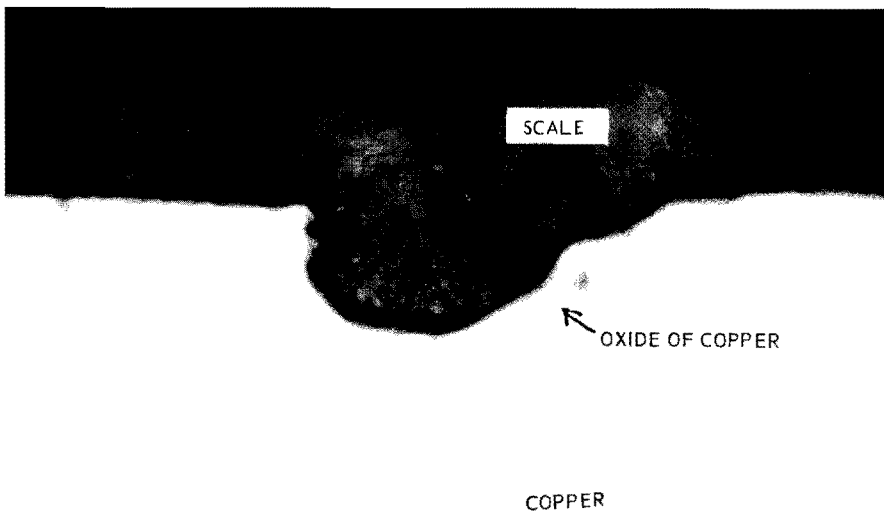
Fig. 14. Conductor C - Sample No. 31007. 750X. Reduced 6%.

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LOCATION 1 - UPSTREAM END

Fig. 15. Conductor D - Sample No. 31417 - Focused on Oxide.
750X. Reduced 26%.



LOCATION 1 - UPSTREAM END

Fig. 15a. Conductor D - Sample No. 31417 - Focused on Scale.
750X. Reduced 26%.

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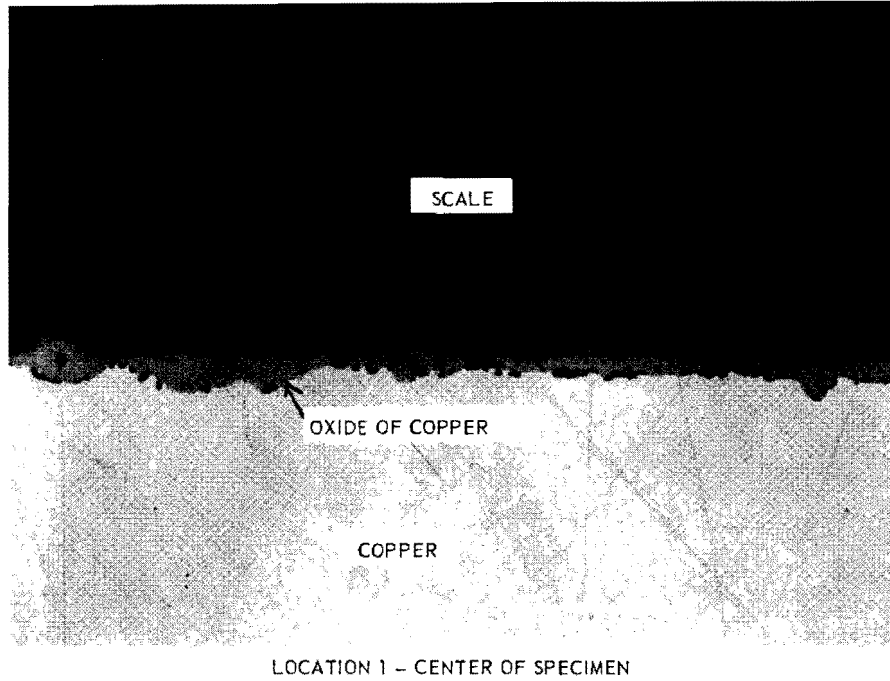


Fig. 16. Conductor D - Sample No. 31417 - Focused on Oxide.
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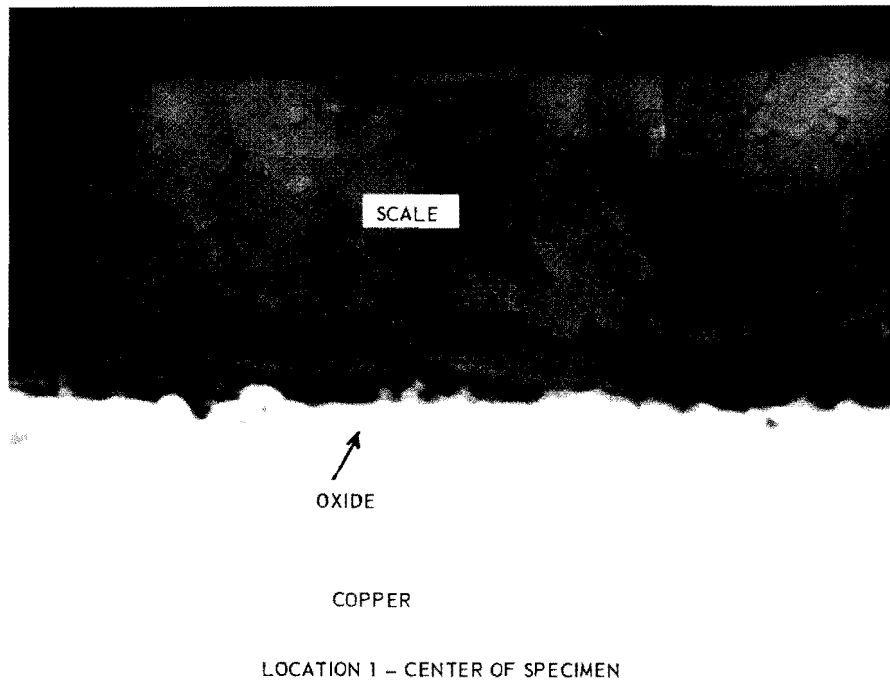
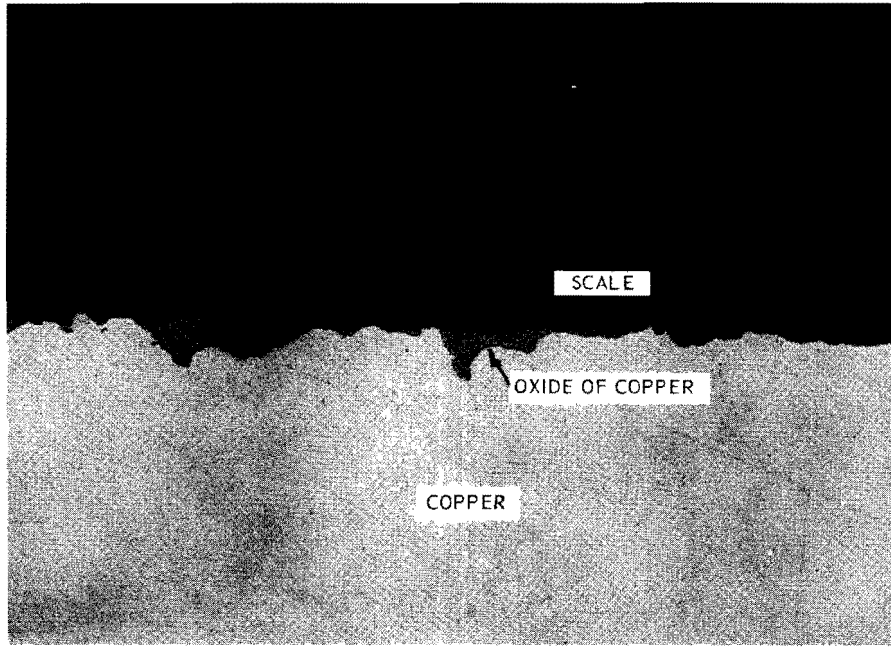


Fig. 16a. Conductor D - Sample No. 31417 - Focused on Scale.
750X. Reduced 26%.

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LOCATION 3 - CENTER OF SPECIMEN

Fig. 17. Conductor D - Sample No. 31419 - Focused on Oxide.
750X. Reduced 26%.

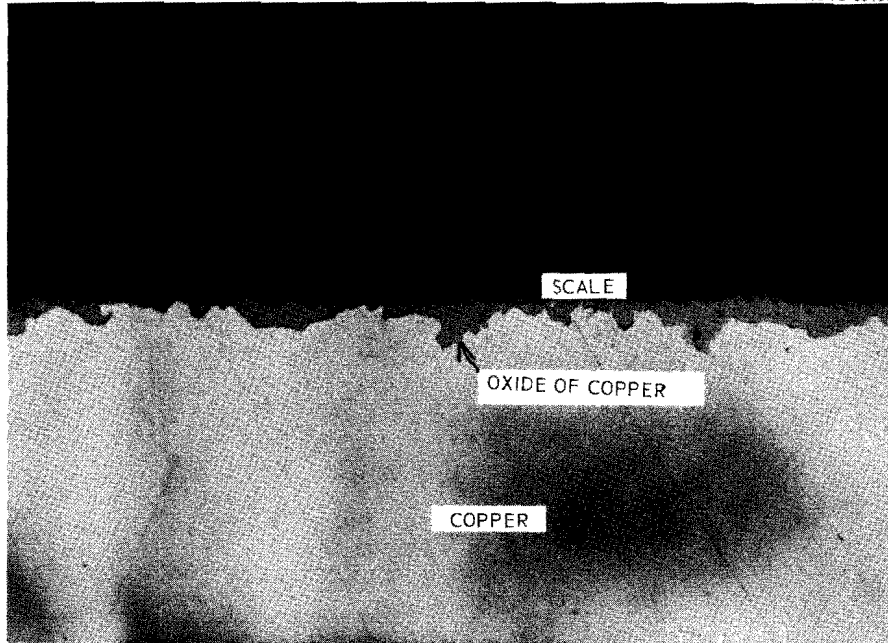


COPPER

LOCATION 3 - CENTER OF SPECIMEN

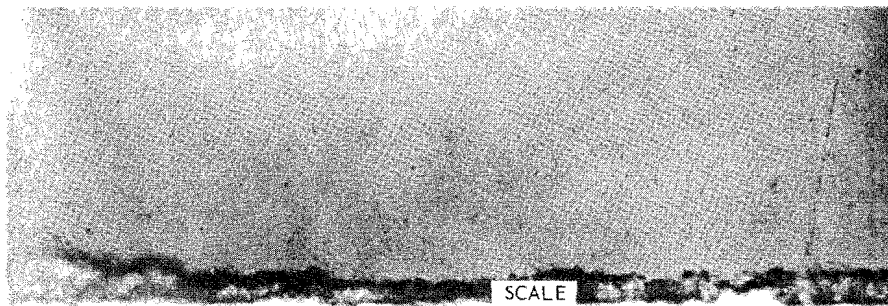
Fig. 17a. Conductor D - Sample No. 31419 - Focused on Scale.
750X. Reduced 26%.

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LOCATION 4 - UPSTREAM END

Fig. 18. Conductor D - Sample No. 31420 - Focused on Oxide.
750X. Reduced 26%.



OXIDE OF COPPER
COPPER

LOCATION 4 - UPSTREAM END

Fig. 18a. Conductor D - Sample No. 31420 - Focused on Scale.
750X. Reduced 26%.



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