Report No. DS-67-4

Project No. 520-001-11X

A STUDY OF THE FIRE RESISTANCE OF ALUMINUM ALLOY TUBING AND FITTINGS

TECHNICAL REPORT

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Prepared by

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National Aviation Facilities Experimental Center

FEDERAL AVIATION ADMINISTRATION

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ABSTRACT

A series of fire tests was conducted on aircraft aluminum alloy 5052-0 (formerly 52S) tubing and standard AN aluminum fittings. Tests consisted of subjecting specimens to a 2000°F flame from a standard 2-gph kerosene torch. The degree of fire resistance of tubing and coupling test specimens was determined for conditions of zero-flow and intermediate-flow rates up to a maximum rate in gallons per minute of five times the square of the inside diameter in inches. Oil and aviation gasoline at ambient temperatures and oil preheated to 200°F were used as the circulating fluids during testing. The investigation covered tube sizes from 1/4 to 2 in. in diameter. Aluminum tubing containing no fluid exhibited very little fire resistance; whereas, tubing containing fluid but without flow showed an increase in fire resistance with eventual failure. Under this latter test condition, the use of fire-retardant coatings on tube samples did not result in any significant increase in fire resistance. Test results revealed that aircraft aluminum tubing retained a high degree of fire resistance as long as fluid continued to circulate through the tubing to conduct heat away from the wall surface.

Couplings of 3/4-in. size and larger leaked at all flow rates tested. Couplings under 3/4-in. size exhibited no signs of leakage. Subsequent inspection of all couplings after testing revealed no signs of damage or deformation.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

Purpose: An investigation of the fire resistance of aircraft aluminum tubing and fittings was conducted for the purpose of obtaining information on the factors affecting failure of this material under powerplant fire conditions.

Background: Flammable fluid lines and fittings in designated fire zones or in any area subject to engine fire conditions must be at least fire-resistant as specified in Federal Aviation Regulations (FAR), Parts 23, 25, 27, 29, and 33. FAR Part 1 states that "fire resistant, with respect to fluid-carrying lines . . . means the capacity to withstand heat as well as aluminum alloy in dimensions appropriate for the purpose for which they are used, under the heat and other conditions likely to occur at the place concerned."

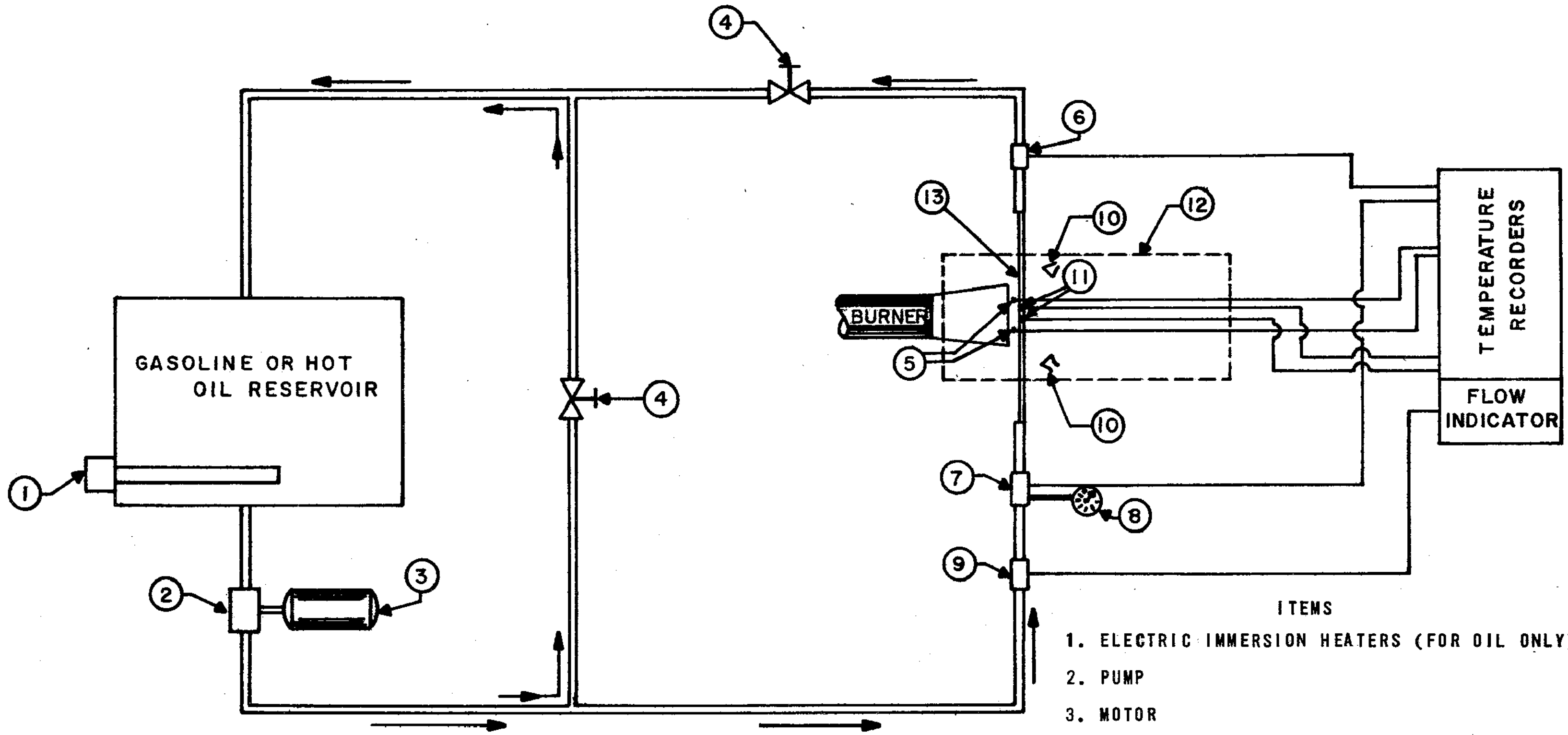
For flexible hose assemblies, the fire-resistant requirements are met by compliance with Technical Standard Order (TSO) C53a. In the absence of a standard for aluminum lines and fittings, TSO C53a was chosen to establish an initial set of test conditions since this standard is used to certify similar equipment for fire resistance. Although TSO requirements specify a flow rate as a function of inside diameter during testing, it is of importance also to consider the effect of zero- and intermediate-flow rates.

Information obtained in the fire-testing of aluminum tubing and fittings could serve as a guide in establishing fire-resistance test requirements.

TEST PROCEDURES AND MEASUREMENTS

A schematic diagram of the system used is shown in Figure 1. A photograph showing some of the equipment used appears in Figure 2. Tubing test samples, 1/4 to 2 in. in diameter, were cut into 36-in. lengths, flared, fitted with the proper size end-fittings, and placed in the test fixture. When testing aluminum couplings, the tubing samples were cut in half and the two pieces joined together by a coupling. Prior to a test run, the circulation system was pressurized to 50 psi and all connections were checked for leaks.

Chromel-alumel thermocouples were secured to the tubing samples to measure wall temperature. The ends of the thermocouple wires were bound to the tubes with high-temperature fiberglas tape and held firmly in place by a steel hose clamp. Fluid inlet and outlet temperatures were measured with chromel-alumel immersion-type probes placed inside a pipe coupling on either side of the test sample. Flame temperature was also measured by chromel-alumel thermocouples insulated by a ceramic core and shielded by an inconel sheath.



ITEMS

1. ELECTRIC IMMERSION HEATERS (FOR OIL ONLY)
2. PUMP
3. MOTOR
4. NEEDLE VALVE
5. FLAME TEMPERATURE PROBES
6. OUTLET FLUID TEMPERATURE PROBE
7. INLET FLUID TEMPERATURE PROBE
8. FLUID PRESSURE GAGE
9. FLOW METER
10. CO_2 EXTINGUISHING NOZZLES
11. TUBE TEMPERATURE PROBES
12. TEST CHAMBER
13. TEST SPECIMEN

FIG. 1 - SCHEMATIC DIAGRAM OF ALUMINUM TUBING FIRE TEST APPARATUS

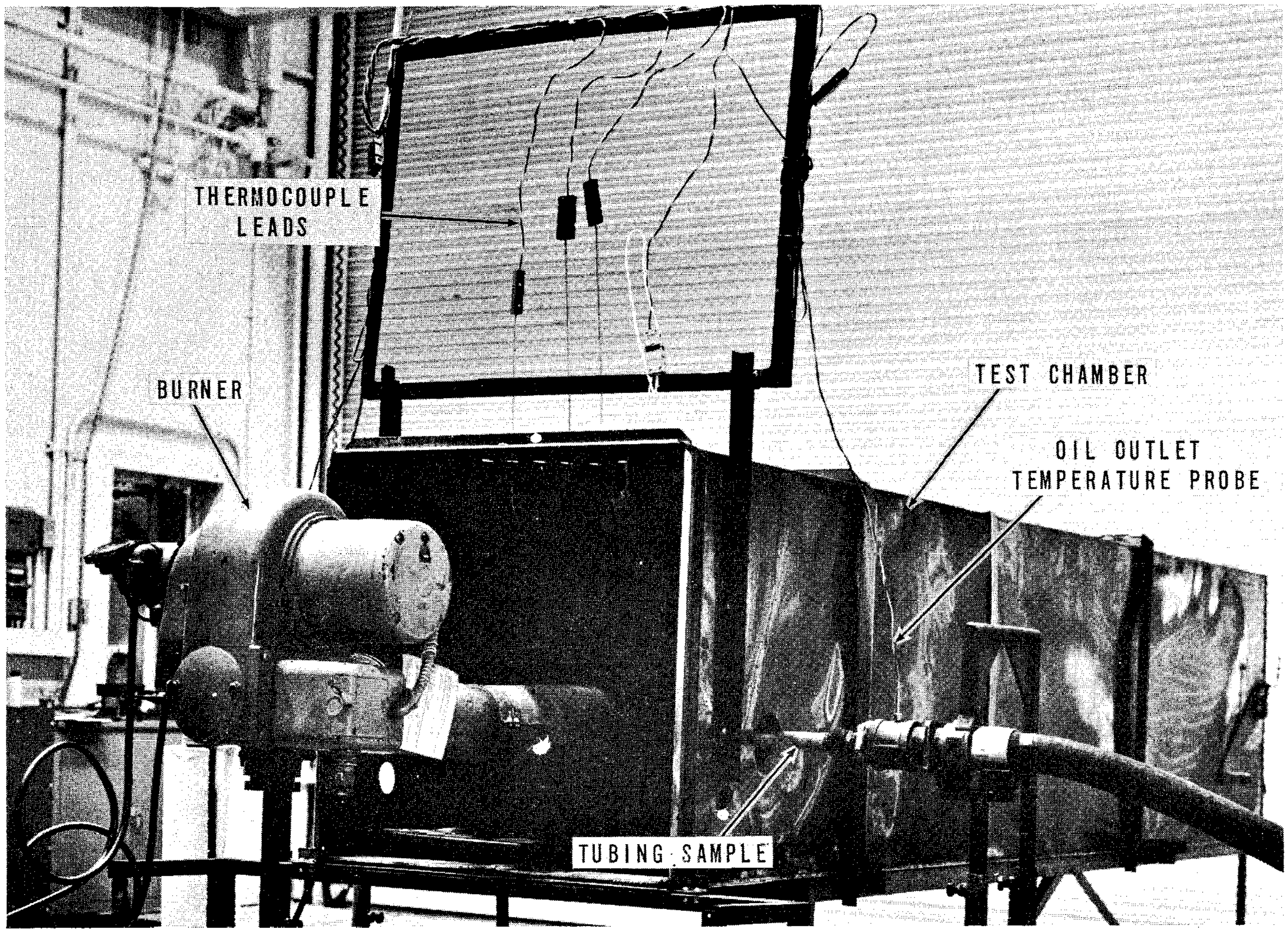


FIG. 2 - STANDARD BURNER AND TEST CHAMBER

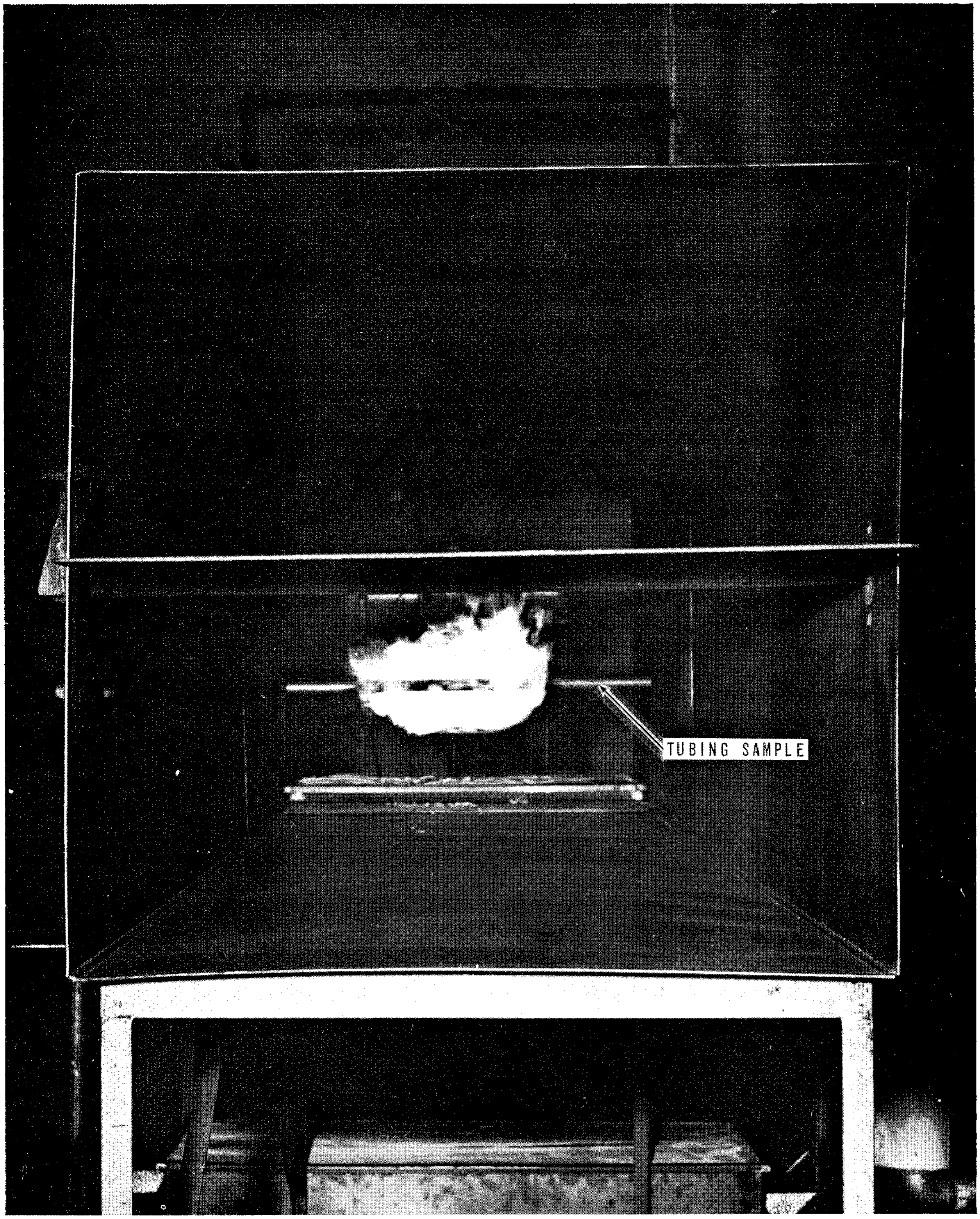


FIG. 3 - UPSTREAM VIEW OF TEST CHAMBER

The test burner used in all tests is described under Item 2, Equipment Description. This burner was adjusted to produce a flame temperature of 2000°F, measured 1/4 in. in front of the tube to be tested. Figure 3 shows an upstream view of the burner in operation with a tube sample in position.

The basic set of test conditions was derived from TSO-C53a, a standard used to establish the fire resistance of flexible hose assemblies. The maximum internal flow rate used in gallons per minute was equal to five times the square of the inside diameter (in inches). A test pressure of 30 psi and a preheat temperature of 200°F was used for the first series of tests with circulating oil. The flow rates during testing varied from zero to maximum as stated above. Zero-flow condition was obtained by closing the valve at the outlet side of the test specimen. Pressure relief in the bypass system prevented buildup in pressure above the preset 30 psi. The test fluids used were Mil-L-7808D turbine oil at room temperature and preheated to 200°F and grade 100/130 aviation gasoline.

A series of tests was conducted to determine the fire resistance of empty aluminum alloy tubing. Failure time was recorded when tube rupture occurred and was that time interval between application of the burner and tube rupture.

EQUIPMENT DESCRIPTION

The equipment used for the testing of the aluminum lines and fittings is described below:

1. Temperature Measurement and Recording: Minneapolis-Honeywell strip-chart recorders, chromel-alumel calibration, 0-2400°F range.

2. Test Burner: A Lennox kerosene burner equipped with a 2 gph, 80° hollow-cone nozzle. The end of the burner tube was fitted with an inconel extension horn to diffuse the flame over a 6 x 11-in. oval area.

3. Fluid Flow Measurement: Potter turbine-type flowmeters with a Potter digital readout frequency counter.

4. Pressure Measurement: 0-200 psi pressure gauges mounted on the test burner to monitor kerosene pressure and in the test fluid supply line at the inlet of the test specimen.

5. Aviation Gasoline Pump: Doerr, 3/4-hp electric motor driving a Blackmer pump model MX1-75.

6. Hot Oil Pump: U. S. Electric, 2-hp electric motor driving a Blackmer pump model GLA2 through a 4.9 to 1 gear box.

7. Hot Oil Reservoir: 115-gal supply heated by 2 thermostatically-controlled 40-kw electric immersion heaters.

TEST RESULTS AND ANALYSIS

For purposes of analysis, the test data are presented under the following four subheadings covering test results of empty tubing, tubing with circulating oil, tubing with circulating gasoline and tubing with fire-retardant coatings.

Fire Resistance of Empty Tubing: Fire-resistance tests were conducted on aluminum tubing constructed of alloy 5052-0. The chemical composition of this alloy is given in Table I. The test results, showing the time of failure for bare tubing in the absence of any fluid cooling or coating insulation, are shown in Table II. The aluminum tubing possessed very little fire resistance and consequently failed very rapidly. Fire resistance increased with increasing wall thickness and diameter.

Fire Resistance of Tubing Containing Circulating Oil: The test results obtained, using oil preheated to 200°F, pressurized to 30 psi, and circulating at various flow rates through the tubing, are shown in Table III. No failure of tubing under maximum flow occurred or appeared imminent up to the 60-min maximum exposure. At zero oil flow, all the tube samples failed except for one thick-walled sample which withstood a 10-min test duration without failure. Typical modes of failure for several tubes under zero oil flow conditions are shown in Figures 4a and 4b.

The effect of oil temperature on the fire resistance of the tube samples is indicated by comparing the test results in Table III with those of Table IV. With an initial oil temperature of 80°F instead of 200°F at a zero flow condition, failure time of the tube samples was approximately doubled.

The temperature rise of circulating preheated oil at a flow rate of 1 gpm through various tube sizes is shown in Table V. The test results show that the increase in oil temperature was relatively low and maintained the tubing at a temperature considerably lower than the melting point of the aluminum alloy. Oil temperature rise versus the parameter area/volume at maximum oil flow rates is shown in Figure 5. This flow rate, based on the inside diameter squared, results in a constant oil flow velocity of 2.04 fps for all tubing sizes. As indicated, the oil temperature rise increases with increasing area/volume ratio or decreasing tube size. In comparing the results shown in Table V with the curve in Figure 5, it can be seen that at constant volume flow (Table V), oil temperature rise increases with increasing tube diameter; whereas, at constant oil velocity (Figure 5), oil temperature rise decreases with increasing tube diameter.

The fire resistance of the tubing-coupling combinations at both maximum and zero flow under conditions similar to tests with tubing alone is shown in Table VI. The test results show that coupling sizes 3/4 in. and larger failed due to leakage within the first 5 min of testing. It should be noted that for flexible hose assemblies, fire-resistance

TABLE I

CHEMICAL COMPOSITION OF ALUMINUM ALLOY 5052-0 (FORMERLY 52S)

Alloying Elements	Weight Percent
Copper	0.10
Manganese	2.20/ 2.80
Iron and Silicon	0.45 max
Chromium	0.15/ .35
Zinc	0.01 max
Other	0.15 max
Aluminum	Remainder

Melting Range: 1100°F Solidus
1200°F Liquidus

TABLE II

FAILURE OF EMPTY TUBING UNDER FIRE TEST

Tube Size OD x Wall X Length (in.)	Time-to-Failure (min:sec)
1/4 x 0.035 x 36	0:10
1/2 x 0.028 x 36	0:12
1/2 x 0.042 x 36	0:17
1/2 x 0.065 x 36	0:35
3/4 x 0.028 x 36	0:15
3/4 x 0.049 x 36	0:25
1 x 0.028 x 36	0:17
1 x 0.049 x 36	0:28
1 x 0.065 x 36	0:38
1 1/2 x 0.028 x 36	0:28
1 1/2 x 0.049 x 36	0:40
2 x 0.035 x 36	0:37
2 x 0.065 x 36	1:03

TABLE III

FIRE RESISTANCE OF TUBING AT MAXIMUM AND ZERO OIL FLOW

Tube Size OD x Wall x Length (in.)	Oil Flow[1] (gpm)	Test Duration (min:sec)	Failure Yes	 No
1/4 x 0.035 x 36	0.15	60:00		x
	0.0	0:20	x	
1/2 x 0.028 x 36	1.0	60:00		x
	0.0	0:55	x	
1/2 x 0.042 x 36	0.9	60:00		x
	0.0	0:36	x	
1/2 x 0.065 x 36	0.7	60:00		x
	0.0	0:30	x	
3/4 x 0.028 x 36	2.4	60:00		x
	0.0	3:38	x	
3/4 x 0.049 x 36	2.1	60:00		x
	0.0	6:33	x	
1 x 0.028 x 36	4.8	60:00		x
	0.0	4:22	x	
1 x 0.049 x 36	4.1	60:00		x
	0.0	6:40	x	
1 x 0.065 x 36	3.8	60:00		x
	0.0	6:22	x	
1 1/2 x 0.028 x 36	10.4	60:00		x
	0.0	4:30	x	
1 1/2 x 0.049 x 36	9.8	60:00		x
	0.0	4:59	x	
2 x 0.035 x 36	18.6	60:00		x
	0.0	3:10	x	
2 x 0.065 x 36	17.5	60:00		x
	0.0	10:00		x

NOTE: (1) The maximum oil flow rate (gpm) = $5D^2$, where D is inside diameter in inches. Inlet oil temperature and pressure were 200°F and 30 psi, respectively. Inlet oil temperature measured at inlet of tubing sample.

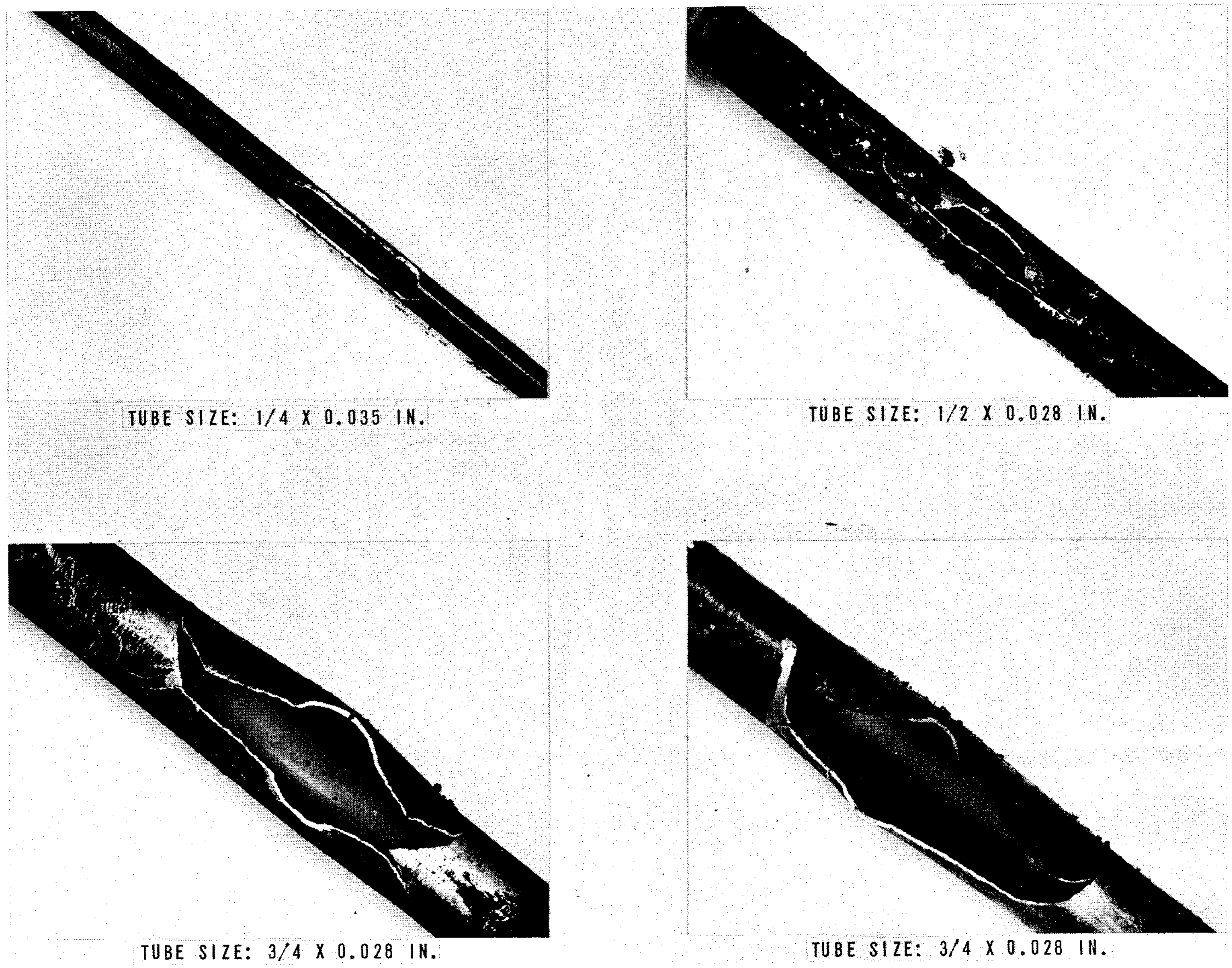
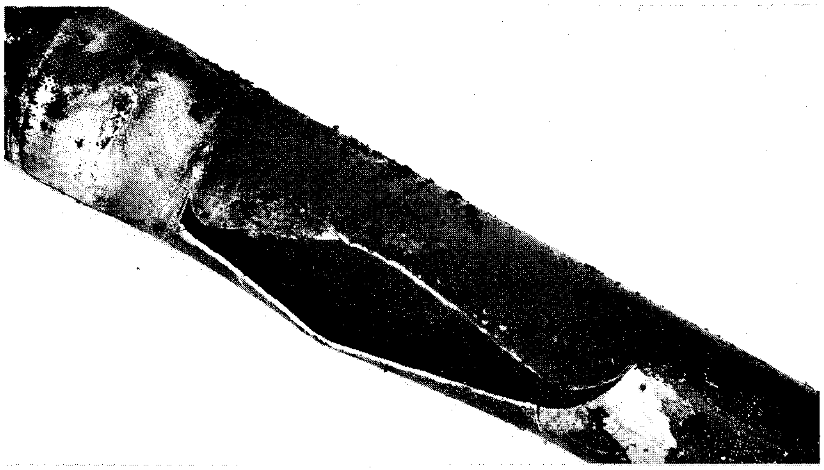
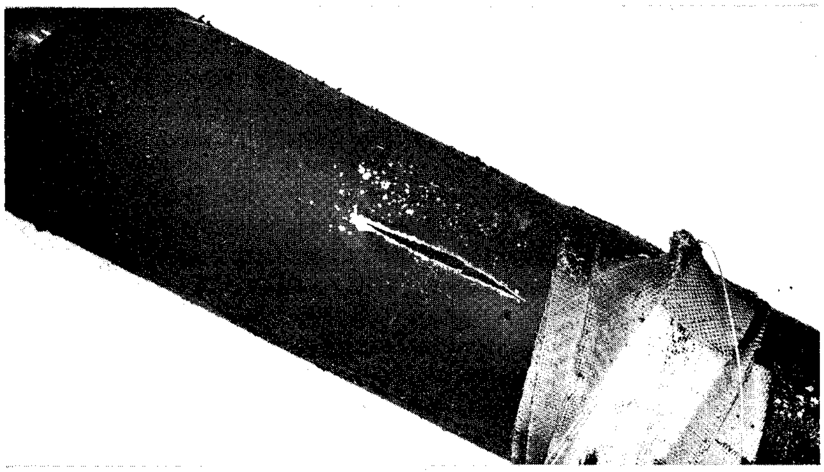


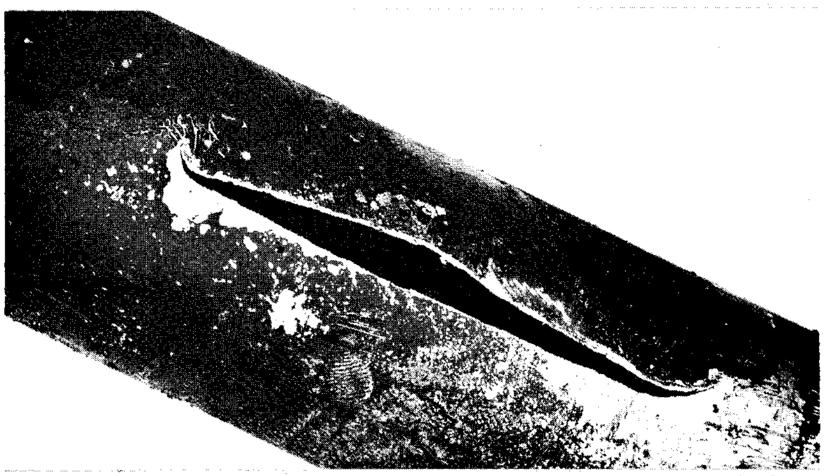
FIG. 4a - SMALL DIAMETER ALUMINUM TUBING FAILURES



TUBE SIZE: 1 X 0.028 IN.



TUBE SIZE: 1½ X 0.028 IN.



TUBE SIZE: 2 X 0.035 IN.

FIG. 4b - LARGE DIAMETER ALUMINUM TUBING FAILURES

TABLE IV

FIRE RESISTANCE OF TUBING AT ZERO FLOW WITH OIL AT ROOM TEMPERATURE

Tube Size OD x Wall x Length (in.)	Oil Pressure (psi)	Inlet Oil Temperature[1] (°F)	Time-to-Failure (min:sec)
1 x 0.028 x 36	30	80	9:23
1 x 0.049 x 36	30	80	12:25
1 x 0.065 x 36	30	80	11:14

NOTE:

(1) Inlet oil temperature measured at inlet of tubing sample.

TABLE V

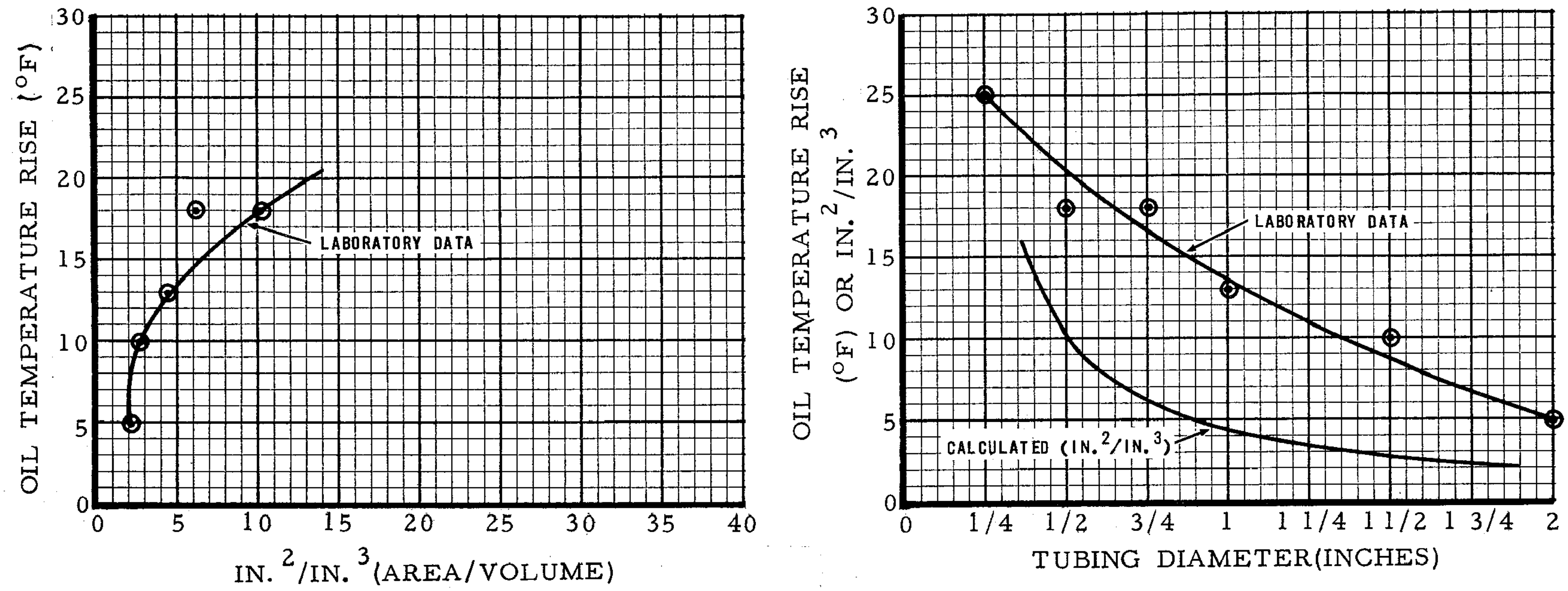
OIL TEMPERATURE RISE FOR VARIOUS TUBING SIZES AT 1 GPM FLOW

Tube Size	Oil Pressure	Oil Temperature Rise[1]	Failure[2]	
OD x Wall x Length (in.)	(psi)	(°F)	Yes	No
1/2 x 0.028 x 36	30	18		x
3/4 x 0.028 x 36	30	28		x
1 x 0.028 x 36	30	59		x
1 1/2 x 0.028 x 36	30	108		x
2 x 0.035 x 36	30	118		x

NOTES:

(1) Outlet and inlet oil temperatures were taken at outlet and inlet of tubing sample, respectively, and are stabilized temperatures. Inlet oil temperature was 200°F.

(2) All tubing listed was fire-tested for 60 min.



NOTES:

1. AREA/VOLUME = SURFACE AREA/OIL VOLUME
2. TUBE WALL THICKNESS FOR CURVES SHOWN IS 0.028 IN. EXCEPT 0.035 FOR 2 IN. TUBE
3. OIL TEMPERATURE RISE BASED ON HEATED OIL (200°F) AT A FLOW RATE IN GPM EQUAL TO $5D^2$ WHERE D² IS INSIDE DIAMETER IN INCHES (CONSTANT VELOCITY = 2.04 fps)

FIG. 5 - OIL TEMPERATURE VARIATION WITH TUBE DIAMETER AND AREA/VOLUME RATIO

requirements are met by operating without leakage for 5 min. Based on this criteria, only sizes smaller than 3/4 in. passed the fire test. In comparing the results in Tables III and VI, it can be seen that failure times were greater at the no-flow condition for line sizes 3/4 in. and larger when a coupling was included. This was probably due to the fact that the leakage around the coupling resulted in a small internal fluid flow, thereby carrying away some of the heat with the consequence of greater time-to-failure.

The temperatures of both the tubing and the coupling at different flow rates including no-flow are shown in Table VII. A tensile strength versus temperature curve for aluminum alloy 5052-0, plotted with information obtained from the "Engineering Materials Handbook" (References), is shown in Figure 6. The test results show a considerable temperature difference between the coupling and tubing. This indicates that differential expansion may be responsible for leakage of oil observed around the coupling. This is further substantiated by the fact that when the burner was shut off, leakage gradually diminished until it stopped completely. There was no apparent physical damage to the coupling itself. The temperatures at the instant of failure give some indication of maximum operating temperature of the alloy at the test pressure.

An analytical method for predicting tubing wall temperature is presented in Appendix 1. A calculated time-temperature rise is based on a predetermined hot-oil flow rate, and a comparison is made between calculated and experimental results, as shown in Figures 2a, 2b, and 2c of the Appendix. The curves show a close agreement.

Fire Resistance of Tubing Containing Circulating Gasoline: The test results with circulating gasoline at 30-psi pressure through small diameter tubing at both maximum and zero flow conditions are shown in Table VIII. The results are similar to those obtained with preheated oil. Failure again occurred only at zero flow.

The results shown in Table IX are for a series of tests conducted on 1/2-in. tubing in which the pressure as well as the flow was varied. Test-monitoring equipment indicated that at low flows, the gasoline began to vaporize in the tube. Reducing the pressure from 30 psi apparently increased the vaporization rate, forming gaseous pockets and so reducing the capacity to carry away the heat. At sufficiently low pressures and flow rate, the tube eventually ruptured. At pressures of 15 and 10 psi at a 0.25-gpm flow rate, rupture occurred within the 5-min test duration.

Fire Resistance of Tubing with Fire-Retardant Coatings: The test results on tubing samples protected by fire-retardant coatings are contained in Tables X and XI. Fire resistance as shown was increased only slightly. The intumescent epoxy coatings (1 and 2 of Tables X and XI), upon swelling, became very fragile. The action of the flame tended to erode this coating, exposing the underlying aluminum tubing. The silicone rubber coating gave slightly better protection, but neither coating offered a significant increase in fire resistance.

TABLE VI

FIRE RESISTANCE OF TUBING-COUPLING COMBINATION AT MAXIMUM AND ZERO FLOW

Tube Size OD x Wall x Length (in.)	Oil Flow(1) (gpm)	Test Duration (min:sec)	Failure(2) Yes	Failure(2) No	Coupling Leakage (3) Yes	Coupling Leakage (3) No
1/4 x 0.035 x 36	0.15	15:00		x		x
	0.0	0:26	x			x
1/2 x 0.028 x 36	1.0	15:00		x		x
	0.0	0:45	x			x
3/4 x 0.028 x 36	2.4	15:00		x	x	
	0.0	8:43	x		x	
1 x 0.028 x 36	4.5	15:00		x	x	
	0.0	6:49	x		x	
1 1/2 x 0.028 x 36	10.4	15:00		x	x	
	0.0	5:24	x		x	
2 x 0.035 x 36	18.6	15:00		x	x	
	0.0	4:54	x		x	

NOTES:

(1) The maximum flow rate (gpm) = $5D^2$, where D is inside diameter in inches. Inlet oil temperature and pressure were 200°F and 30 psi, respectively.

(2) Failure consists of tubing rupture.

(3) Coupling sizes 3/4 in. and larger leaked under maximum oil flow and zero flow, constituting a failure. The couplings themselves did not rupture.

TABLE VII

TEMPERATURE RISE OF TUBING-COUPLING COMBINATION AT VARIOUS OIL FLOW RATES FOR 1 1/2-INCH TUBING

Tube Size OD x Wall x Length (in.)	Oil Flow (gpm)	Coupling Temperature (°F)	Tube Temperature (°F)	Temperature Difference between Coupling and Tube (°F)
1 1/2 x 0.028 x 36	10.4(1)	640	475	165(2)
1 1/2 x 0.028 x 36	1.0	715	615	100(2)
1 1/2 x 0.028 x 36	0.0	760	710	50(3)
1 1/2 x 0.028 x 36	0.0	850	835	15(4)

NOTES:

(1) Maximum flow rate for this tube size. Inlet oil temperature and pressure for all tests in this table were 200°F and 30 psi, respectively.

(2) Tubing and coupling temperatures are stabilized temperatures.

(3) Temperatures 1 min before tube failure.

(4) Temperatures at instant of tube failure.

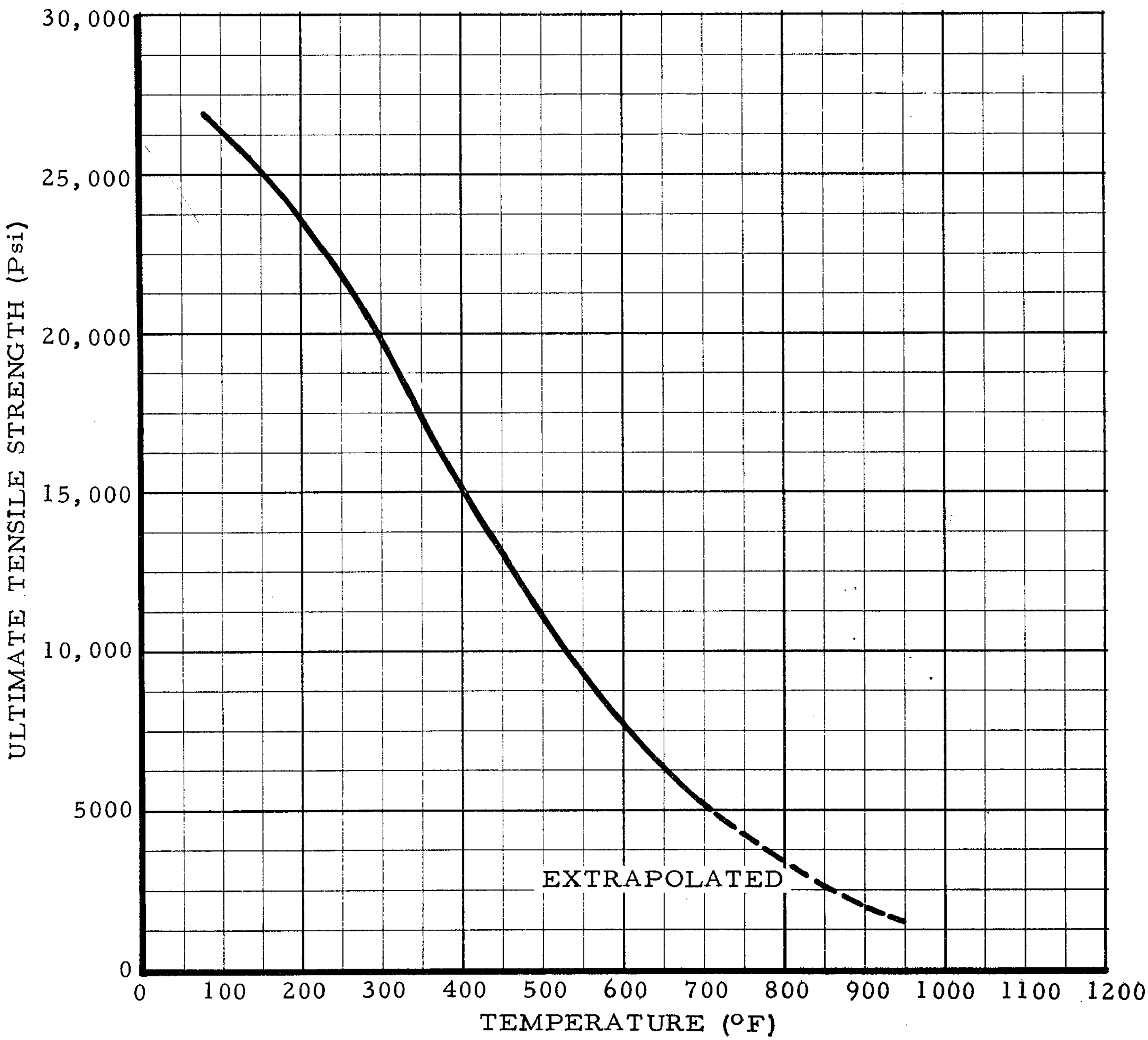


FIG. 6 - TENSILE STRENGTH VARIATION WITH TEMPERATURE FOR ALUMINUM ALLOY 5052-0

TABLE VIII

FIRE RESISTANCE OF TUBING AT MAXIMUM AND ZERO GASOLINE FLOW

Tube Size OD x Wall x Length (in.)	Gasoline Flow [1] (gpm)	Test Duration (min:sec)	Failure Yes	 No
1/4 x 0.035 x 36	0.05 (2)	15:00		x
1/4 x 0.035 x 36	0.0	0:16	x	
1/2 x 0.028 x 36	1.00 (2)	15:00		x
1/2 x 0.028 x 36	0.0	0:41	x	

NOTES:

(1) Inlet gasoline temperature and pressure were 40°F and 30 psi, respectively.

(2) Maximum gasoline flow rate (gpm) = $5D^2$, where D is inside diameter in inches.

TABLE IX

FIRE RESISTANCE OF 1/2-INCH TUBING AT VARIOUS GASOLINE FLOW RATES AND PRESSURES

Tube Size OD x Wall x Length (in.)	Gasoline Flow (gpm)	Gasoline Pressure (psi)	Gasoline(2) Temperature In(°F)	Gasoline(2) Temperature Out(°F)	Tube(3) Temperature (°F)	Test Duration (min:sec)	Failure Yes	Failure No
1/2 x 0.028 x 36	1.0 (1)	30	40	55	250	5:00		x
	1.0 (1)	20	40	55	250	5:00		x
	1.0 (1)	10	40	55	250	5:00		x
1/2 x 0.028 x 36	0.5	30	40	80	255	5:00		x
	0.5	20	40	80	255	5:00		x
	0.5	10	40	80	255	5:00		x
1/2 x 0.028 x 36	0.25	30	55	145	290	5:00		x
	0.25	25	55	135	275	5:00		x
	0.25	20	55	130	275	5:00		x
	0.25	15	55	125	275 (4)	4:50	x	
	0.25	10	55	125	275 (5)	2:57	x	
1/2 x 0.028 x 36	0.0	30	-	-	-	0:30	x	
	0.0	30	-	-	-	0:41	x	

NOTES:

(1) Maximum flow rate for this tube size.
(2) Gasoline outlet and tubing temperatures are stabilized temperatures.
(3) Tubing temperatures were measured within flame area.
(4) 275°F tubing temperature is stabilized temperature before failure. Peak temperature at instant of failure was 900°F.
(5) 275°F tubing temperature is stabilized temperature before failure. Peak temperature at instant of failure was 1000°F.

TABLE X

DESCRIPTION OF FIRE-RETARDANT COATING SPECIMENS

Tube Number	Tube Size OD x Wall (in.)	Coating Type	Nominal Coating Thickness (in.)	Nominal Coating Weight (oz/in.)
1	1/2 x 0.028	Intumescent Epoxy	0.012	0.004
2	1/2 x 0.028	Intumescent Epoxy	0.013	0.004
3	1/2 x 0.028	Silicone Rubber	0.091	0.017
4	1/2 x 0.028	Silicone Rubber	0.100	0.21

NOTE: Coatings were cured according to manufacturers' recommendations.

TABLE XI

FIRE RESISTANCE OF COATED TUBING AT ZERO GASOLINE FLOW

Tube Number	Tube Size OD x Wall (in.)	Test Duration (min:sec)	Failure Yes	Failure No
1	1/2 x 0.028	0:55	x	
2	1/2 x 0.028	0:55	x	
3	1/2 x 0.028	0:55	x	
4	1/2 x 0.028	1:06	x	

NOTE: Gasoline pressure was maintained at 30 psi. Failure times for uncoated tubes were 30 sec and 41 sec (See Table IX).

CONCLUSIONS

Within the limits of the fire tests and the requirements for a 5-min exposure to a standard burner, it is concluded that:

1. Empty aluminum tubing possesses very little fire resistance and generally fails in less than 1 min.

2. Oil and gasoline pressurized aluminum tubing generally fails in less that 5 min. when the flow is reduced to zero.

3. Small diameter aluminum tubing will fail in less than 5 min at low gasoline flow rates and pressures.

4. Internal fluid flow is essential in providing aluminum tubing with sufficient fire resistance to endure 5 min test duration.

5. Fire resistance of fluid lines is limited by leakage around the coupling with only the smaller sizes capable of operating without leakage.

6. Aluminum tubing shows no significant increase in fire resistance when protected with the types of fire-retardant coatings tested.

RECOMMENDATIONS

Based on test results, observations, conclusions and the test requirement for a 5-min exposure to a standard burner, it is recommended that:

1. Criteria for fire resistance be that the installation under consideration operate under fire test without leakage or failure for 5 min under any normal condition of fluid flow rate, pressure and temperature, including no flow, if applicable.

2. The type of fluid employed during fire testing be that as specified for the particular installation involved.

3. Where applicable, tubing be tested with a coupling or any device that may be used, in the installation involved, for joining two or more sections of tubing in a fire zone.

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APPENDIX 1

A THEORETICAL METHOD FOR CALCULATING WALL TEMPERATURE RISE OF ALUMINUM TUBING WITH CIRCULATING OIL

APPENDIX 1

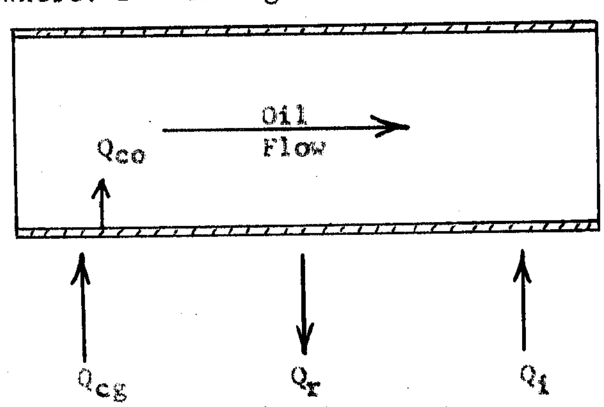
A THEORETICAL METHOD FOR CALCULATING WALL TEMPERATURE RISE OF ALUMINUM TUBING WITH CIRCULATING OIL

Definition of Symbols:

Q_a	- heat absorption rate of aluminum tube = $\frac{dT_w}{dt}$ Btu/ft^2-sec
Q_i	- radiant heat incident upon tube = 6.8 Btu/ft^2-sec (measured)
a	- absorption coefficient of tube = 0.2
Q_r	- heat radiated from tube = seT_w^4
Q_{cg}	- heat transferred to tube from burner gases by convection = $h_g(T_g - T_w)$
Q_{co}	- heat transferred to oil from tube by convection = $h_o(T_w - T_o)$
M	- mass of tube per unit area (lbs/ft^2)
c	- specific heat of aluminum
s	- Stefan-Boltzman constant - 0.48×10^{-12} Btu/ft^2-sec-$^oR^4$
e	- emissivity of aluminum tube = a
T_g	- temperature of burner gases = 2000^{o}F.
T_o	- temperature of oil = 200^{o}F.
T_w	- temperature of tube wall
t	- time, seconds

oil flow (gpm) = $5 D^2$

Where: D - tubing inside diameter (in.)



Elemental Tube Section

Derivation of Tube Wall Temperature Equation:

Basic heat transfer equation:

$$Qa = Q_i a + Q_{cg} - Q_{co} - Q_r \qquad (1)$$

Equation 1 in differential form,

$$Mc \frac{dT_w}{dt} = Q_i a + h_g(T_g - T_w) - h_o(T_w - T_o) - seT_w^4 \qquad (2)$$

Substitute the following:

$$K = Mc$$

$$K_1 = Q_i a + h_g T_g + h_o T_o$$

$$K_2 = h_g + h_o$$

$$K_3 = se = 0.48 \times 0.2 \times 10^{-12}$$

Therefore,

$$\frac{dT_w}{dt} = \frac{1}{K}(K_1 - K_2 T_w - K_3 T_w^4) \qquad (3)$$

Within the scope at this analysis, assume $K_3 T_w^4$ as negligible, therefore,

$$\frac{dT_w}{dt} = \frac{K_1 - K_2 T_w}{K} \qquad (4)$$

At stabilized or equilibrium temperature (steady state) $\frac{dT_w}{dt} = 0$, using equation (4),

$$T_w = \frac{K_1}{K_2} \qquad (5)$$

Rewriting equation (4),

$$t = K \int \frac{dT_w}{K_1 - K_2 T_w} \qquad (6)$$

By integration,

$$t = -\frac{K}{K_2} \ln (K_1 - K_2 T_w) + C \qquad (7)$$

Boundary condition, at $t = 0$, $T_o = T_w = 200$, substituting into equation (7),

$$C = \frac{K}{K_2} \ln (K_1 - 200K_2)$$

Substituting C into equation (7),

$$t = -\frac{K}{K_2} \ln (K_1 - K_2T_w) + \frac{K}{K_2} \ln (K_1 - 200K_2) \qquad (8)$$

Rewriting equation (8),

$$T_w = \frac{K_1}{K_2} - \frac{1}{K_2} (K_1 - 200K_2)e^{-K_2t/K} \qquad (9)$$

Procedure for determining time-temperature formulas:

General equations:

$$T_w = \frac{K_1}{K_2} \qquad (5)$$

$$T_w = \frac{K_1}{K_2} - \frac{1}{K_2}(K_1 - 200K_2)e^{-K_2t/K} \qquad (9)$$

Where:

$K = Mc$

$K_1 = Q_i a + h_g T_g + h_o T_o$

$K_2 = h_g + h_o$

K is calculated from the formula,

$$K = \frac{1.015}{D_1} (D^2{}_1 - D^2{}_2) \text{ Btu/ft}^2\text{-}^\circ\text{F}$$

Where:

D_1 - outside diameter (in.)

D_2 - inside diameter (in.)

K_1 and K_2 are calculated with the use of Figure 1 of the Appendix.

TABLE I

SUMMARY OF THEORETICAL TIME-TEMPERATURE FORMULAS FOR VARIOUS TUBE SIZES

Tube Size OD x Wall (in.)	Oil Flow (gpm)	h_g	h_o	K	K_1	K_2	T_w Steady State (°F)	$T_w = f(t)$
1/4 x 0.035	0.16	0.00267	0.15500	0.1222	9.8	0.01817	539	$T_w = 539 - 339e^{-0.148t}$
1/2 x 0.028	1.0	0.00191	0.01420	0.1074	8.02	0.01611	498	$T_w = 498 - 298e^{-0.150t}$
1/2 x 0.042	0.8	0.00191	0.01428	0.1563	8.03	0.01619	496	$T_w = 496 - 296e^{-0.103t}$
1/2 x 0.065	0.7	0.00191	0.01439	0.2296	8.16	0.01630	494	$T_w = 494 - 294e^{-0.011t}$
3/4 x 0.028	2.4	0.00157	0.01365	0.1095	7.23	0.01522	475	$T_w = 475 - 275e^{-0.139t}$
3/4 x 0.049	2.1	0.00157	0.01374	0.1859	7.25	0.01531	473	$T_w = 473 - 273e^{-0.082t}$
1 x 0.028	4.5	0.00137	0.01327	0.1105	6.75	0.01464	461	$T_w = 461 - 261e^{-0.132t}$
1 x 0.049	4.1	0.00137	0.01333	0.1891	6.76	0.01470	460	$T_w = 460 - 260e^{-0.078t}$
1 x 0.065	3.8	0.00137	0.01337	0.2467	6.77	0.01474	459	$T_w = 459 - 259e^{-0.060t}$
1 1/2 x 0.028	10.4	0.00112	0.01276	0.1115	6.15	0.01388	443	$T_w = 443 - 243e^{-0.124t}$
1 1/2 x 0.049	9.8	0.00112	0.01280	0.1924	6.15	0.01392	442	$T_w = 442 - 242e^{-0.072t}$
2 x 0.036	18.6	0.00098	0.01245	0.1396	5.81	0.01343	433	$T_w = 433 - 233e^{-0.096t}$
2 x 0.065	17.5	0.00098	0.01248	0.2253	5.82	0.01346	432	$T_w = 432 - 232e^{-0.060t}$

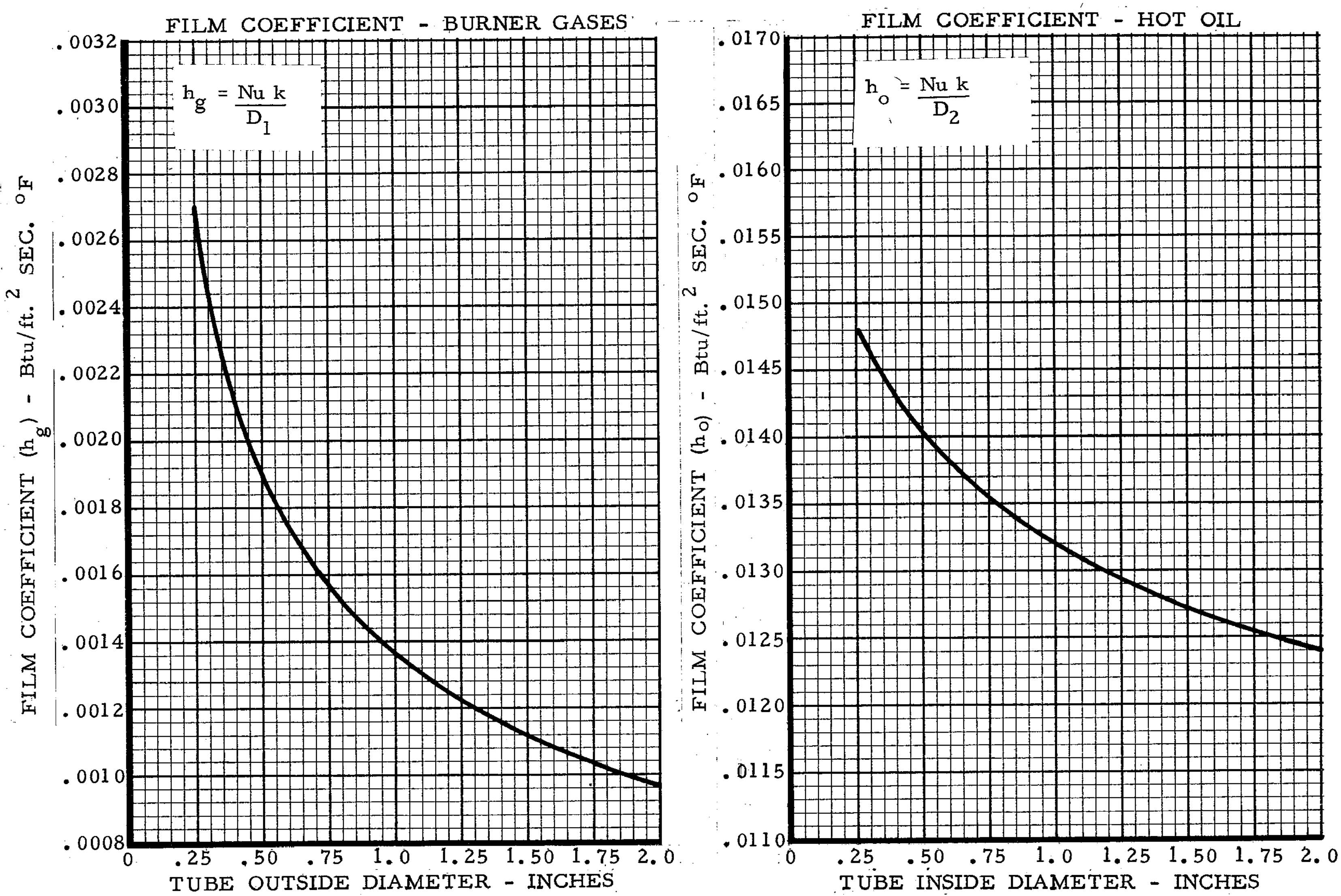


FIG. 1 - VARIATION OF FILM COEFFICIENTS WITH TUBE DIAMETER

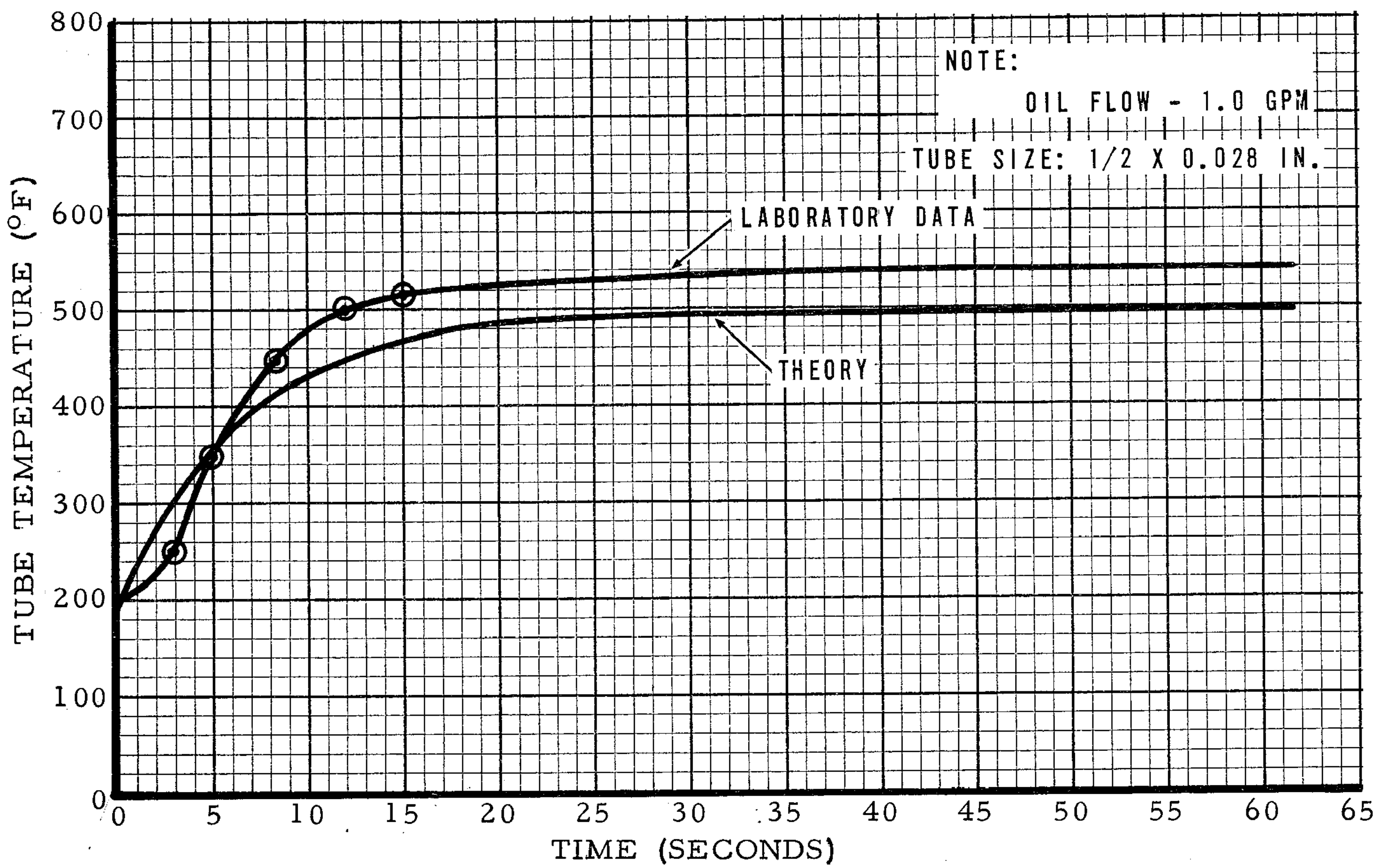


FIG. 2a - COMPARISON OF LABORATORY AND CALCULATED WALL TEMPERATURE RISE FOR 1/2-INCH TUBE

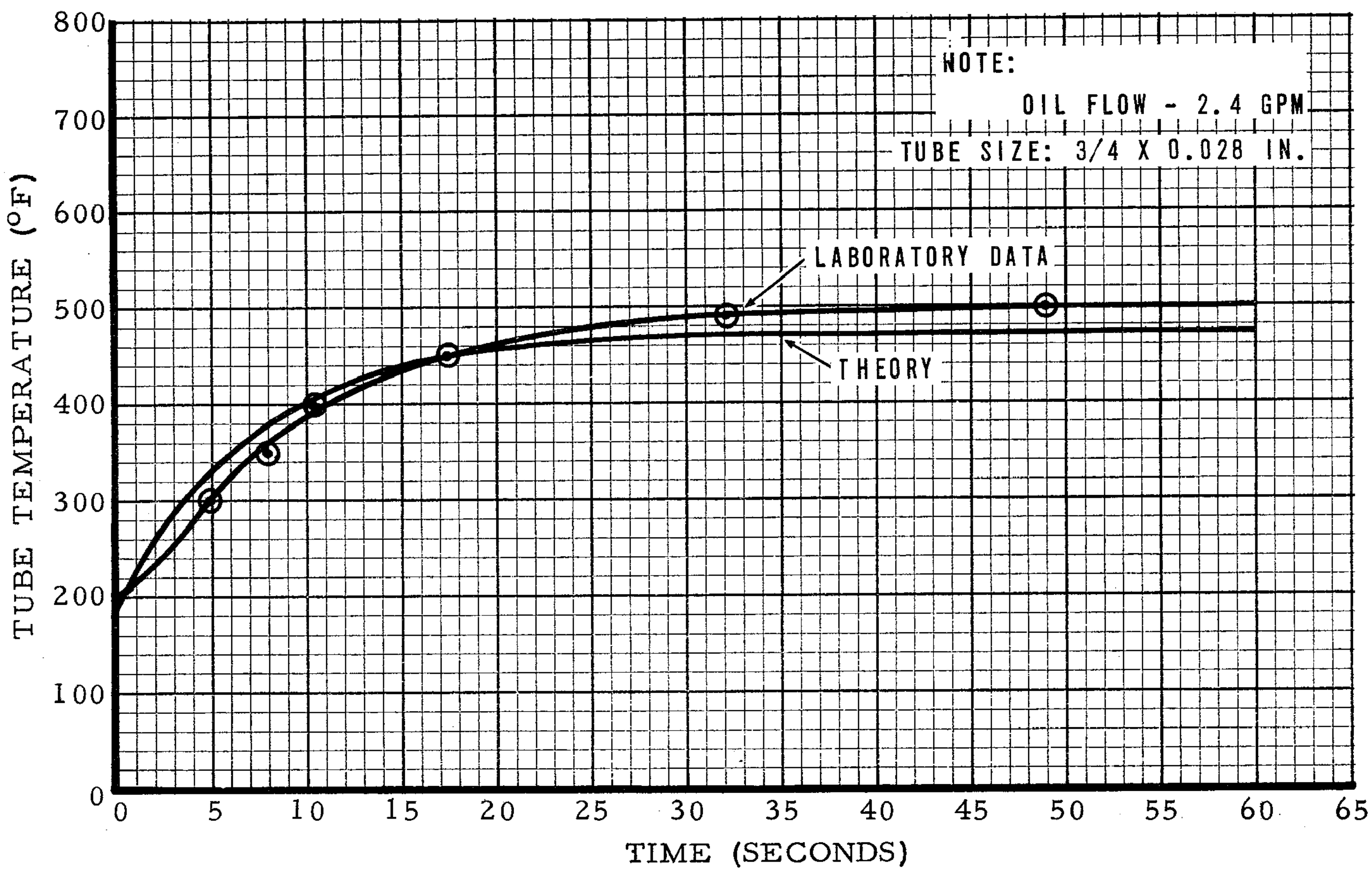


FIG. 2b - COMPARISON OF LABORATORY AND CALCULATED WALL TEMPERATURE RISE FOR 3/4-INCH TUBE

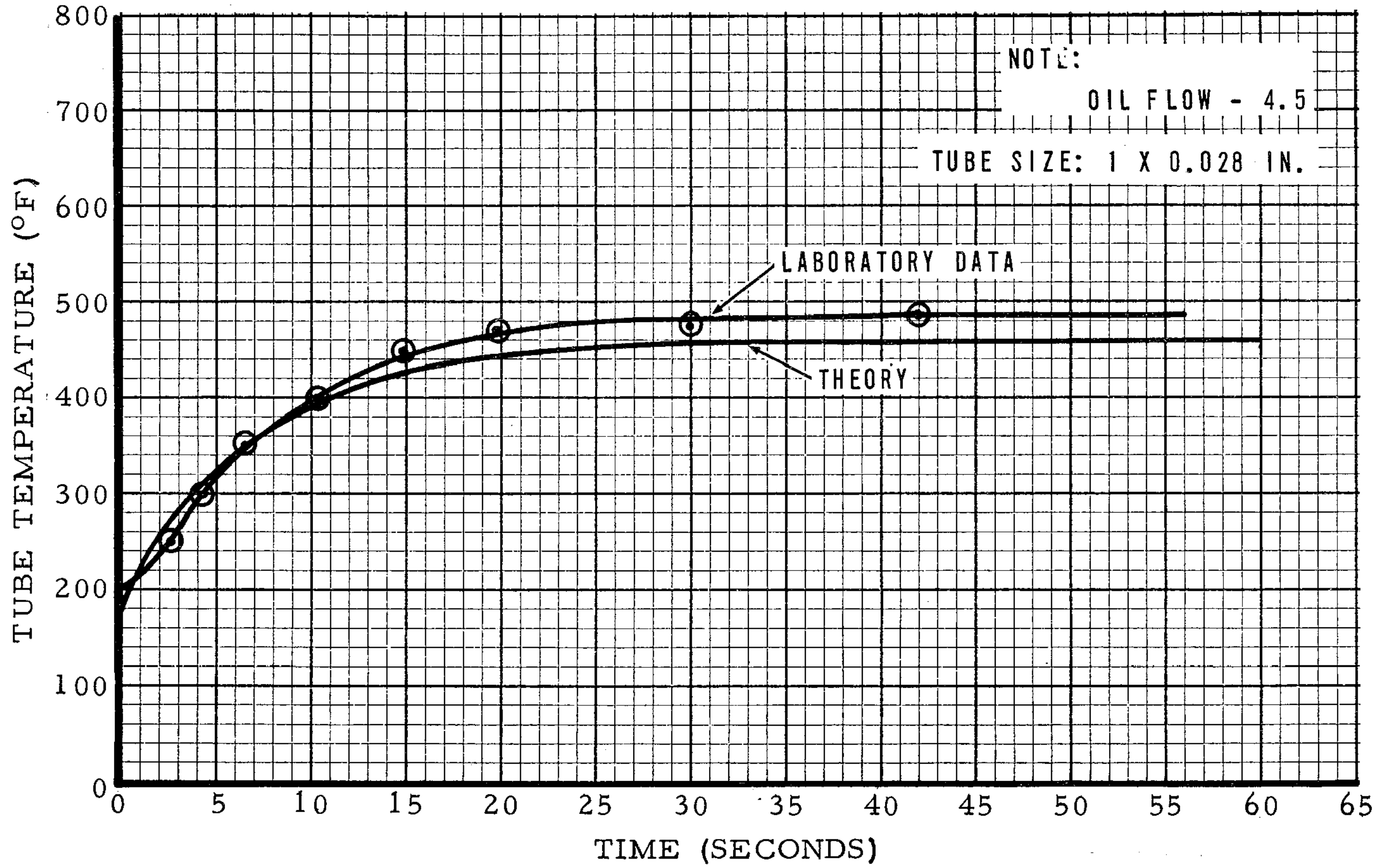


FIG. 2c - COMPARISON OF LABORATORY AND CALCULATED WALL TEMPERATURE RISE FOR 1-INCH TUBE