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Heat Transfer Testing In the AFFDL High Temperature Facility Using the Phase Change Coating Technique.

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ABSTRACT

The basic information necessary to plan, conduct and analyze heat transfer tests in the AFFDL High Temperature Facility (HTF) using the phase change coating technique is presented. The HTF operating conditions, physical dimensions, and test instrumentation are discussed, and test model design considerations are presented. Phase change coatings and the photographic equipment used to obtain phase change coating data are discussed and analysis of the data is described. Factors to be considered in the actual performance of the tests are also described.

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SYMBOLS

Cp	Model wall specific heat, Btu/lb_m °R
h	Heat Transfer Coefficient $\dot{q}/ T_{aw} - T_w)$, Btu/ft^2 - sec - °R
H	Enthalpy, Btu/lb_m °R
k	Model wall thermal conductivity, Btu/ft - sec - °R
T	Temperature, °F or °R
t	Time of model exposure to heating, sec.
ρ	Density, lb_m/ft^3
α	Thermal diffusivity, ft^2/sec.

Subscripts:

aw	Adiabatic wall
i	Initial conditions (t = 0)
PC	Phase Change
w	Model wall

Section I

Introduction

Over the past few years a method has been developed whereby quantitative heat transfer data on arbitrary shapes can be determined by using a phase change coating. In this method the heat transfer coefficients depend only on the thermal properties of the model material and the time required for a visible phase change of a fusible temperature indicator which is applied to the model as a thin surface coating. The time required for the phase change to occur is determined from sequence or motion picture photography, and the heat transfer coefficients are obtained from solution of the transient one-dimensional heat conduction equation for a semi-infinite slab. Lateral conduction effects are minimized by using model materials having very low thermal conductivities and, in effect, the entire surface of a model is instrumented. The phase change coating technique appears particularly useful for complex configurations which are difficult to instrument with thermocouples or for configurations subjected to interference effects for which the desirable placement of thermocouples is not known beforehand.

The purpose of this report is to present the information necessary for planning and conducting a test utilizing phase change coatings in the AFFDL High Temperature Facility (HTF) and for analyzing the resulting data. The HTF will be discussed first, and will include the range of test conditions, pertinent test cabin dimensions, model design considerations, standard diagnostic instrumentation, and phase change coatings. This is followed by a discussion of the photographic equipment available, including both sequence and Schlieren photography. Next will be a discussion of important factors to be considered in the actual performance of the tests and finally a discussion of data reduction, including both the standard diagnostic data and the phase change coating data.

Section II

High Temperature Facility

1. Description of Facility

The AFFDL High Temperature Facility is a hypersonic blowdown wind tunnel which uses a zirconia pebble bed heater as its heat source. Figure 1 shows a schematic of the general arrangement of the tunnel circuit and associated systems. The tunnel can be operated at a nominal Mach number of 9, 10, or 11 at stagnation pressures from 100 to 600 psia and at stagnation temperatures up to 4000 °R. The nozzle system consists of an axisymmetric 150 inch long contoured Mach 10 nozzle with a 24 inch exit diameter, or an axisymmetric 150 inch long contoured nozzle with interchangeable Mach 9 and 11 throats and 32 inch exit diameter. The tunnel has an open jet test section. Vacuum capability consists of a 60,000 cubic foot sphere with 3 stages of vacuum pumping which provide run times of up to 3 minutes.

2. Test Cabin Details

The pertinent test cabin dimensions needed to determine clearances in designing test models and model mounting sting are shown in Figure 2. A sting-to-model-support-strut adaptor is available for use which allows the mounting end of the sting to be fabricated with a plain 1 1/2 inch diameter. The adaptor is essentially a collet and provides fore and aft adjustment of the sting. It is recommended that the adaptor be used whenever practical.

3. Design Considerations For Model & Sting

The conditions that should be considered in designing a model for use with the phase change coating technique are as follows.

a. The thermal diffusivity of the model material should be low enough to minimize lateral conduction and yet sufficient to allow adequate test time, without damaging areas of high heating rate.

b. The model must withstand high injection accelerations.

c. The model must be able to withstand thermal shock.

d. The model wall material must be uniform to insure accurate determination of its thermophysical properties and should be such that the properties will be repeatable in making more than one model.

e. The model material should be impervious to the phase change coating and thinner used.

f. Means should be provided to monitor and record model surface temperature in the region where coatings are applied.

Experience has shown that Teflon (TFE) is a suitable model material. Its main limitation is the relatively short duration test time available (5 secs at P_o = 500 PSIA in the HTF). The thermal characteristics of Teflon (TFE) are shown in Table I.

TABLE I

THERMAL PROPERTIES OF TEFLON (TFE)

Cp	0.25 Btu/lb °R
~~R~~ k	0.389 (10^{-4}) Btu~~/sec~~ °R $\frac{BTU}{FT-SEC-°R}$
ρ	137.0 lb/ft^3
α	0.114 (10^{-5}) Ft^2 sec
MAX	OPER. TEMP: SHORT DUR. 1000 °F LONG DUR. 500 °F

The conditions that should be considered in designing a model and sting specifically for use in the HTF are as follows.

a. The total frontal area exposed to the tunnel flow by the model and sting must be less than 10% of the nozzle exit area for tunnel blockage constraint.

b. The sting material should be suitable to withstand 3 minutes of continuous run time at the most severe test point condition to be encountered in a test.

4. Standard Tunnel Instrumentation

The standard data provided for each test utilizing phase change coatings can be divided into two categories; strip chart data and digital data. The strip chart data is recorded by a Sanborn Model 358 rectilinear strip chart recorder and includes three data channels providing timing information. Figure 3 is an illustration of the standard strip chart data. The center channel gives the time from the instant the system is activated to insert the model into the flow until the system is again activated to remove the model from the flow. The right channel shows the position of the model relative to the tunnel centerline, and the left channel shows the flashing of the strobe lights when taking sequence photos and provides timing marks for determining the time at which each photo was taken. (See Section V-1 for determination of zero time point). The strip chart data thus provides the information necessary to determine the time required for phase change of the model coating to occur. There are 5 additional strip chart data channels available for use at the discretion of the test engineer. The digital data is measured by analog instrumentation devices and converted to digital data by an analog-to-digital converter, then recorded and analyzed by a Control Data 160A computer.

The resulting data printout from the computer includes both the measured data and additional calculated data. Table II shows the data in both the measured and calculated groups.

TABLE II

Standard Tunnel Data

Measured data:

TIME (SEC)	test time when data pt. taken
P_o (PSIA)	reservoir pressure
T_o (°R)	stagnation temp.
ALPHA(DEG)	angle of attack
PTC(MM HG)	test cabin pressure
PNS (MM HG)	nozzle static pressure
PTZ(MM HG)	impact pressure (probe)
DEW POINT(°F)	dew point temperature
PD1 (MM HG)	diffuser inlet pressure

Calculated data:

MDOT (1b/SEC)	mass flow rate
MINF	M_{oo} free stream Mach number
R/FT (1/FT)	Re_{oo}, free stream Reynolds number
P_{oo} (MM HG)	free stream static pressure
T_{oo} (°R)	free stream temp.
q_{oo} (PSI)	free stream dynamic pressure
ρ_{oo} (LB SEC^2/FT^4)	free stream density

and gives the computer print out symbol and a brief explanation of each. There are approximately 100 additional digital data channels available.

5. Phase Change Coatings

The phase change coating found most suitable for use is Tempilaq.®[1] This coating undergoes a phase change from an opaque solid to a clear liquid at known temperatures. Tempilaq® is available in a range from 100 °F to 2500 °F in increments ranging from a minimum of 3°F between 100 and 110°F up to a maximum of 50° between 1500 and 2500°F. The color of the coating varies depending upon the phase change temperature. The coatings are supplied by the manufacturer in aerosal cans or in bulk ready to mix. The paint in aerosal cans appears to have a longer shelf life. For best results it is recommended that the coating material be removed from the aerosal can, thinned 50% with the recommended thinner from the manufacturer, and then applied with a Devilbiss Type-MBC sprayer with a No. 30 nozzle (or equivalent). When the model is sprayed with a very thin coating of Tempilaq®, it appears to be covered with small opaque crystals. Care must be taken to apply the coating in a layer sufficiently thin to prevent running of the melted coating which can cause errors due to the latent heat of melting. In general, just enough phase change coating should be sprayed on the model to fog the surface (less than 0.001 inch thick). This coating thickness can be closely achieved by making one spray pass over a given area of the model surface with the Devilbiss spray gun at a distance of approximately 12 to 15 inches. The temperature at which the coating changes phase should be chosen to provide as long a

[1] manufactured by the Tempil ® Corporation, 132, W. 22nd Street, New York, New York, 10011.

test duration as possible without damage to the model.

Section III

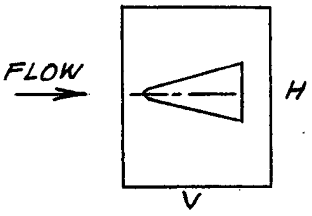
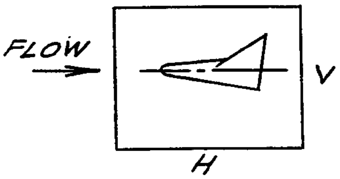
Photographic Equipment

1. Sequence Cameras

There are two fixed mount cameras available for taking 35 mm sequence photographs of the test model. One camera is mounted in the top of the test cabin and the other in the side of the test cabin as shown in Figure 4. In addition, either camera can be tripod mounted to photograph through the Schlieren part (see Fig. 4). This can be done only when Schlieren photos are not required. The sequence cameras are both Automax Model G-1 35 mm cameras. The cameras are synchronized with each other and with two strobe light units by an intervalometer. This allows sequence photos to be taken of two model surfaces simultaneously. The cameras have a sequencing frequency of up to 8 frames/second. The field of view of each sequence camera at the tunnel centerline is shown in Table III.

Table III

Field of View of Sequence Cameras With
Various Lenses

LENS FOCAL LENGTH	FIELD OF VIEW	
	TOP	SIDE
4 in. (100 MM)	11 3/4 V x 16 1/4 H	9 1/2 V x 14 1/2 H
5 1/2 in. (135 MM)	8 3/4 V x 12 H	7 1/4 V x 10 3/4 H
10 in. (250 MM)	4 3/4 V x 6 1/2 H	4 V x 5 3/4 H
		

There is only one lens of each focal length available so a different lens must be chosen for each camera. The field of view for each camera when tripod mounted depends on its distance away from the Schlieren port. Both black-and-white and color film is available for use in either camera. In general, black- and-white film provides satisfactory results; however, at some conditions color film provides better contrast. It is therefore necessary to take sample pictures prior to testing to determine if proper contrast is obtained with black-and-white film and to optimize camera exposure settings for whichever film is required.

2. Lighting

Lighting for the sequence cameras is provided by either strobe lamps or tungsten filament incandescent bulbs. Figure 5 shows the locations of the strobe lamps and Figure 6 shows the locations of the incandescent bulbs. The voltage to the incandescent bulbs can be controlled to provide color temperatures of 2900 °K, 3200°K, and 3400°K (2900°K for B&W, the others for color). It is recommended that the strobe lighting be used whenever possible. If it becomes necessary to use the incandescent lighing it is recommended that phase change coatings with melt temperatures less than 150°F not be used. Below this temperature thermal radiation from the bulbs may heat the coating sufficiently to cause significant error in the determination of aerodynamic heat transfer rate which depends on the coating being initially the same temperature as the bulk of the model.

3. Schlieren Photographs

Schlieren photographs of the flow field can be taken simultaneously with sequence photos even while using the strobe lights. The Schlieren photos are recorded with a 35 mm single lens reflex camera.

Section IV

Test Considerations

The purpose of this section is to present some miscellaneous information which experience has shown to be helpful in conducting such a test in the HTF. The information will be given in the general order of pre-test, test, and post-test activities.

1. Check the model orientation in the vertical and horizontal planes using an inclinometer and check to be sure the model is not unintentionally yawed relative to the tunnel centerline.
2. Re-check the model orientation after angle of attack changes or when the model has been reinstalled.
3. Realign cameras after each model angle of attack change.
4. Use the lowest cabin lighting intensity available when working with models coated with low temperature coatings (100-150°F).
5. Do not allow coated surfaces to be touched with anything (including paper run identifying slates).
6. Check the pebble bed temperature before each run to be sure it is at a temperature which will provide the required stream temperature.
7. Have the heater evacuated for 30 minutes prior to each test run to remove moisture resulting from heater combustion.
8. Observe the painted surface as the test is performed to determine if the coating changes phase too fast or too slow indicating improper coating temperature.
9. Cool the model after the test run to keep the model from exceeding the maximum allowable to maintain material integrity and to return the model surface temperature to room temperature. One way to do this

is to spray the model with a CO_2 fire extinguisher.

10. Smooth the model surface after each run by sanding the surface very lightly with fine sandpaper (Teflon models especially). Check for damage to the surface due to the impact of solid particles in the tunnel flow.
11. Clean off any coating remaining on the model surface after a test run with the thinner recommended by the coating manufacturer before re-painting the model.
12. Check the digital data printout as soon as it is available to be sure all instrumentation is functioning properly.
13. Pick up the strip chart data at the end of the day's final run.

Section V

Data Reduction

1. Standard Diagnostic Data

As mentioned earlier, the standard diagnostic data obtained in each test utilizing phase change coatings can be divided into strip chart data and digital data. The digital data is reduced by computer but the strip chart data must be reduced "by hand". It is up to the test engineer to determine the "zero time" point and the elapsed time for each sequence photo frame. The "zero time" point is defined to be that instant at which the vertical centerline of the model support strut crosses the edge of the tunnel boundary layer. This point has been found from tunnel calibration data to occur when the model support strut has traversed 70% of its angular displacement from the "maximum out" position to the centerline position. This point is reached 1.10 seconds after the strut begins its rotation. Thus, for a model located on the model support strut centerline, the zero time point is taken as 1.10 seconds after the beginning of injection of the model into the flow (See Figure 7).

2. Phase Change Coating Data

The method used to determine heat transfer coefficients from the phase change coating data is described in Reference 3. The basic assumption of the method is that the depth of heat penetration into the model wall is small compared with the wall thickness and surface radius of curvature so that the wall acts like a semi-infinite slab. This assumption allows the relationship between the heat transfer coefficient and phase change time, test conditions, and model thermal properties to be determined from the solution to the one-dimensional transient heat flow equation. The resulting equation after consideration of appropriate boundary conditions is as follows:

$$\bar{T} = 1 - e^{\beta^2} \operatorname{erfc} \beta \qquad (1)$$

where:

$$\bar{T} = \frac{T_W - T_i}{T_{AW} - T_i} \qquad \beta = \frac{h\sqrt{t}}{\sqrt{\rho_W c_{P_W} k_W}}$$

It is assumed that the phase change coating is at the model surface temperature, thus:

$$T_W \equiv T_{PC} \;, \text{THEN} \quad \bar{T} = \frac{T_{PC} - T_i}{T_{AW} - T_i} \qquad (2)$$

Other assumptions are as follows:

1. The model is isothermal before injection into the flow.
2. The surface experiences an instantaneous step in the heat transfer coefficient at time zero and this coefficient is invariant with temperature.
3. The thermal diffusivity of the model does not vary with temperature.

Equation 1 is plotted in Figure 8. With β obtained from this plot, heat transfer coefficient, h, may be calculated for a given phase change time, t, and model material thermal properties. For a specific model material it is possible to use the foregoing relationships to plot heat transfer coefficient, h, versus temperature ratio, $\bar{T}$, as a function of phase change time. Figure 9 shows h vs. $\bar{\bar{T}}$ for Teflon (TFE).

Accurate determination of heat transfer coefficients using the phase change coating technique requires that the zero time point (t =0) and initial wall temperature (T_i) be accurately determined. The latter is particularly true for low temperature phase change coatings (T_{pc} = 100-150°F), becoming less critical as higher temperature coatings are used. This is because of the increasing effect T_i has on the numerator of the $\bar{\bar{T}}$ expression (eqn. 2) as T_i approaches T_{pc}. In addition, for low values of T_{pc}, it is essential to cool the model to near room temperature for each test. The zero time point is difficult to judge because, in being injected into the tunnel flow, the model first encounters the tunnel boundary layer some finite time before reaching the tunnel centerline. The effect of error in choosing the zero time point decreases as the total test time increases. Thus, the value of the phase change temperature, T_{pc}, should be selected to obtain reasonably long phase change times while not exceeding the thermal diffusion time of the model material.

The whole object of the sequence photo data is to determine the time required for a given paint on the body to reach the known temperature T_{pc}. To analyze the data it is generally necessary to get it into a form more amenable to analysis than 35 mm transparencies. This can be done by making enlarged prints, or by projecting the photographs onto a screen, or in some other manner tracing the distance versus time progression of the phase change melt line. References 5 and 6 both deal with analysis of actual test data and more fully illustrate the tracing of the coating melt line.

Section VI

Conclusion

The preceding report has outlined the basic information necessary to plan, conduct, and analyze heat transfer tests in the AFFDL High Temperature Facility using the phase change coating technique. Information presented includes operational and dimensional details of the test facility, model design considerations, instrumentation and data reduction details, and operating guidelines.

References

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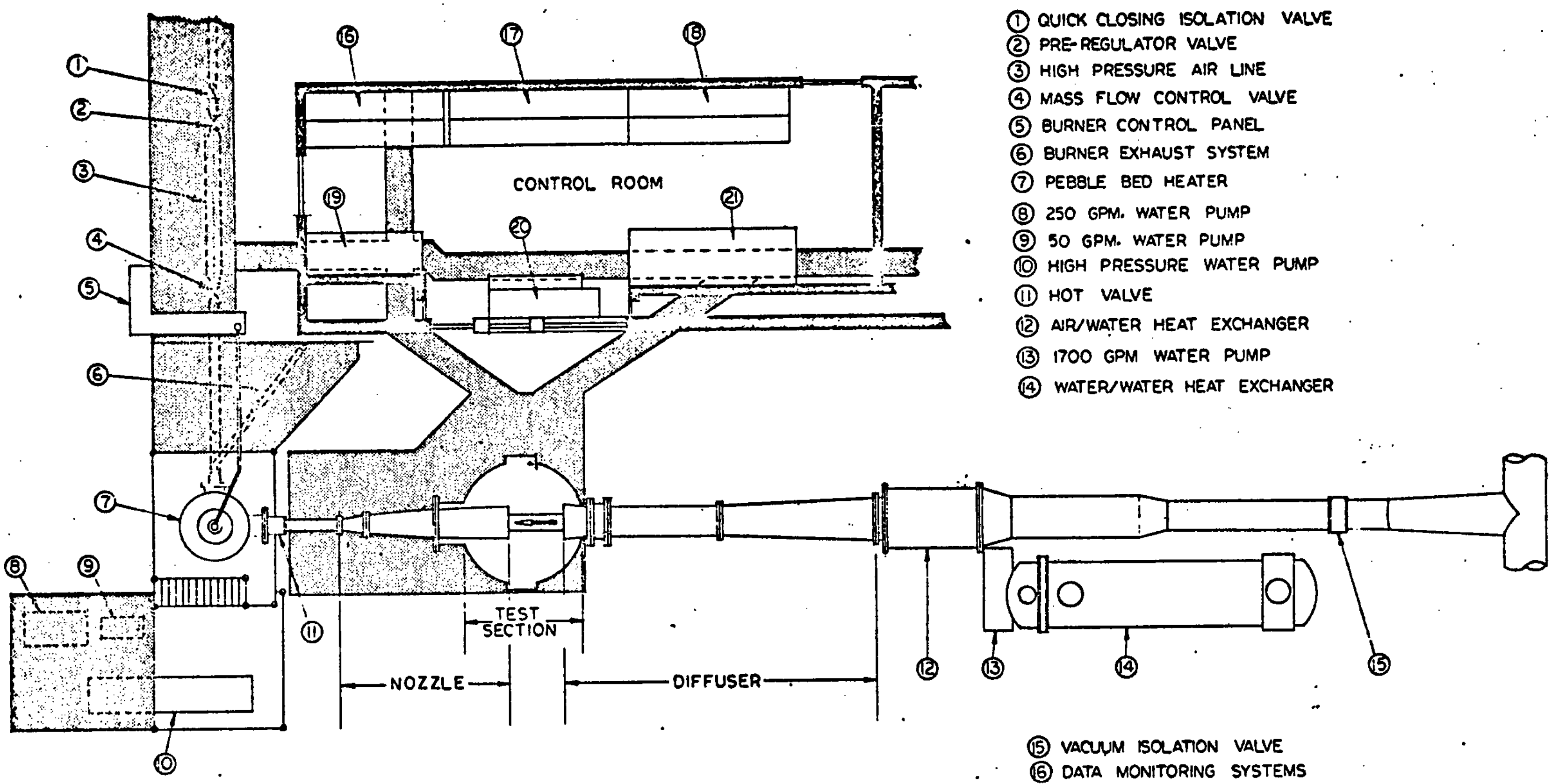
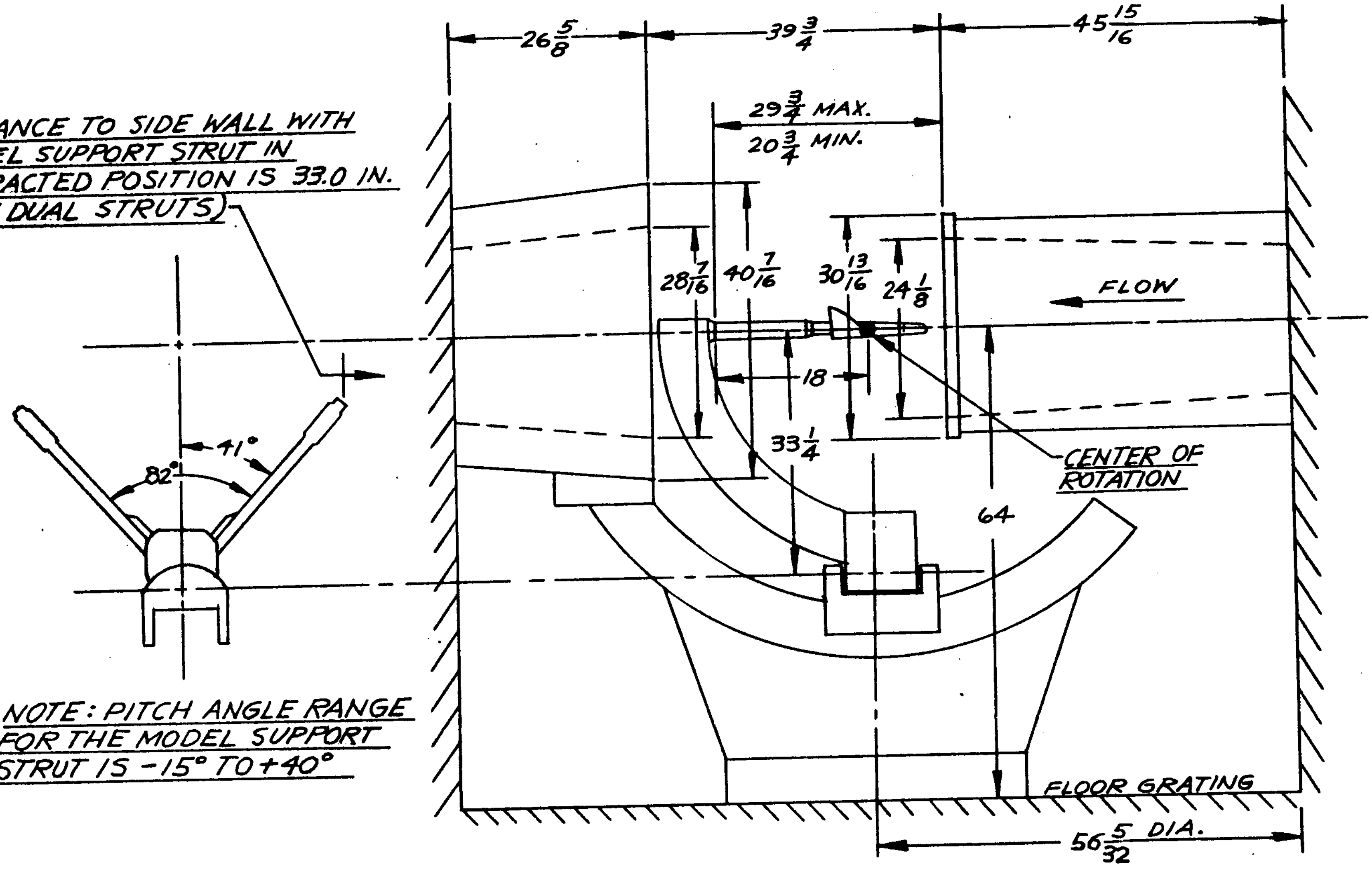


FIGURE 1. GENERAL ARRANGEMENT OF HIGH TEMPERATURE FACILITY

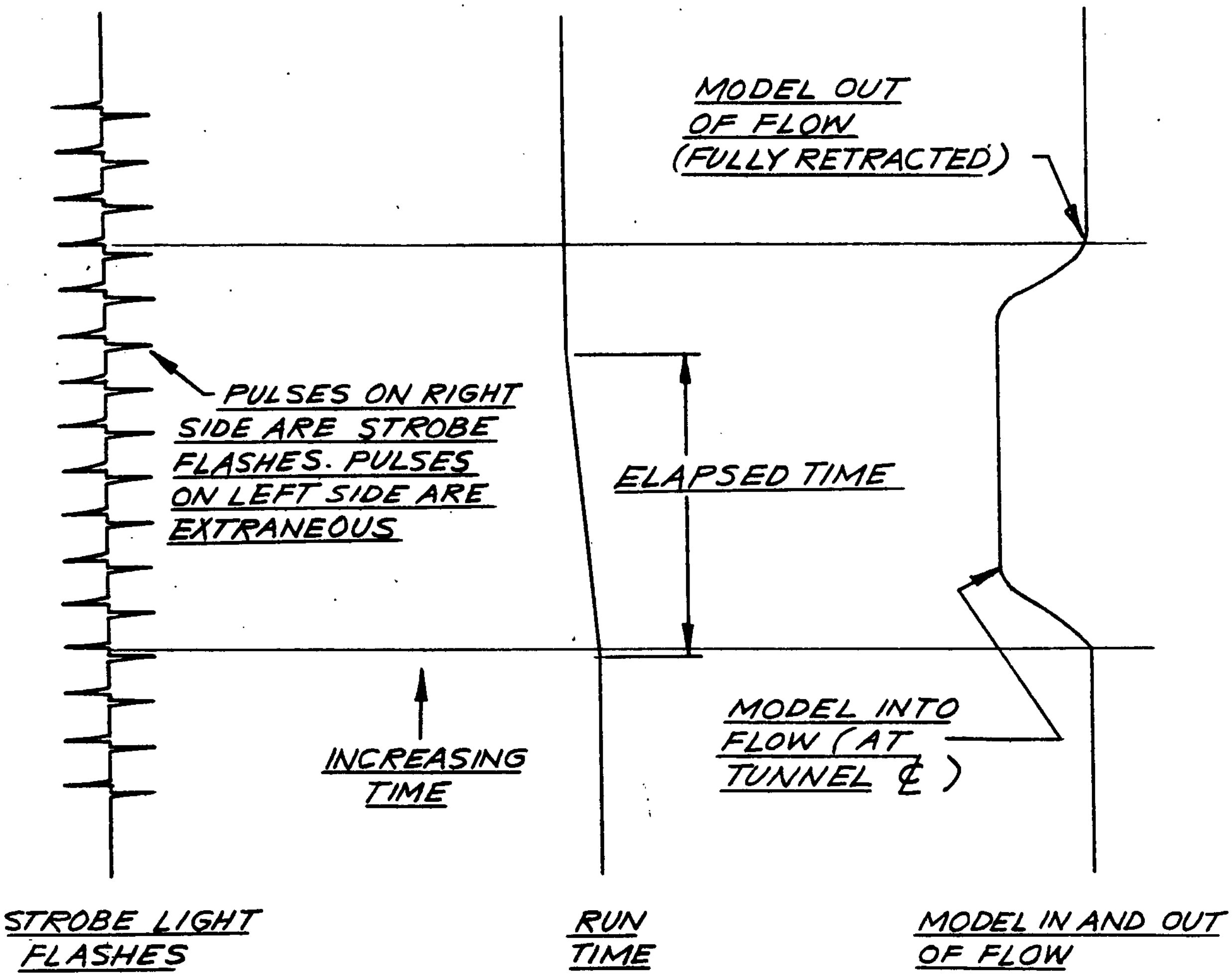
ALL LINEAR DIMENSIONS ARE GIVEN IN INCHES.
ALL ANGULAR DIMENSIONS ARE GIVEN IN DEGREES



DISTANCE TO SIDE WALL WITH MODEL SUPPORT STRUT IN RETRACTED POSITION IS 33.0 IN. (NOTE DUAL STRUTS)

NOTE: PITCH ANGLE RANGE FOR THE MODEL SUPPORT STRUT IS -15° TO +40°

FIGURE 2 TEST CABIN DIMENSIONS



THIS DATA IS RECORDED ON A TIME GRID OF VARIABLE SCALE (10 MM = 1 SEC IS A CONVENIENT SCALE)

FIGURE 3 STRIP CHART DATA

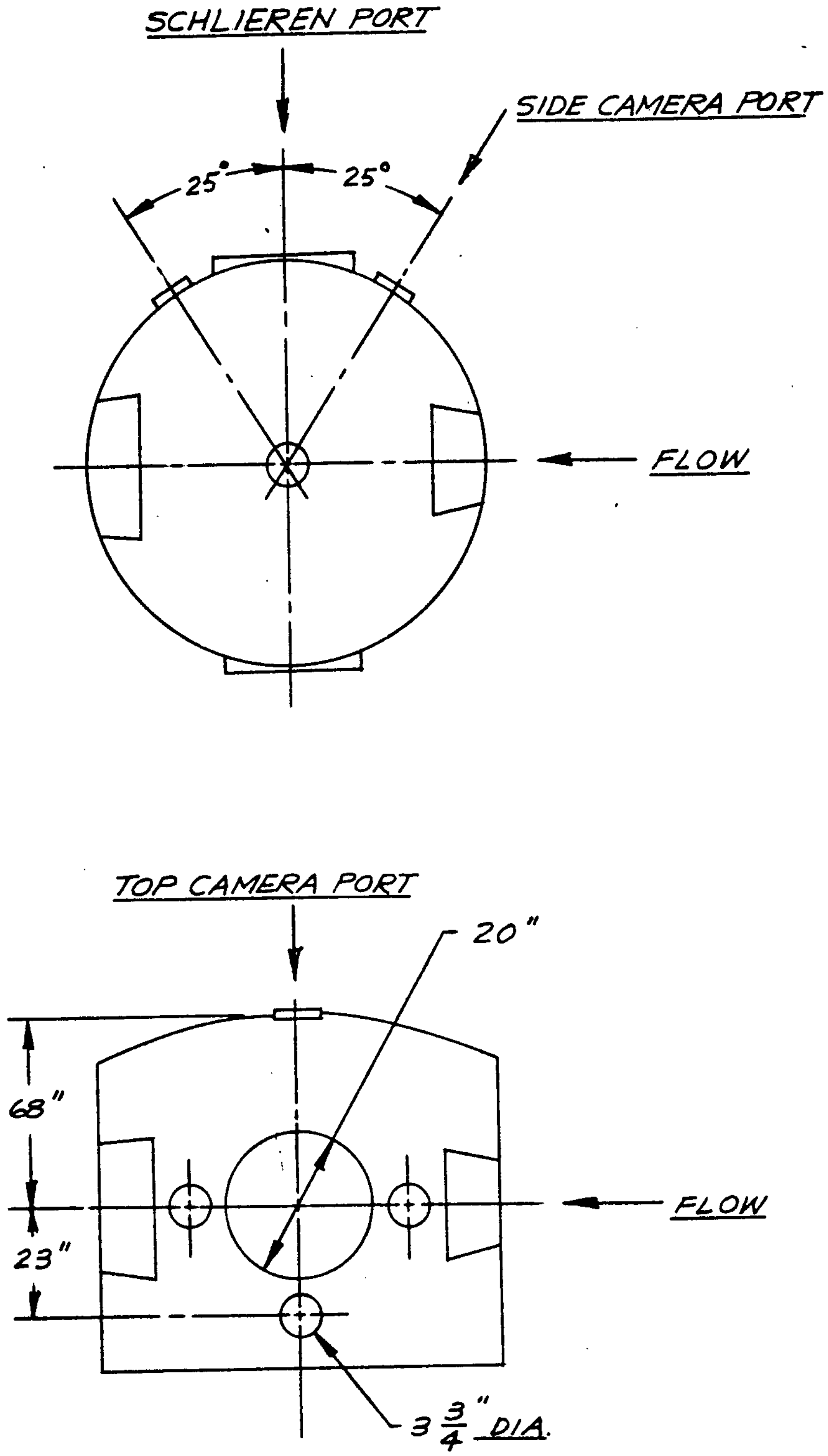


FIGURE 4 - LOCATION OF CAMERA PORTS

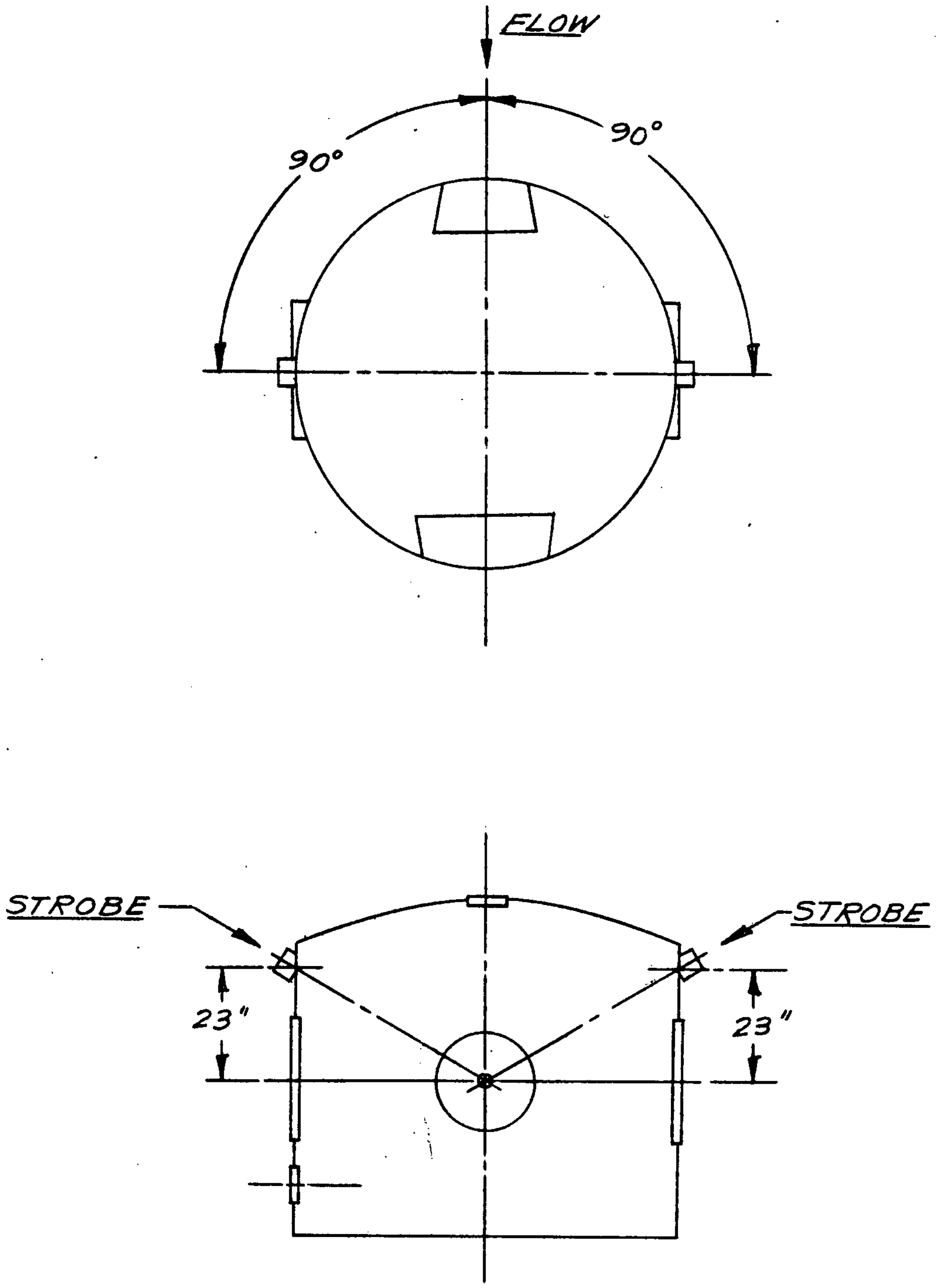


FIGURE 5 – LOCATION OF STROBE LIGHTS

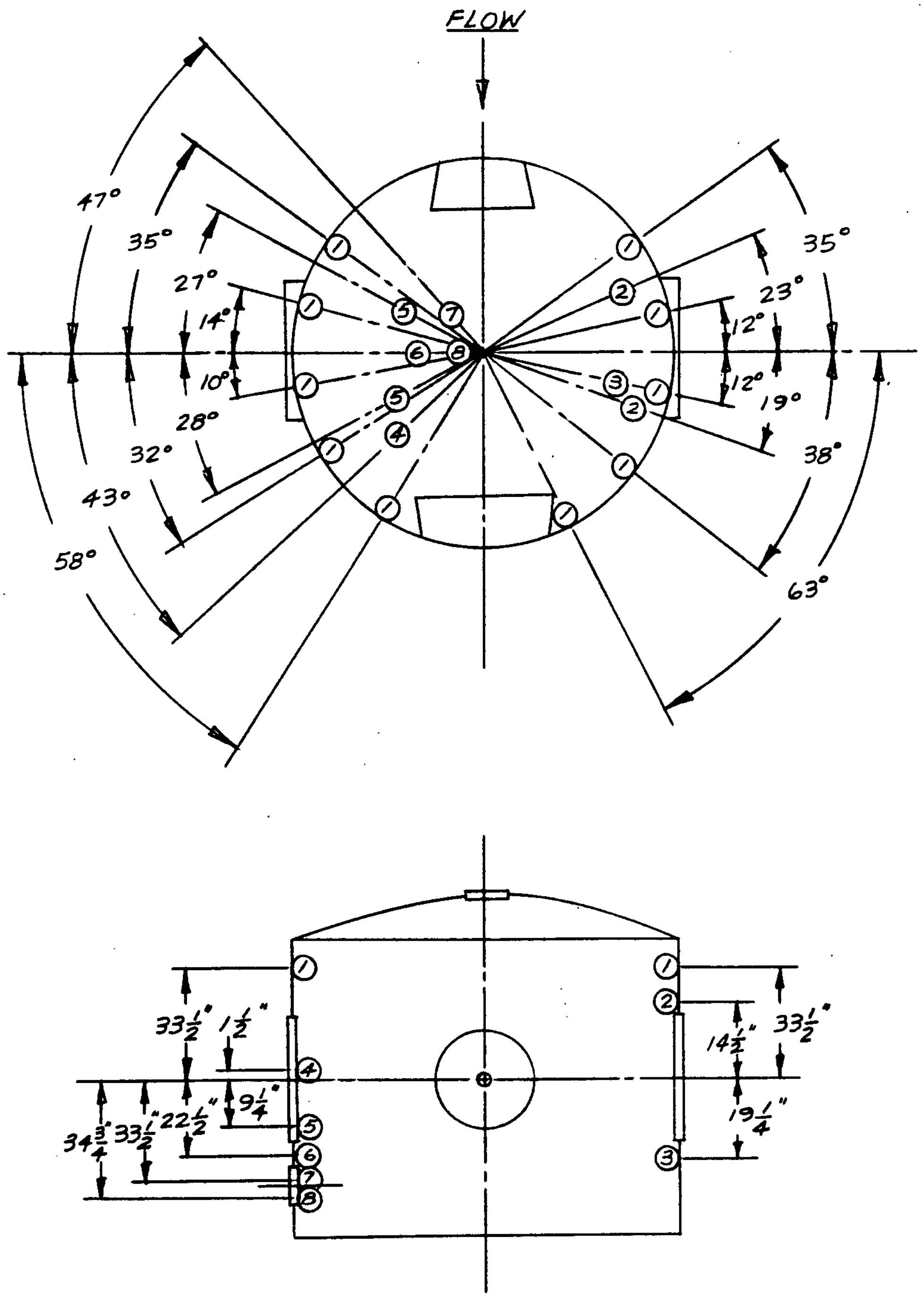


FIGURE 6 - LOCATION OF INCANDESCENT LIGHTING

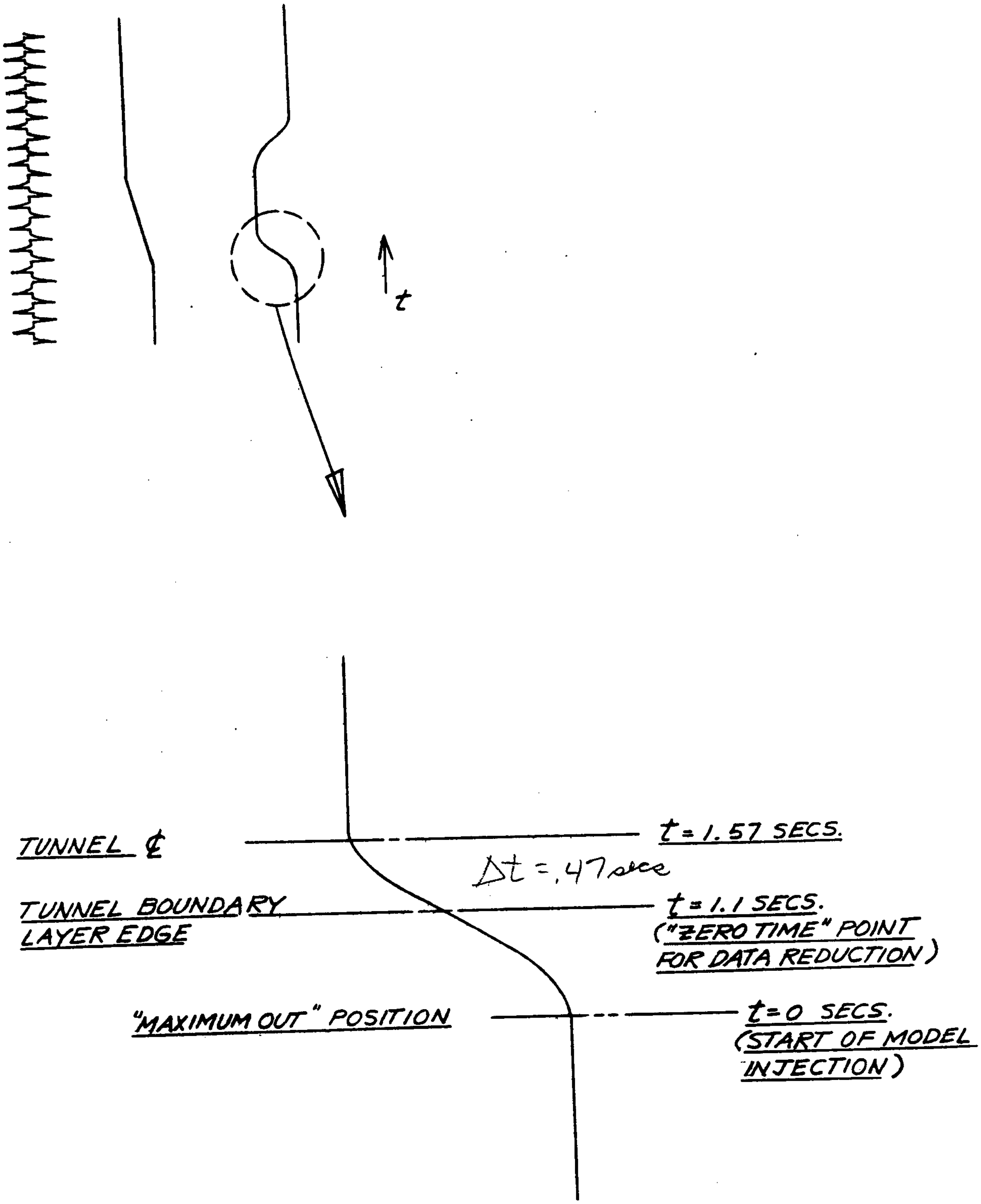


FIGURE 7 – DETERMINATION OF "ZERO TIME" POINT

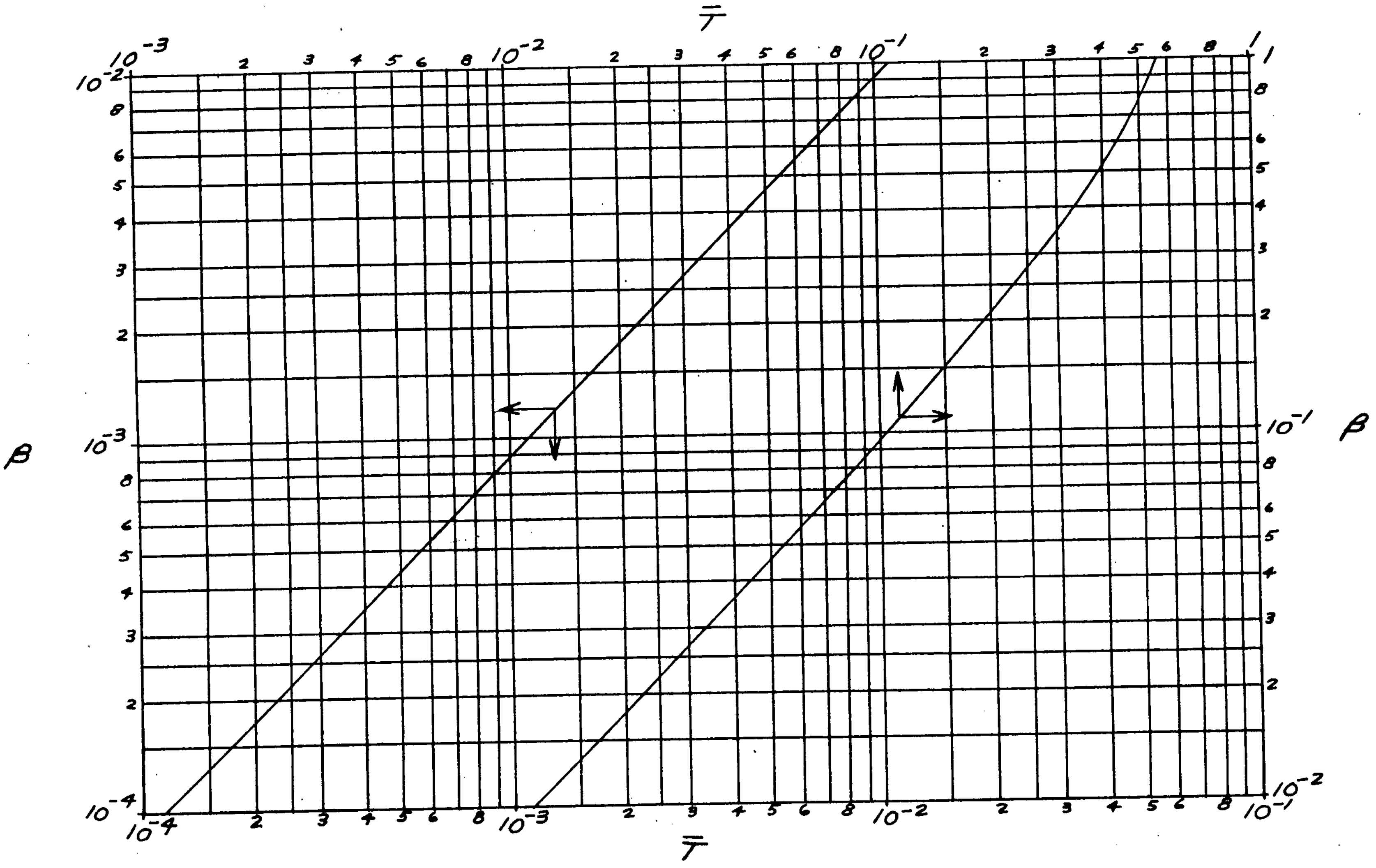
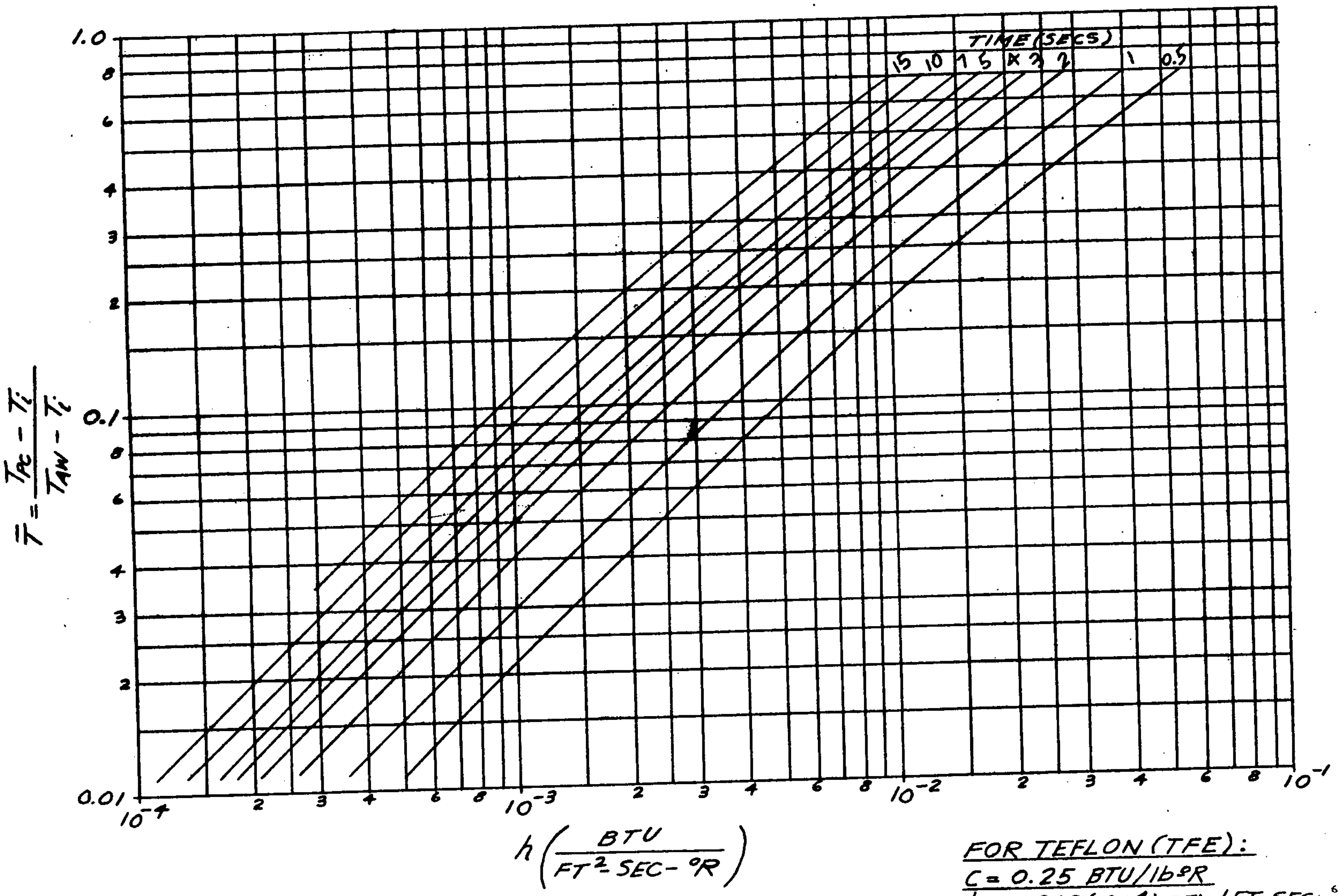


FIGURE 8 ~ SOLUTION OF ONE DIMENSIONAL TRANSIENT HEAT CONDUCTION EQUATION



FOR TEFLON (TFE):
$C = 0.25$ BTU/lb°R
$k = 0.389(10^{-4})$ BTU/FT-SEC-°R
$\rho = 137.0$ lb/FT3
$\alpha = 0.114(10^{-5})$ FT²/SEC

FIGURE 9 ~ h VS. $\bar{T}$ FOR TEFLON (TFE)