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EXPERIMENTAL INVESTIGATION OF BAFFLE EFFECTIVENESS IN A CONFINED FLUID SUBJECTED TO WALL AND NONUNIFORM SOURCE HEATING

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A final word of appreciation is due my wife, Pat, for her encouragement during these many months.

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NOMENCLATURE

Latin Letters

B	baffle width, in.
E	effectiveness parameter defined by equation (5)
H	height of liquid, in.
h	heat transfer coefficient, Btu/(hr)(sq in.)($^{\circ}$F)
k	thermal conductivity, Btu/(hr)(in.)($^{\circ}$F)
L	wall thickness, in.
M_T	temperature moment defined by equation (5a)
N	temperature nonuniformity parameter defined by equation (4)
n	number of baffles
q''	heat flux, Btu/(hr)(sq in.)
T	temperature, $^{\circ}$F
t	time, min
V	volume of fluid, cu in.
W	tank width, in.
X	axial distance measured from tank bottom, in.

Greek Letters

α	constants used in equation (6)
θ	temperature difference, $^{\circ}$F

ABSTRACT

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Biesiadny, Thomas John. M.S.M.E., Purdue University, August 1966. Experimental Investigation of Baffle Effectiveness in a Confined Fluid Subjected to Wall and Nonuniform Source Heating. Major Professor: Robert J. Schoenhals.

Heating of liquid hydrogen in the propellant tank of a nuclear rocket was simulated in a two dimensional view tank with and without baffles present. The effectiveness of the baffles in preventing the occurance of large fluid temperature differences was determined. To accomplish this objective a mixture of trichloroethane and ethyl alcohol was used to represent the liquid hydrogen because its thermal radiation absorption characteristics are similar to the nuclear absorption properties of liquid hydrogen. Both wall and nonuniform source heating occur in nuclear rocket propellant tanks. In this study infrared rays from quartz lamps were used to produce the two types of heating required.

The tanks were subjected to similar heating conditions with and without baffles, and visual information concerning fluid behavior was obtained using schlieren photographs. Fluid temperatures were measured using thermocouples. Quantitative comparisons were made possible by calculating a temperature nonuniformity parameter for each case.

Baffles were found to be quite effective during the early

portion of each transient run and throughout most of the transient period for each run carried out with a low wall heating rate. With a sizeable rate of nonuniform source heating present, the effectiveness of the baffles was decreased as compared with their effectiveness under similar conditions but in the absence of source heating.

EXPERIMENTAL INVESTIGATION OF BAFFLE EFFECTIVENESS IN A CONFINED FLUID SUBJECTED TO WALL AND NONUNIFORM SOURCE HEATING

INTRODUCTION

In the development of nuclear powered space vehicles many heat transfer and fluid flow problems have been encountered. Among these is the loss of liquid hydrogen due to heating of the propellant tank. The hydrogen represents a confined fluid subjected to wall heating (heating from the outer space environment) and nonuniform source heating (nuclear heating from the rocket's reactor).

The work of Anderson and Kolar (1), and a number of other investigators, has established that wall heating produces a boundary layer which terminates in a stratified layer. Figure 1, a schlieren photograph of a confined fluid subjected to side wall heating, shows the buildup of a boundary layer along the vertical wall and its eventual termination in a stratified layer below the vapor-liquid interface. At the interface a thin, highly turbulent region (surface layer) can be seen. This flow phenomenon is reproduced schematically in Figure 2. The thickness of this stratified layer increases with time. Within this layer the temperature varies from the temperature of the cool fluid below the layer to the hotter temperature at the surface which corresponds approximately to the vapor pressure of the

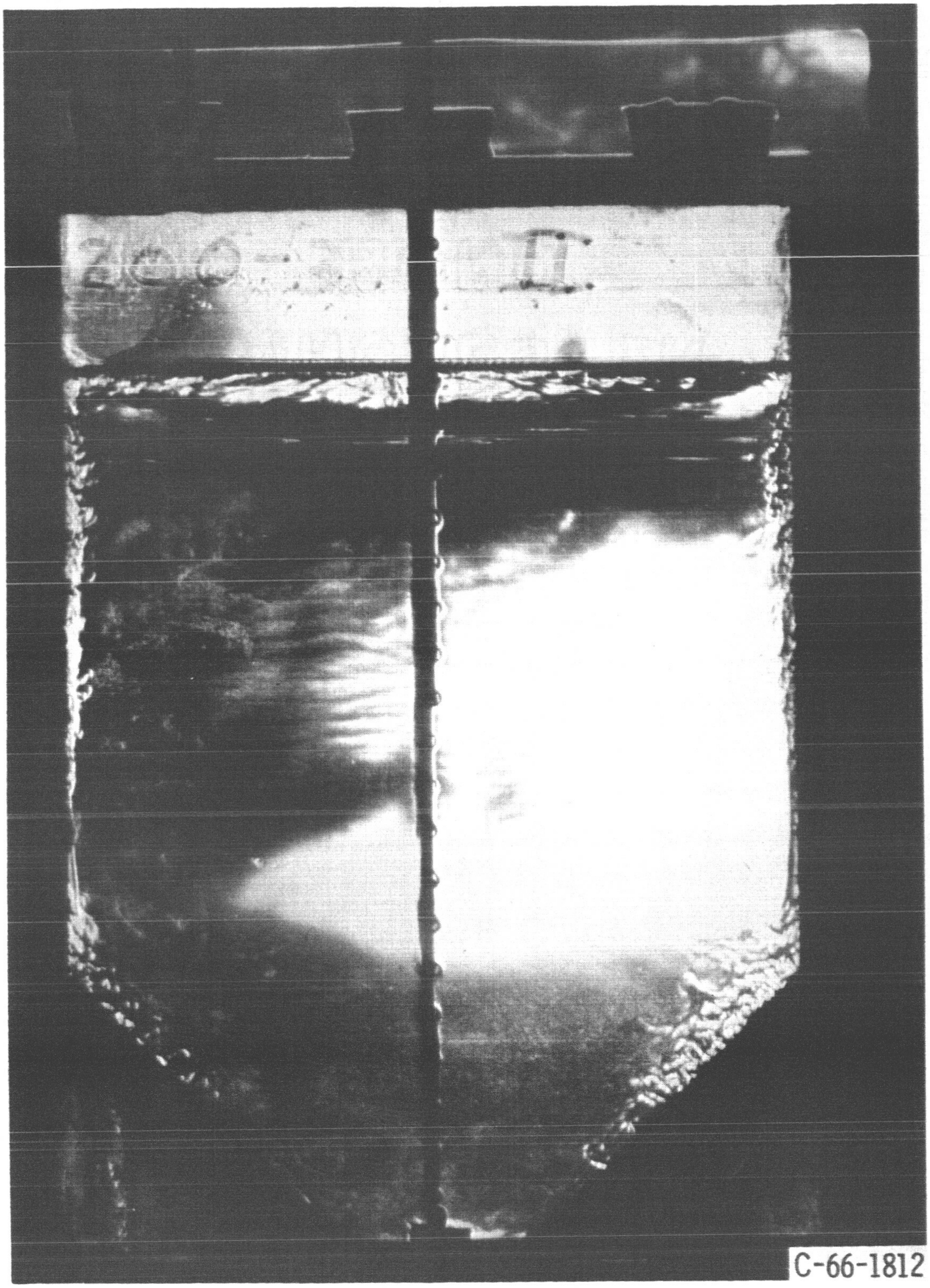

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Figure 1. - Schlieren photograph of fluid with only side wall heating present.

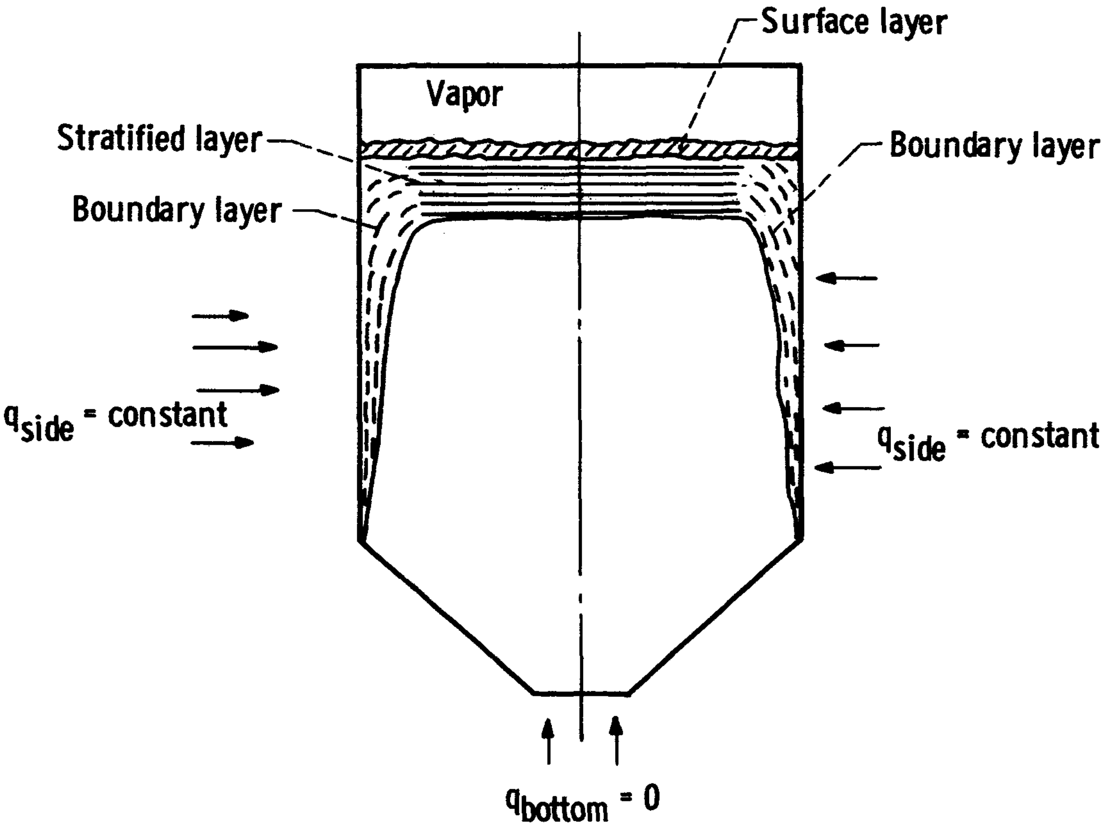

Figure 2. - Schematic outline of fluid behavior with only side wall heating present.

ullage gas (saturation temperature at the ullage gas partial pressure).

Nonuniform source heating is produced in the nuclear rocket propellant tank by absorption of gamma rays and neutrons in the liquid. The resulting effect is somewhat similar to that produced by simply heating the bottom of the container. The schlieren photograph presented in Figure 3 shows the effect of bottom heating on the fluid motion. The general pattern which persists during the application of this type of heating is presented in the sketch shown in Figure 4. In contrast to the situation produced by wall heating alone (Figures 1 and 2), uniform mixing develops in the fluid, and there is no evidence of either a boundary layer or a surface layer.

The stratified layer is of particular interest because the temperature at the liquid-gas interface is known to be at or near the saturation point (2). Further, the stratified layer thickness increases with time. Release of this hot fluid layer from the tank can give rise to a hazard if its mass is large because it can lead to vapor formation and cavitation in the supply lines and pump, respectively.

Various methods have been suggested for decreasing the temperature difference across the stratified layer. Huntley (3) noted that stirring the liquid decreased the surface temperature and slightly increased the fluid bulk temperature. Use of this procedure can essentially eliminate the stratified layer by reducing the temperature difference across the layer to a very small value. In References (2) and (3), insulation of the tank walls was suggested as a means of preventing heat flow to the liquid surface. These techniques

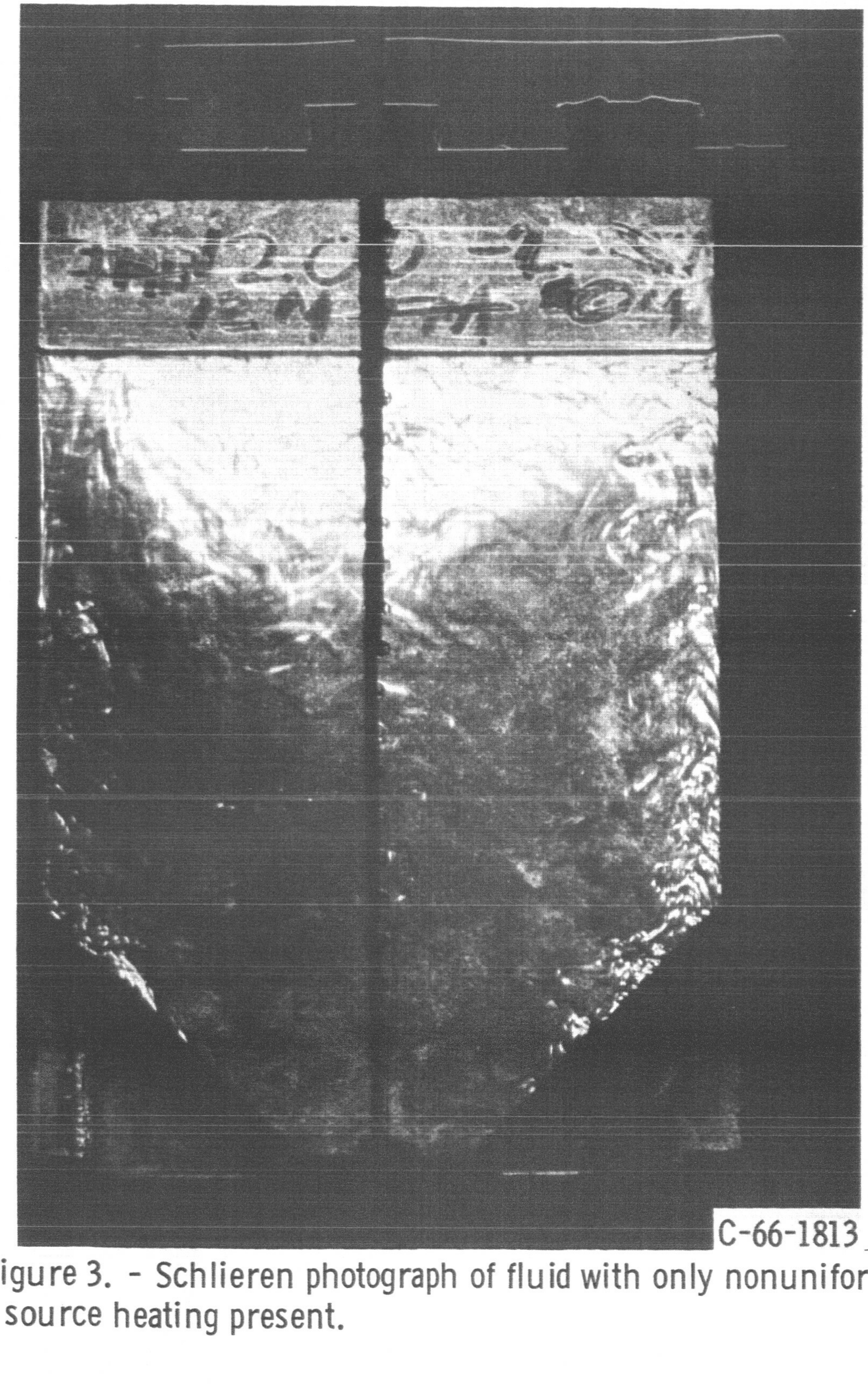

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Figure 3. - Schlieren photograph of fluid with only nonuniform source heating present.

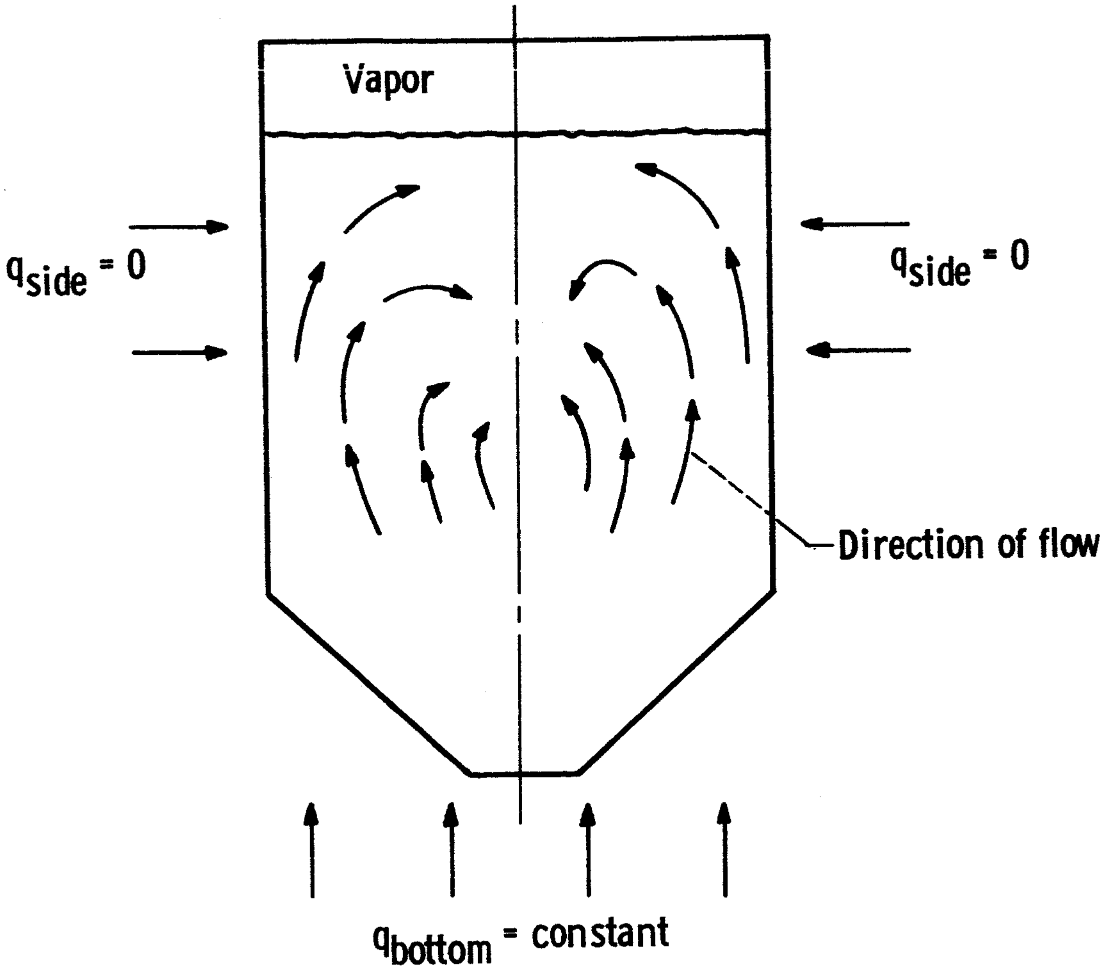

Figure 4. - Schematic outline of fluid behavior with only non-uniform source heating present.

may lead to prevention of vapor formation and cavitation, but they have the unfavorable effect of requiring a larger and heavier structure.

The above-mentioned techniques have received considerable attention from a number of investigators. However, the use of baffles has not been sufficiently studied to ascertain the value of this method as a means of decreasing the detrimental effects of stratification. Some efforts along these lines have already been made (4). The method involves placing obstructions in the boundary layer to prevent the boundary layer fluid from passing directly into the stratified layer.

The system used in the investigation and reported in Reference (1) was readily available (Figure 5) and offered a convenient means for investigating baffling, particularly visually. With this apparatus the fluid, a mixture of trichloroethane and ethyl alcohol, could not only be subjected to side wall heating but also to nonuniform source heating by means of infrared absorption in the fluid. This represents a more direct means of nonuniform source heating than was used in (4). The absorption characteristics of the mixture were found to be similar to those of liquid hydrogen. For purposes of this study, therefore, the mixture was a more suitable fluid than water, which was used in the investigation associated with Reference (4).

It was the purpose of this research to determine whether baffles could favorably influence fluid behavior to a significant extent and thus bring about a more uniform temperature distribution. One

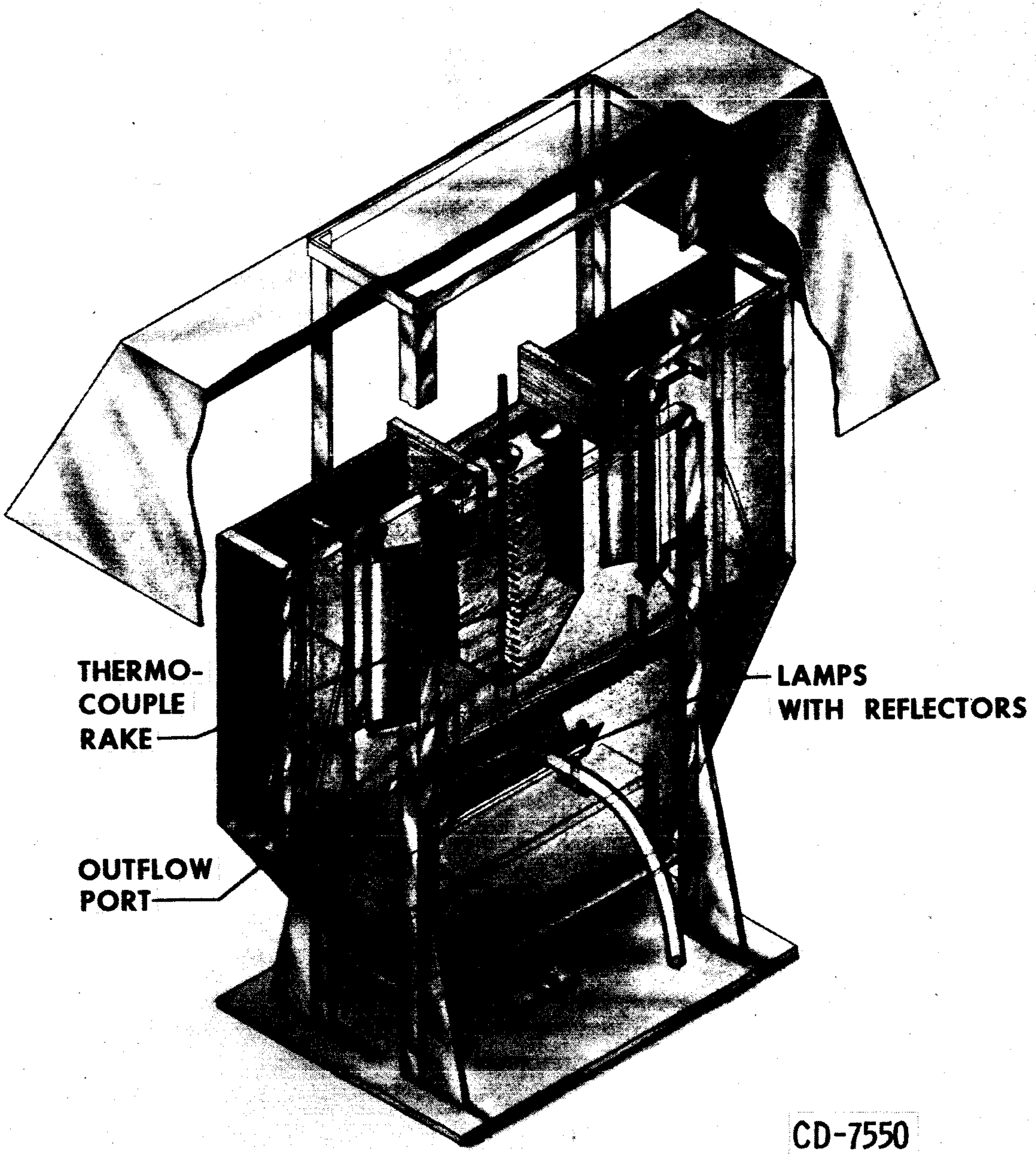

Figure 5. - Flow visualization test apparatus.

two-dimensional view tank without baffles and one with baffles were each subjected to various combinations of wall and nonuniform source heating rates. Schlieren photographs and temperature measurements were obtained and compared for the two systems. A temperature nonuniformity parameter was defined and measured fluid temperatures were used to calculate numerical values of this parameter for purposes of quantitative comparison. Measured wall and fluid temperatures were used for determining heat transfer coefficients for the case of vertical wall heating. In addition, the baffle effectiveness parameter presented in Reference (4) was applied to the fluid temperature data. Finally, the critical transition point separating the laminar and turbulent boundary layer regions was calculated and the results were compared with experimental observations.

A review of the results obtained from the experiments showed baffles to be most effective during the early portion of each transient run and throughout most of the transient period for each run carried out with a low rate of vertical wall heating. Baffle effectiveness decreased with increasing amounts of nonuniform source heating present.

APPARATUS AND PROCEDURE

Apparatus

A number of baffling arrangements were proposed originally because of a desire to study dissimilar boundary layer lengths above and below the baffles. However, due to the amount of time necessary to fabricate each tank, one tank without baffles (Figure 5) and one with baffles (Figure 6) were chosen. The system employed by Anderson and Kolar (1), with some modification, was used to test the effectiveness of this baffling arrangement. It is appropriate to discuss some of the components of the apparatus at this point in the presentation.

Tanks

Each tank (Figure 5) was constructed of Pyrex glass, had inside dimensions of 12 in. high by 8 in. wide by 2 in. deep, and featured inclined walls set at a 45^{o} angle. The front and back faces were 1/4 in. thick and the remaining walls were 1/8 in. thick. The vertical walls were painted with black enamel to prevent absorption by the fluid of infrared rays produced by the lamps used for heating of the vertical walls. The enamel absorbed the rays and served to produce the desired heating in these walls. The inclined walls, which represented the cross sectional shape of a conical-bottomed

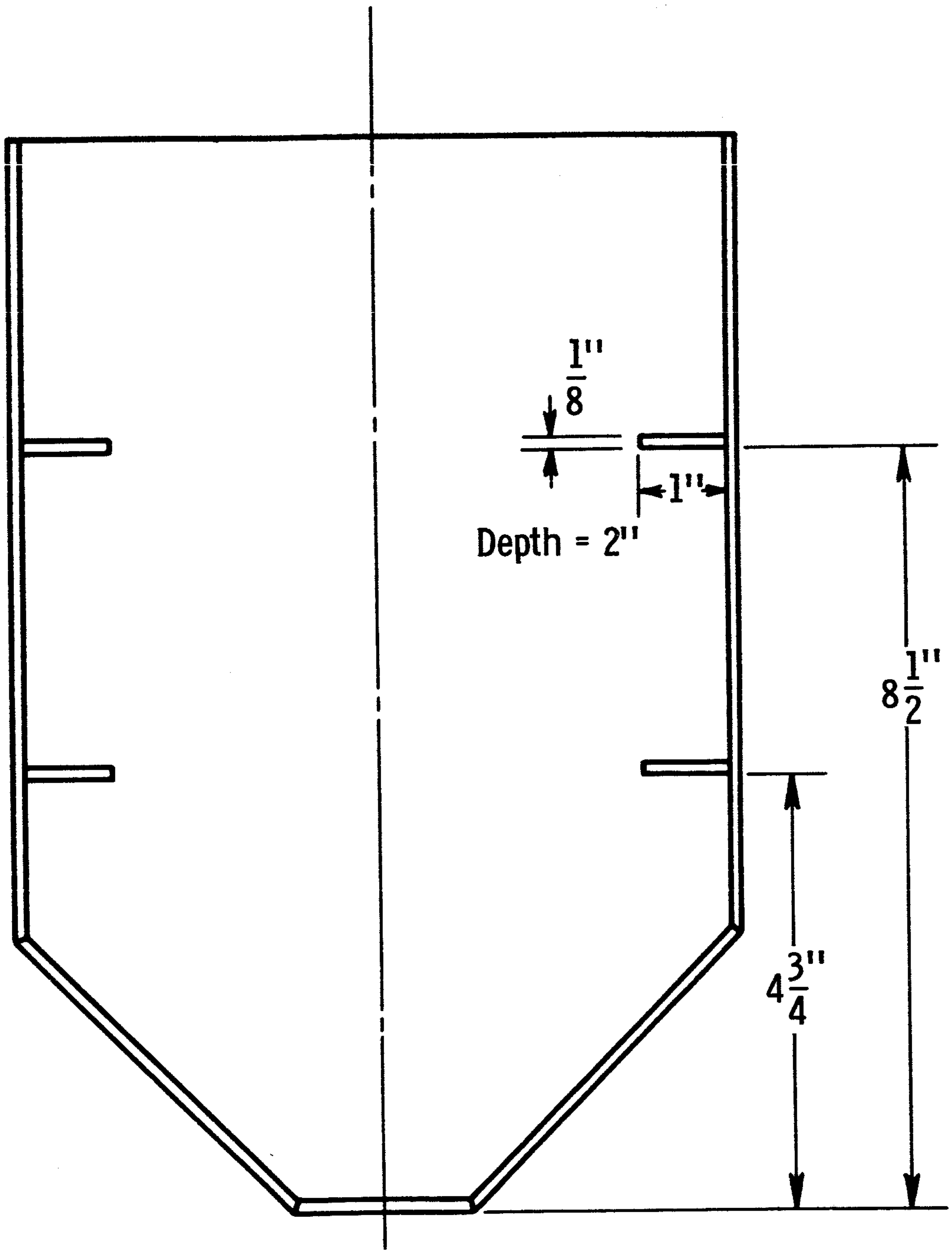

Figure 6. - Baffle locations in test tank.

tank, were not painted nor was the bottom section surrounding the discharge port. The clear glass at the bottom allowed passage of infrared rays from the bottom lamp to the fluid thereby simulating nonuniform source heating through absorption of the rays in the fluid (see Reference (1)).

The only required modification of the tanks involved covering of the horizontal bottom section of glass and the discharge tube with reflective tape. This was done in an attempt to minimize fluid heating in and near the discharge tube. It was found that fluid in this tube passed upward into the tank unless heating in this region was reduced.

Baffles

The baffles attached to the tank walls were made of an insulating material to minimize conduction from the vertical wall to the fluid and to also minimize absorption by the baffles of infrared rays from the bottom lamp. The one inch length (Figure 6) was sufficient to insure diversion of the boundary layer to the fluid bulk. With too short a baffle, boundary layer fluid could conceivably continue its growth around the baffle.

The top baffle was placed so that the buildup of the boundary layer would be retarded before termination in the surface layer. The lower baffle was used to divide the boundary layer so that two dissimilar lengths of boundary layer could be studied.

Fluid

The fluid used in testing the effectiveness of the baffles was a solution of two parts trichloroethane and one part ethyl alcohol. A listing of some of its properties is presented in Table 1. The similarity of this fluid's infrared absorption characteristics to the absorption characteristics of liquid hydrogen prompted its use. Another consideration was the ease with which the fluid could be safely handled.

The fluid was contained in a glass reservoir located above the tank and was transferred to the tank by gravity feed. The fluid was removed from the tank through the discharge port to a lower reservoir, was filtered, and then pumped back to the upper reservoir.

Table 1. - Properties of Two Parts Trichloroethane and One Part Ethyl Alcohol Solution

Specific heat	0.3494 Btu/(lb)($^{\circ}$F)
Thermal conductivity	3.2×10^{-3} Btu/(hr)(in.)($^{\circ}$F)
Temperature coefficient of volume expansion	7.65×10^{-4} 1/$^{\circ}$F
Density	0.0406 lb/cu in.
Absolute viscosity	0.132 lb/(in.)(hr)

Lamps

Heating of the fluid was accomplished by infrared rays from three 1000-watt quartz lamps located as shown in Figure 5. Parabolic reflectors were placed around the lamps to reduce the scatter of light. In addition, 1/8 in. by 1/4 in. aluminum strips were placed

1/2 in. from the vertical lamps as shown in Figure 7 to insure that the tank walls would receive a uniform amount of infrared rays. Further, shields which extended 3 in. above the bottom edge of the tank were placed 2 in. from the vertical walls (Figure 7). The purpose of these shields was to prevent infrared rays from the vertical lamps from entering the fluid through the unpainted inclined surfaces.

Thermocouples

Fluid and wall temperatures were obtained from 30 gage nylon-coated copper-constantan thermocouples located as shown in Figure 8. The 20 thermocouples along the axis of the tank were used to measure fluid bulk temperatures. Shielding was provided to prevent direct infrared absorption by the thermocouples. The heat transferred from the lamps through the walls to the fluid was determined from temperature measurements obtained using 13 pairs of wall thermocouples. The fluid and wall temperature measurements obtained from these thermocouples were recorded on three 10-channel Leeds and Northrup recorders having a recording speed of two seconds per channel.

Schlieren System

Visual observation of fluid density changes was accomplished by means of a schlieren photographic system. The layout of the schlieren system showing the location of the source light, reflecting mirrors, and camera in relation to the test section is presented in Figure 9. The system was particularly useful for studying boundary layer behavior and for determining how this behavior was affected by the baffles.

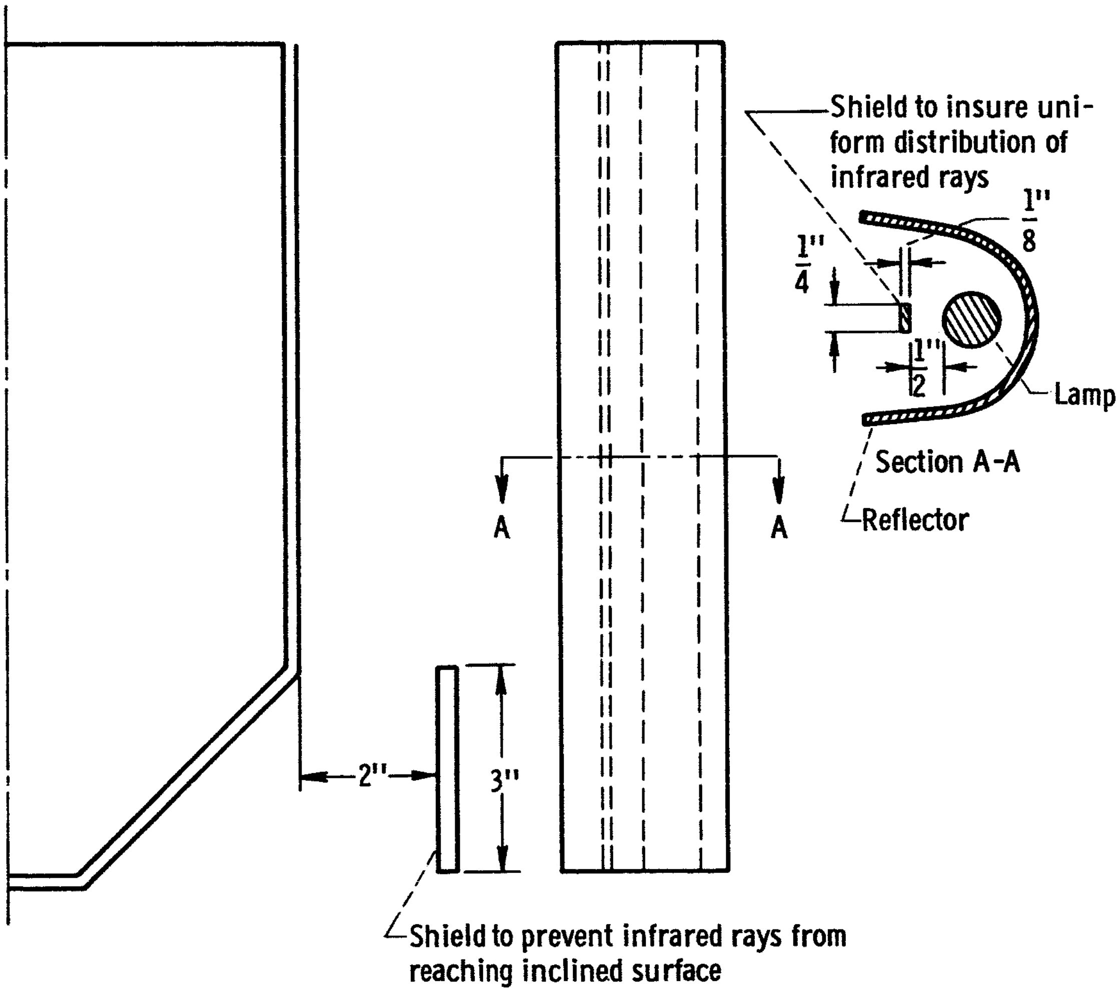

Figure 7. - Location of shields in relation to vertical lamp.

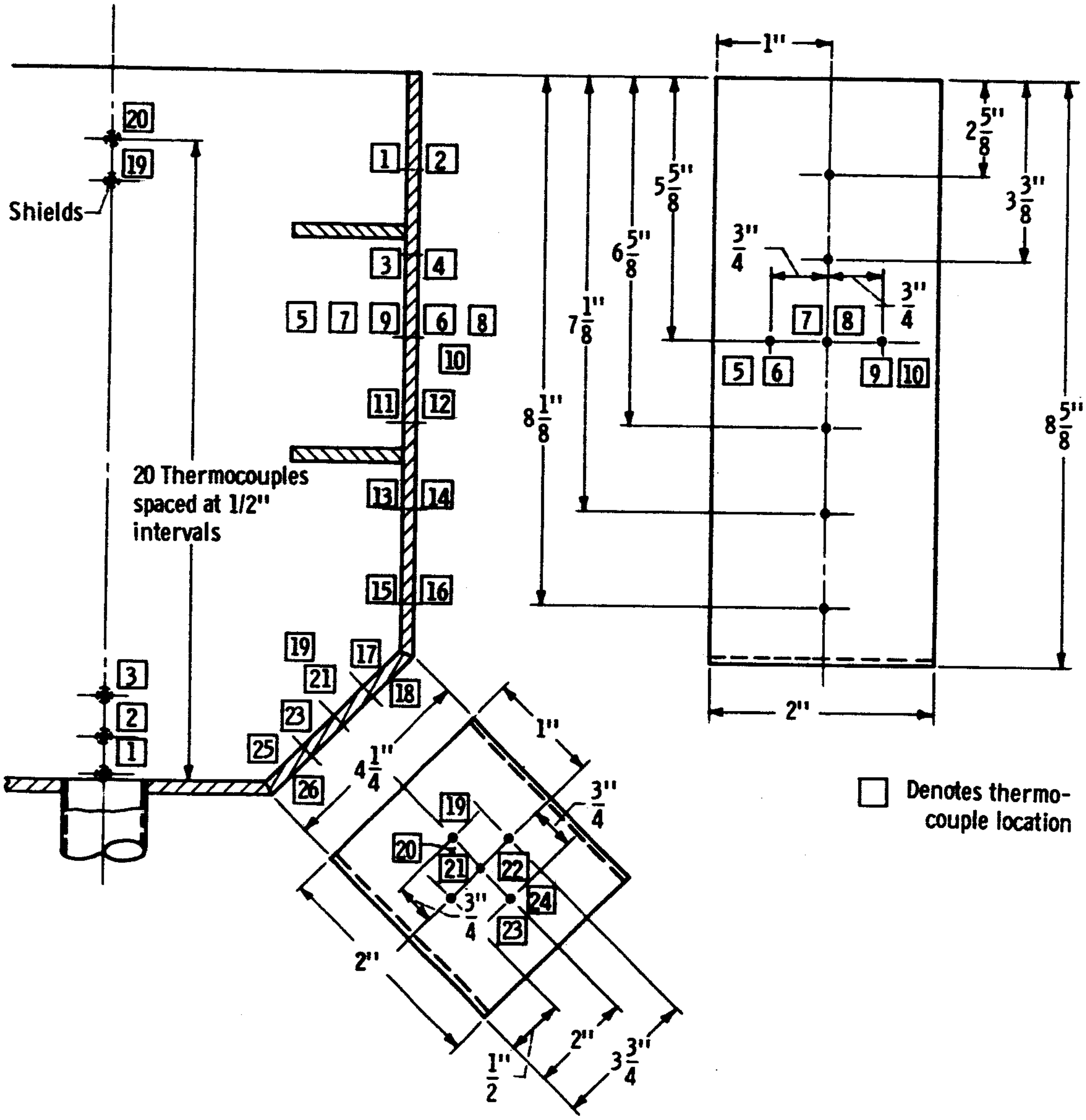

Figure 8. - Location of fluid and wall thermocouples.

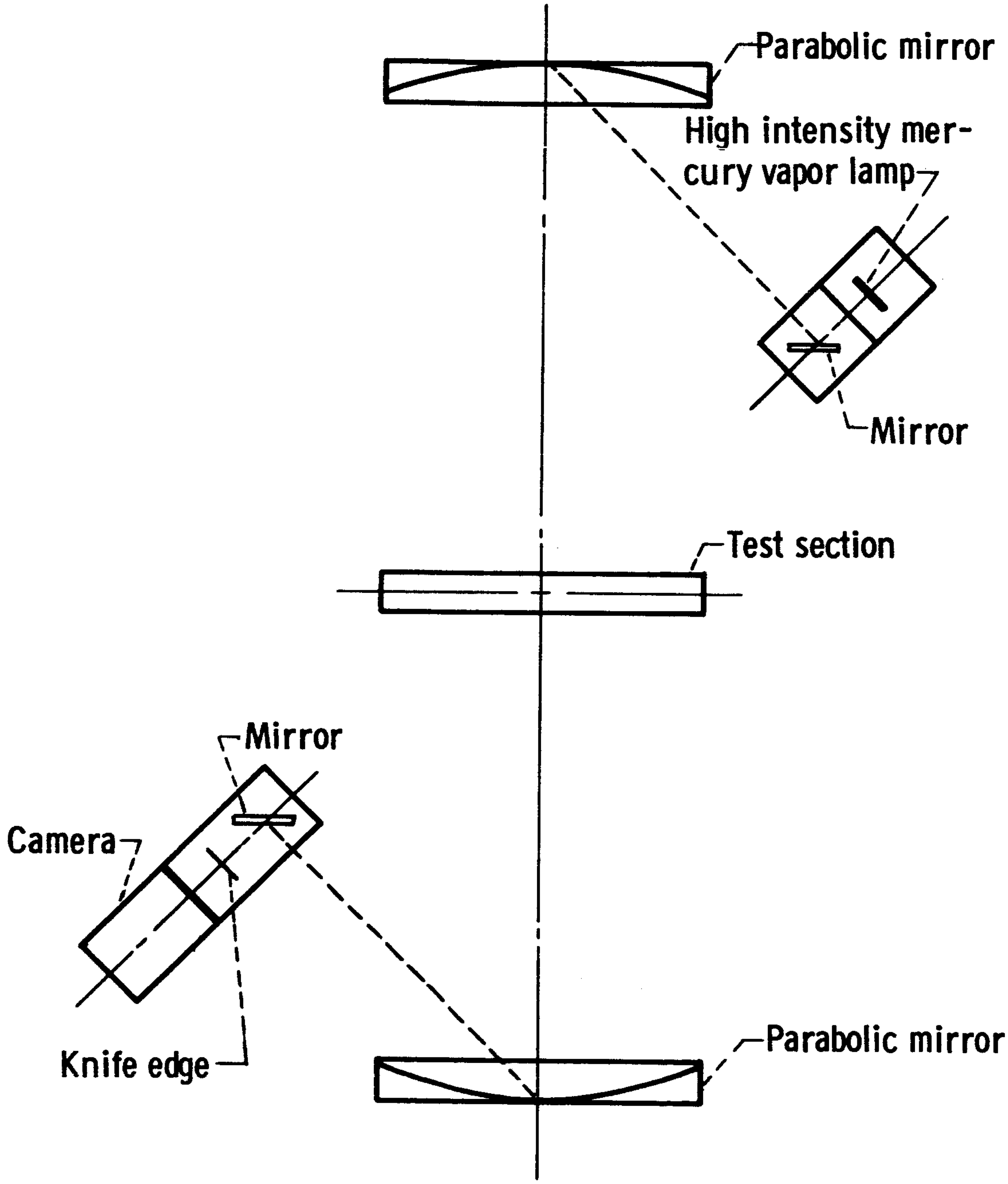

Figure 9. - Schlieren system layout.

Test Parameters

Test variables and recorded temperatures, as presented in Table 2, and schlieren photographs were duplicated for the tanks with and without baffles for the purpose of comparing fluid behavior in the two tanks. Specifically, the duplicated test conditions were the following:

1. Fluid height was maintained at 9.5 inches so that the uppermost axial thermocouple was at the liquid surface.

2. Three separate voltages were used for the vertical lamps,* 0, 100, and 150 volts, and 0, 100, 150, and 200 volt settings were used for the bottom lamps. The adhesion of the bonding agent between the glass plates was found to deteriorate at the high wall heating rate provided by a 200 volt vertical lamp setting, so tests planned for this situation were eliminated.

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*For vertical lamp settings of 100 and 150 volts the corresponding heat fluxes across the vertical walls were determined to be 3.0 and 6.1 Btu/(hr)(sq in.) respectively. These values were arrived at by employing the heat conduction equation,

$$q'' = \frac{k}{L} \Delta T$$

where

ΔT = the temperature difference between the thermocouples on the outer and inner surface of the wall

k = the thermal conductivity of borosilicate low-expansion glass; see Reference (5)

L = the thickness of the vertical wall

No attempt was made to calculate the heating rates due to the bottom lamps. However, Anderson and Kolar (1) have estimated that a 100 volt bottom lamp setting provided a source heating rate of 55.5 Btu/hr and that 150 and 200 volts produced rates of 103.5 and 163.2 Btu/hr, respectively.

Table 2. - Summary of Run Conditions

Tank configuration	Voltage setting		Thermocouple measurements (see Figure 8 for location)	
	Vertical lamps	Bottom lamp	Axial	Wall
No baffles	0	100	1 to 20	17 to 26
	0	150	1 to 20	17 to 26
	0	200	1 to 20	17 to 26
	100	0	7 to 20	1 to 16
	100	100	9 to 20	1,2,3,4,7,8,11,12, 13,14,15,16,17,18, 21,22,25, and 26
	100	150		
	100	200		
	150	0	7 to 20	1 to 16
	150	100	9 to 20	1,2,3,4,7,8,11,12, 13,14,15,16,17,18, 21,22,25, and 26
	150	150		
	150	200		
Baffles	0	100	1 to 20	17 to 26
	0	150	1 to 20	17 to 26
	0	200	1 to 20	17 to 26
	100	0	7 to 20	1 to 16
	100	100	9 to 20	1,2,3,4,7,8,11,12, 13,14,15,16,17,18, 21,22,25, and 26
	100	150		
	100	200		
	150	0	7 to 20	1 to 16
	150	100	9 to 20	1,2,3,4,7,8,11,12, 13,14,15,16,17,18, 21,22,25, and 26
	150	150		
	150	200		

3. Run duration was ten minutes for all tests. The 200° F recording limit of the L & N recorder would have been exceeded in some tests had the run time been longer. Also, within ten minutes a sufficient amount of information was obtained from the schlieren photographs to derive generalized conclusions regarding fluid behavior.

4. Thirty thermocouples were chosen for each run (a compromise between the best temperature coverage and the L & N capacity) and are presented in Table 2.

5. Schlieren photographs were taken at one, five, and ten minutes after initiation of heating.

RESULTS AND DISCUSSION

In all, 22 test runs were completed, 11 using the baffled tank and 11 using the tank without baffles (Table 2). Each of 11 runs in each set of experiments was made using a different combination of vertical and bottom lamp voltages. Of these, five runs for each tank were selected as representative of the heat transfer and fluid flow phenomena in a confined fluid subjected to wall and nonuniform source heating. The runs consisted of side wall heating alone (vertical lamp settings of 100 and 150 volts), nonuniform source heating alone (bottom lamp setting of 150 volts), and a combination of both types of heating (bottom lamp setting of 150 volts and vertical lamp settings of 100 and 150 volts).

A discussion of the results of the test runs is divided into two major sections, one dealing with experimental results and another dealing with performance parameters calculated using these experimental results. Schlieren photographs of density changes produced at the various lamp voltage settings with and without baffles are presented in the experimental comparison discussion. Also included are the plots of fluid temperatures as measured along the tank centerline. Quantitative comparison of the data was carried out using a derived parameter, previously referred to as the temperature nonuniformity, which depends on the fluid temperature distribution along the tank centerline.

To check the validity of the test results, critical lengths for the transition from laminar to turbulent flow along a heated vertical wall were predicted using a modified Grashof number (6) of approximately 10^{10} (see Reference (7)). These predictions were compared with the critical lengths determined from the experimental observations. Additionally, effectiveness values were calculated for purposes of comparing the results of this investigation with those presented in Reference (4).

Experimental Results

Schlieren Photographs

Visual results of the selected experiments can be seen in the schlieren photographs presented in Figures 1, 10, 11, 12 and 13. Without baffles and with wall heating (vertical lamps set at 150 volts), the boundary layer grew along the vertical wall until it reached the liquid surface as shown in Figure 1. Thereupon the boundary layer fluid moved into the stratified layer and with time this stratified layer increased in thickness.

Density changes in the baffled tank under similar heating conditions (vertical lamps set at 150 volts) are shown in Figure 10 and indicate a pattern of fluid motion presented schematically in Figure 14. Here the boundary layer grew along the vertical wall up as far as the first baffle. On contact with this obstruction, the fluid was dispersed into the main body of fluid. In addition, part of the fluid moved past the baffle causing a highly disturbed region above the baffle. Although it cannot readily be seen in the photograph,

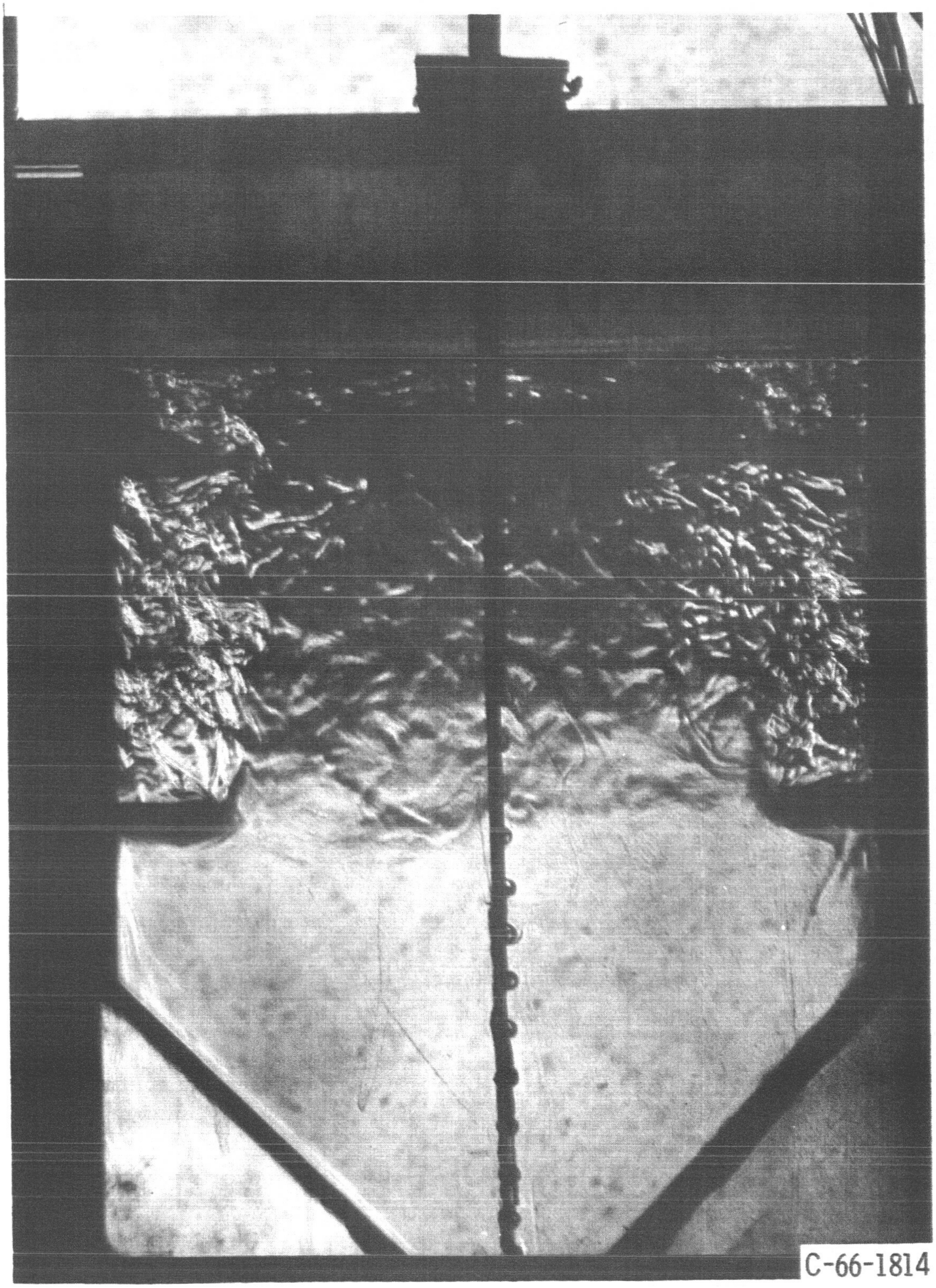

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Figure 10. - Schlieren photograph of fluid density variations in the presence of baffles one minute after initiation of side wall heating (vertical lamps set at 150 volts).

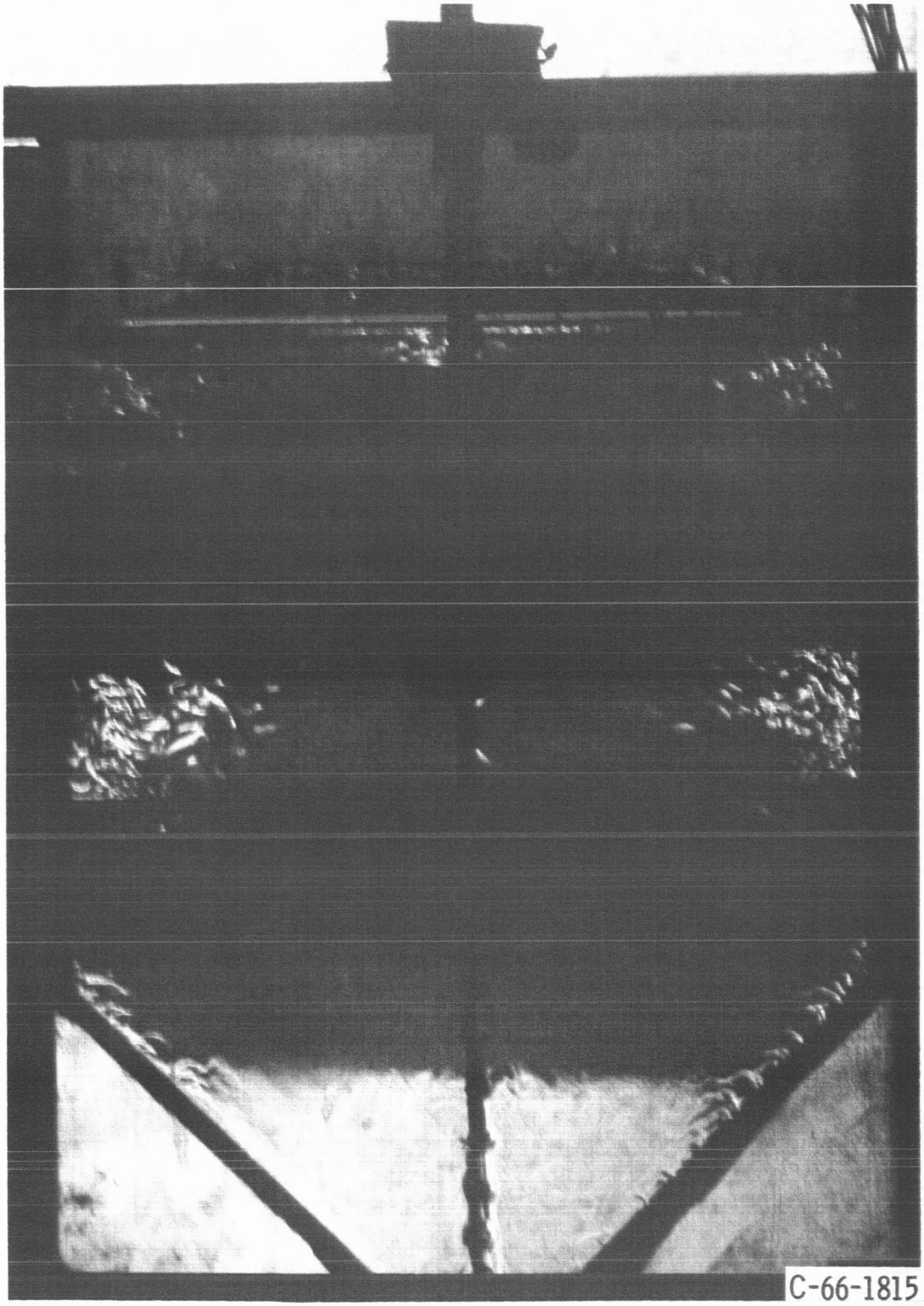

Figure 11. - Schlieren photograph of fluid density variations in the presence of baffles ten minutes after initiation of side wall heating (vertical lamps set at 150 volts).

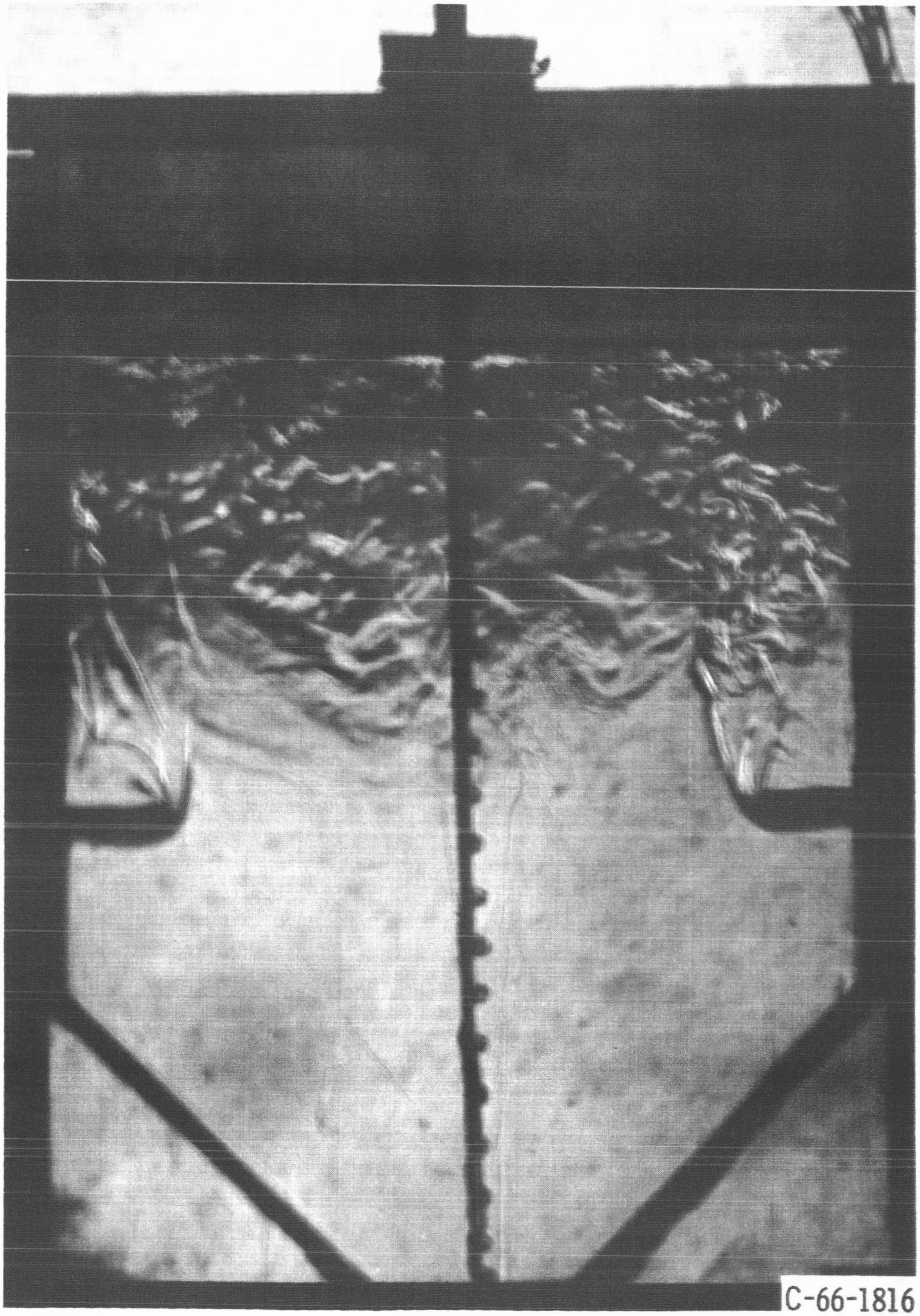

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Figure 12. - Schlieren photograph of fluid density variations in the presence of baffles one minute after initiation of side wall heating (vertical lamps set at 100 volts).

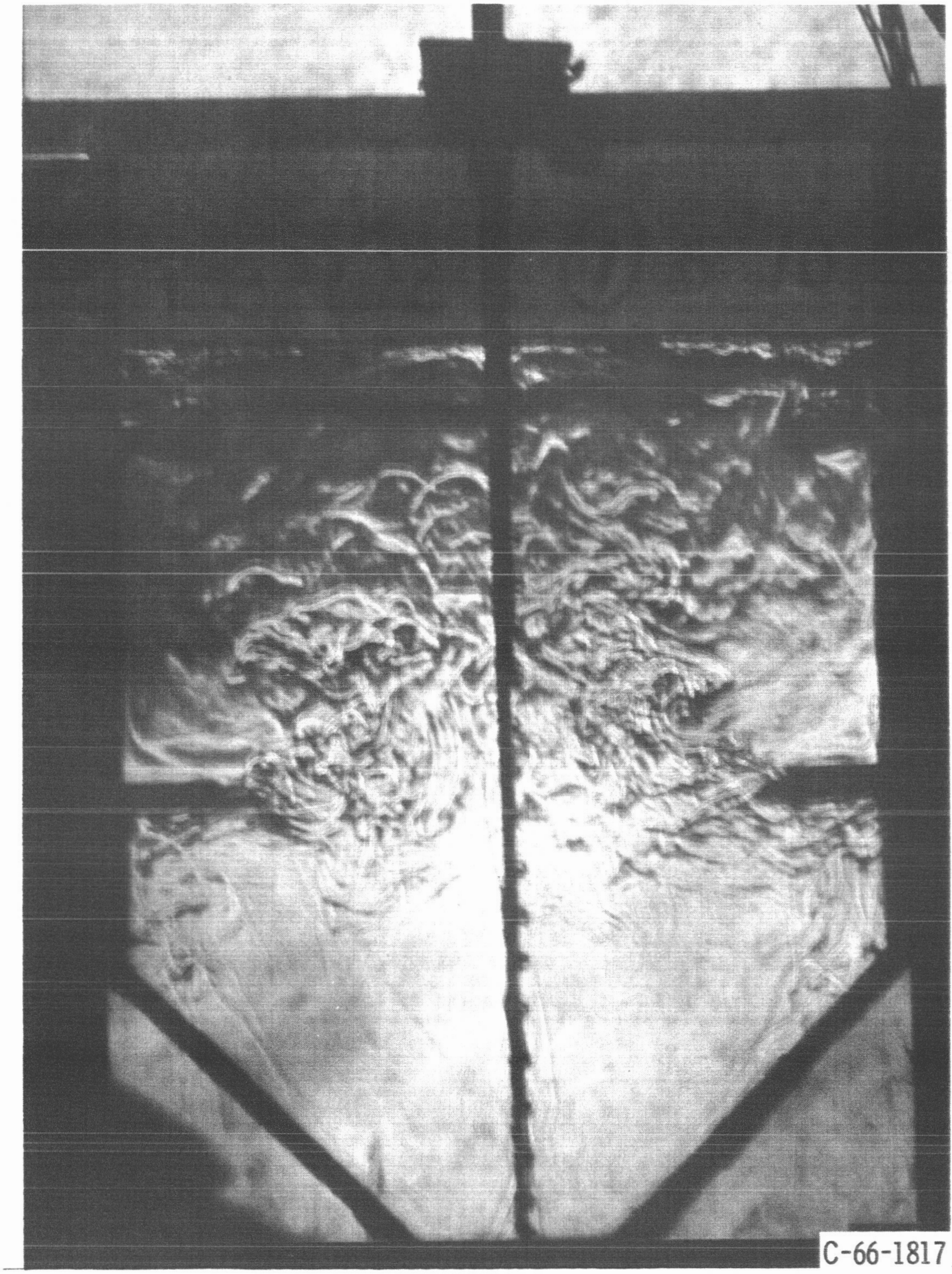

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Figure 13. - Schlieren photograph of fluid density variations in the presence of baffles one minute after initiation of both side wall and nonuniform source heating (vertical and bottom lamps set at 100 volts).

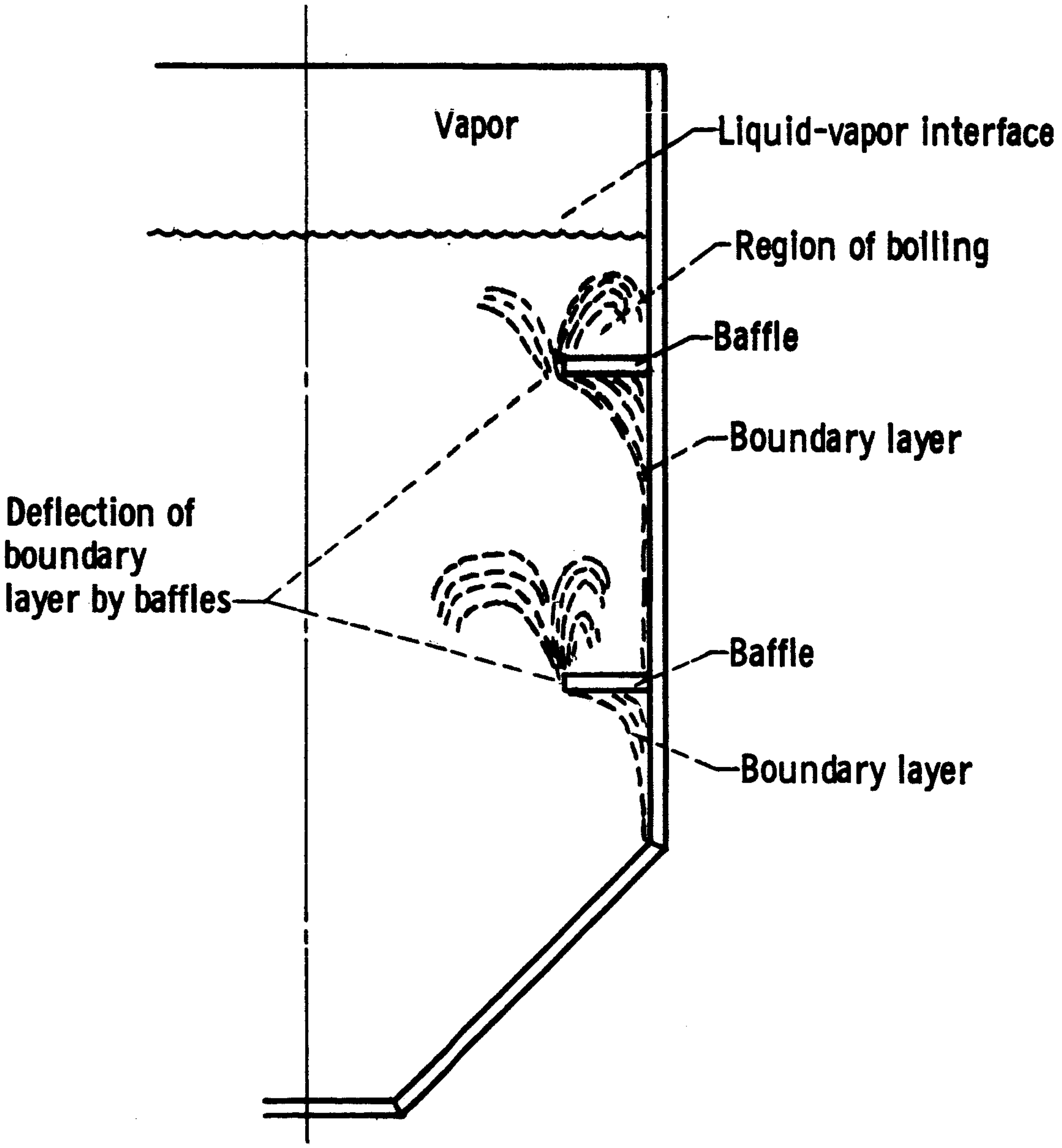

Figure 14. - Observed fluid behavior in a baffled tank with side wall heating.

a second boundary layer was observed to begin above this first baffle and to continue until contact was made with the second baffle. The dispersal pattern of boundary layer fluid was repeated there. However, the proximity of the liquid-gas interface to the second baffle altered the flow pattern. In particular, what appeared to be a boiling region was formed in the space between the baffle and the interface, near the vertical wall.

At this same wall heating rate, but at later times, the deflecting effects of baffles appeared to diminish (Figures 10 and 11). At a given time after initiation of heating, the deflecting effects of the baffles appeared to diminish with increased wall heating rate (Figures 10 and 12).

A schlieren photograph of the fluid when subjected to nonuniform source heating (bottom lamp set at 150 volts) in addition to wall heating (vertical lamps set at 100 volts) is presented in Figure 13. A schematic representation of the corresponding fluid motion is shown in Figure 15. It can be seen (Figures 12 and 13) that the baffles appear to have less influence on fluid activity than in the case of the same vertical wall heating in the absence of nonuniform source heating. This decreased influence of the baffles results from the large amount of mixing caused by the nonuniform source heating.

Fluid Temperatures

Another view of the experimental results can be obtained from study of the fluid temperature plots shown in Figures 16, 17, 18 and 19. With wall heating and baffles present, the fluid temperatures

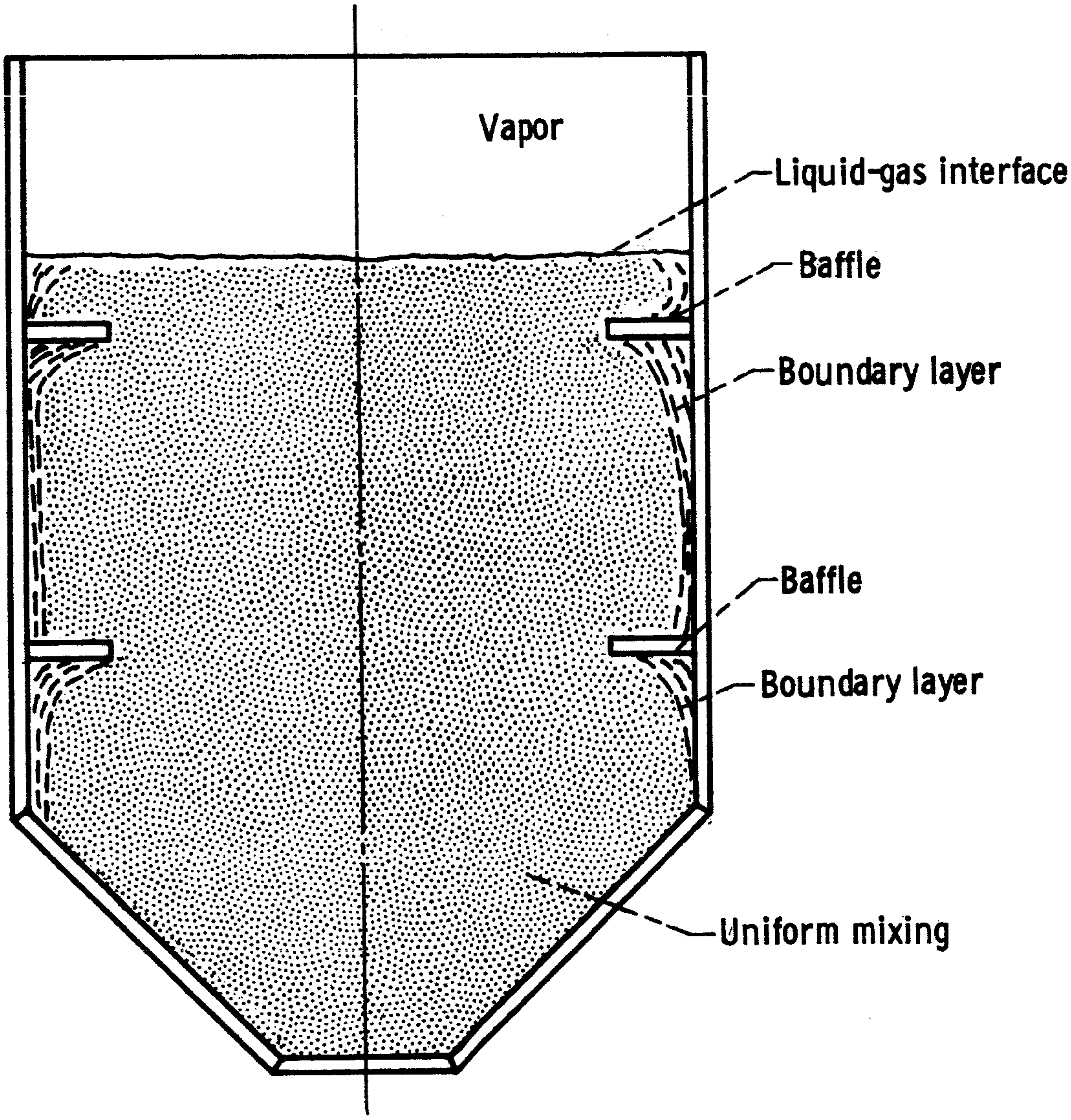

Figure 15. - Observed fluid behavior in a baffled tank with side wall and nonuniform source heating.

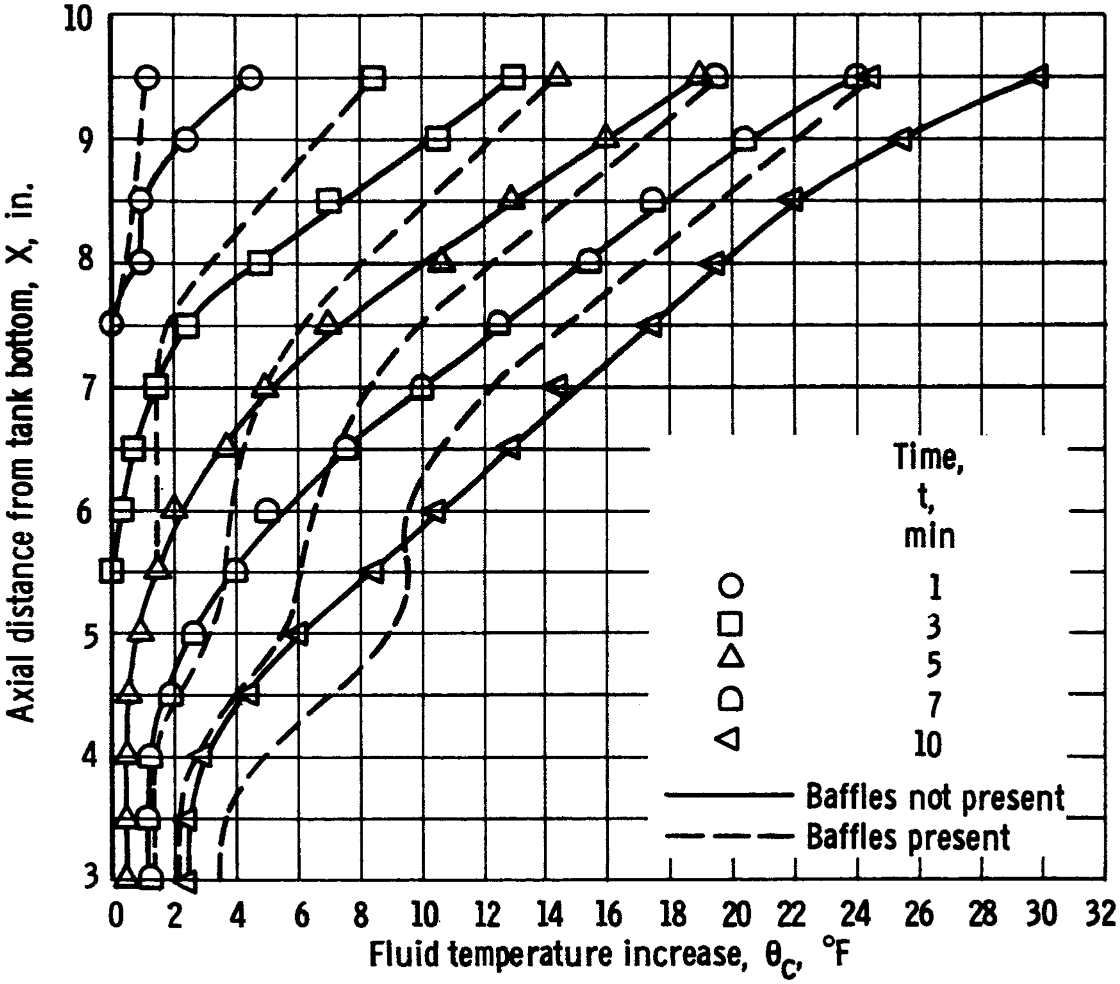

Figure 16. - Axial variation of centerline fluid temperature with side wall heating (vertical lamps set at 100 volts).

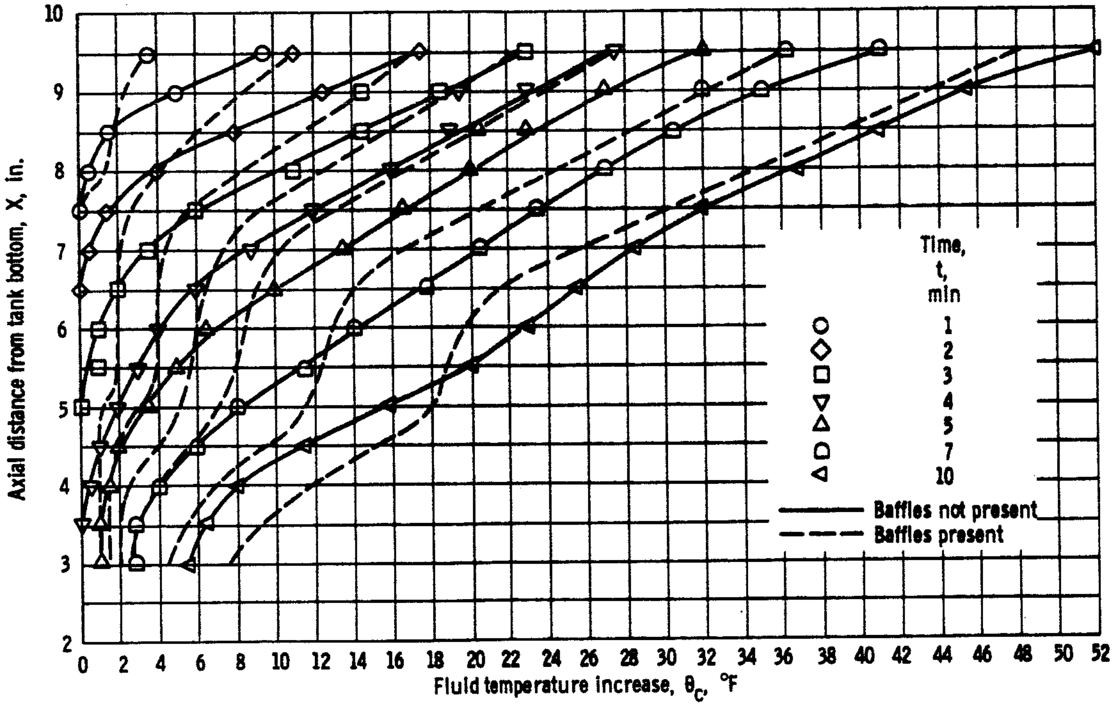

Figure 17. - Axial variation of centerline fluid temperature with side wall heating (vertical lamps set at 150 volts).

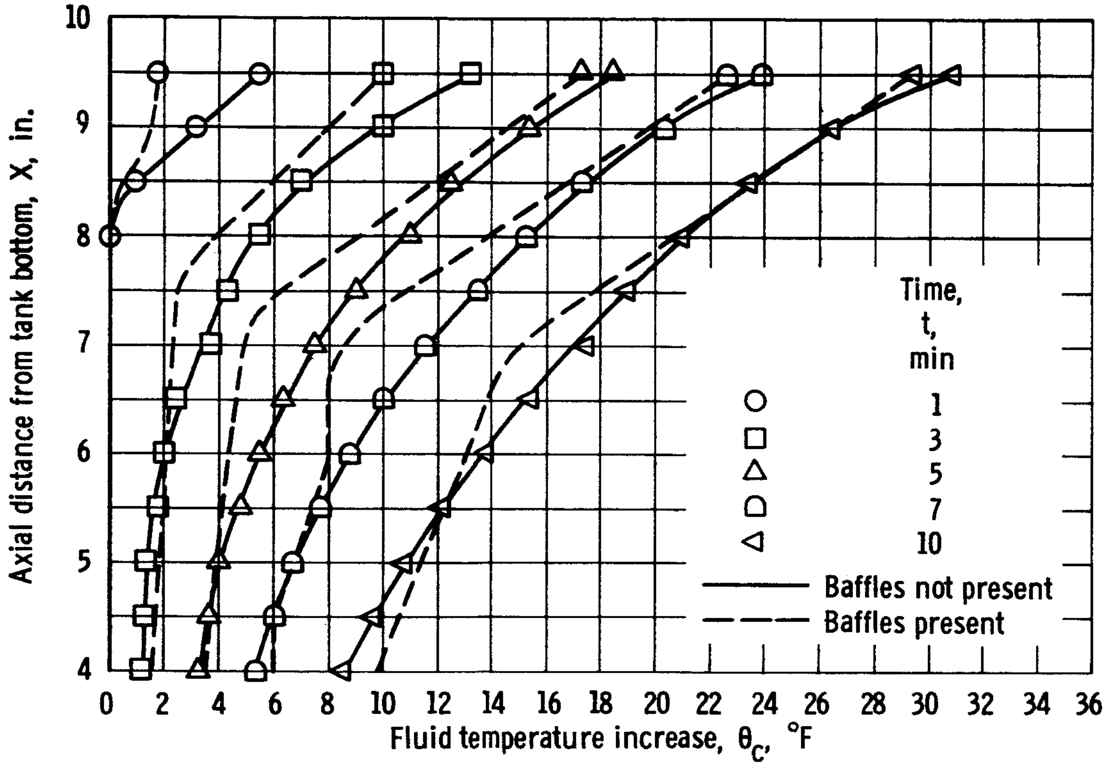

Figure 18. - Axial variation of centerline fluid temperature with both side wall and nonuniform source heating (vertical lamps set at 100 volts and bottom lamp set at 150 volts).

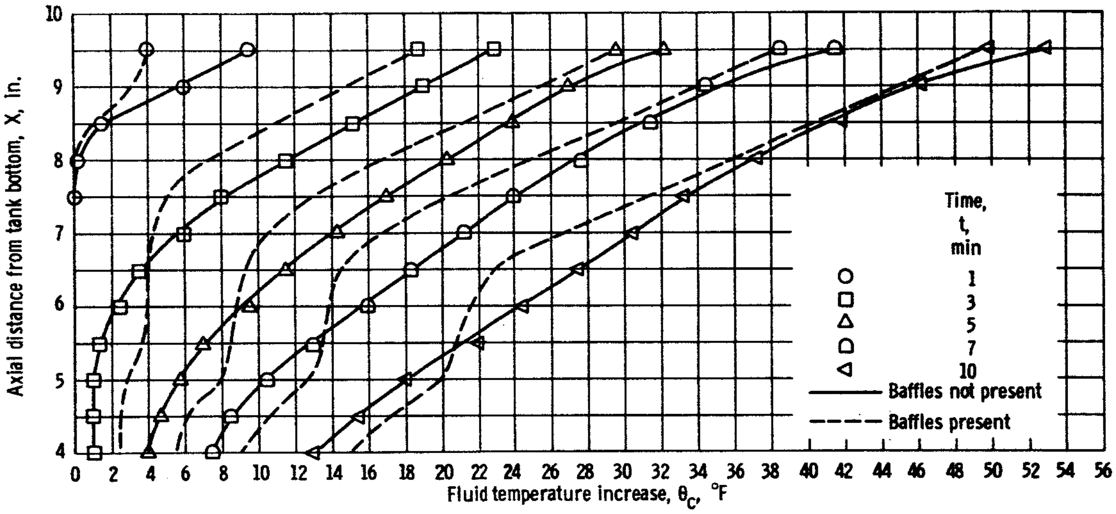

Figure 19. - Axial variation of centerline fluid temperature with both side wall and nonuniform source heating (vertical and bottom lamps set at 150 volts).

(Figures 16 and 17) at axial positions below the first baffles were higher than when no baffles were present under similar heating conditions. That is, the fluid deflected by this pair of baffles caused the bulk temperature to rise. However, in what had been the stratified region in the unbaffled case the fluid temperatures are lower with baffles present. In other words, boundary layer fluid that would have increased the temperature of the stratified layer was partially prevented from reaching the stratified layer. This heated fluid instead passed into the region below the stratified layer.

As was noted in the schlieren photographs, the baffles became less effective with time for a particular heating rate. The measured fluid temperatures substantiate this conclusion as is particularly evident in Figure 17. It can be seen that the temperature distributions in the stratified region for the baffled and unbaffled cases approached each other very closely for large values of time.

Another point of agreement between the schlieren photographs and the temperature plots can be noted from Figures 16 and 17. As the wall heating rate increased the difference between baffled and unbaffled bulk fluid temperature distributions decreased. For example, with a vertical lamp setting of 100 volts and $t = 10$ minutes, the approximate difference between the fluid temperatures for the baffled and unbaffled cases was approximately 2.7° F for any height greater than 7 inches. With an increase in lamp voltage to 150 volts the temperature difference decreased to about 1.5° F.

With the application of nonuniform source heating in the two above-mentioned situations, the fluid temperature distributions for the baffled and unbaffled cases became more similar. This can be confirmed by comparing Figure 16 with Figure 18 and Figure 17 with Figure 19. For the above-mentioned example, the presence of source heating caused the observed differences in the fluid temperatures to become negligibly small for a vertical lamp setting of 100 volts (Figure 18). For 150 volts the difference obtained was approximately 0.5° F. The difference was greater for 150 volts than for 100 volts in this instance in opposition to the trend observed, but the small discrepancy here is of the same order of magnitude as the precision of the measurements. Therefore, this deviation does not represent a significant result which would contradict the general trend described. It should be noted that the conclusions drawn in regard to nonuniform source heating are in agreement with those obtained from inspection of the schlieren photographs.

Calculated Performance Parameters

Temperature Nonuniformity Parameter

The introduction of a temperature nonuniformity parameter establishes still another means of comparing the baffled and unbaffled experiments. This parameter provided a means for specifying numerically the nonuniformity of the fluid temperature distribution. The physical quantities associated with this parameter are shown in Figure 20 which also contains a pictorial description of each important term.

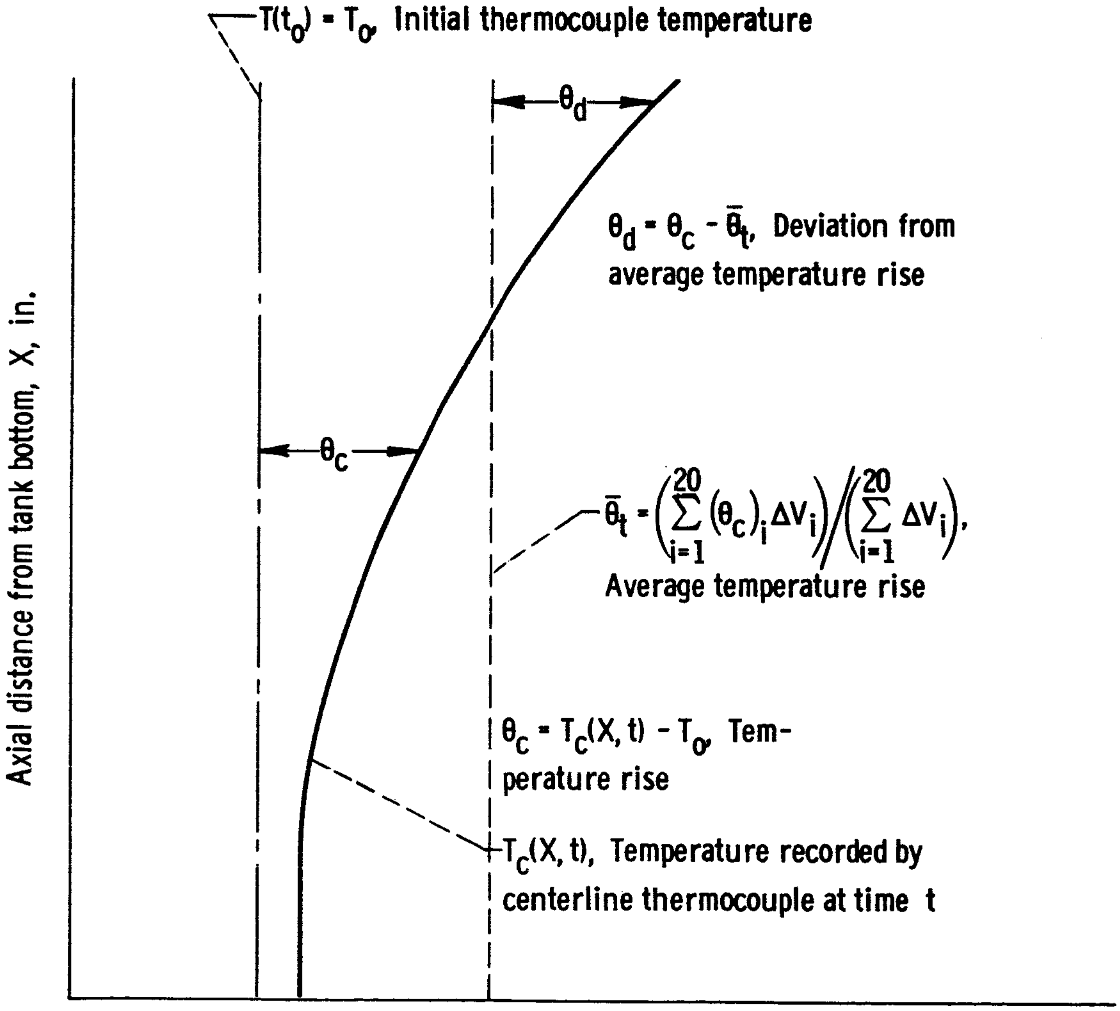

Figure 20. - Terms used in derivation of temperature nonuniformity parameter, N.

The bulk fluid was first divided into twenty volumetric increments with a fluid centerline thermocouple at the center of each volume. The average fluid temperature of each of these elements was assumed to be the temperature measured by the centerline thermocouple. Since radial temperature differences in the core were small, each measured value represented an idealized mixed mean temperature for the cross section associated with it within the approximation that the volume occupied by the boundary layer was small compared to the volume occupied by the core. The temperature rise at time t at the centerline location X is defined as

$$\theta_c = T_c(X, t) - T_o \qquad (1)$$

In accordance with the above discussion concerning the idealized average temperature concept, the average temperature rise for the total fluid volume at time t is given by

$$\bar{\theta}_t = \frac{\sum_{i=1}^{20} (\theta_c)_i \, \Delta V_i}{\sum_{i=1}^{20} \Delta V_i}$$

The deviation of the element average temperature rise from the total volume temperature rise is given by

$$\theta_d = \theta_c - \bar{\theta}_t \qquad (3)$$

This deviation, θ_d, was squared in order to obtain a positive numerical value for each element. By using this technique negative numerical values were converted to positive numbers. The temperature nonuniformity parameter, N, was defined as

$$N = \frac{\sum_{i=1}^{20} (\theta_d)_i^2 \, \Delta V_i}{\sum_{i=1}^{20} \Delta V_i} \qquad (4)$$

N is then the rms (root mean square) temperature deviation, a measure of the temperature nonuniformity of the fluid as a whole. That is, the temperature nonuniformity parameter is the square root of the volume average of the square of the temperature deviation from the average temperature of the entire fluid bulk.

In Figure 21 a plot is given which shows selected results in terms of calculated values of the temperature nonuniformity parameter obtained for three separate run conditions. These conditions were: vertical lamp settings of 100 and 150 volts with a bottom lamp setting of 0 volts, and a vertical lamp setting of 100 volts with a bottom lamp setting of 150 volts. As can be seen from Figure 21, N values for the baffled case were always lower than for the unbaffled case. In other words, greater uniformity of fluid temperature existed when baffles were present. This is evident from the results even for $t = 1$ minute when the fluid temperature differences were small and accurate values were difficult to obtain.

With time, the nonuniformity values increased for each of the baffled cases. This again points to the fact that baffles were more effective during the early portions of runs. The higher side wall heating rate for the baffled and unbaffled cases produced larger

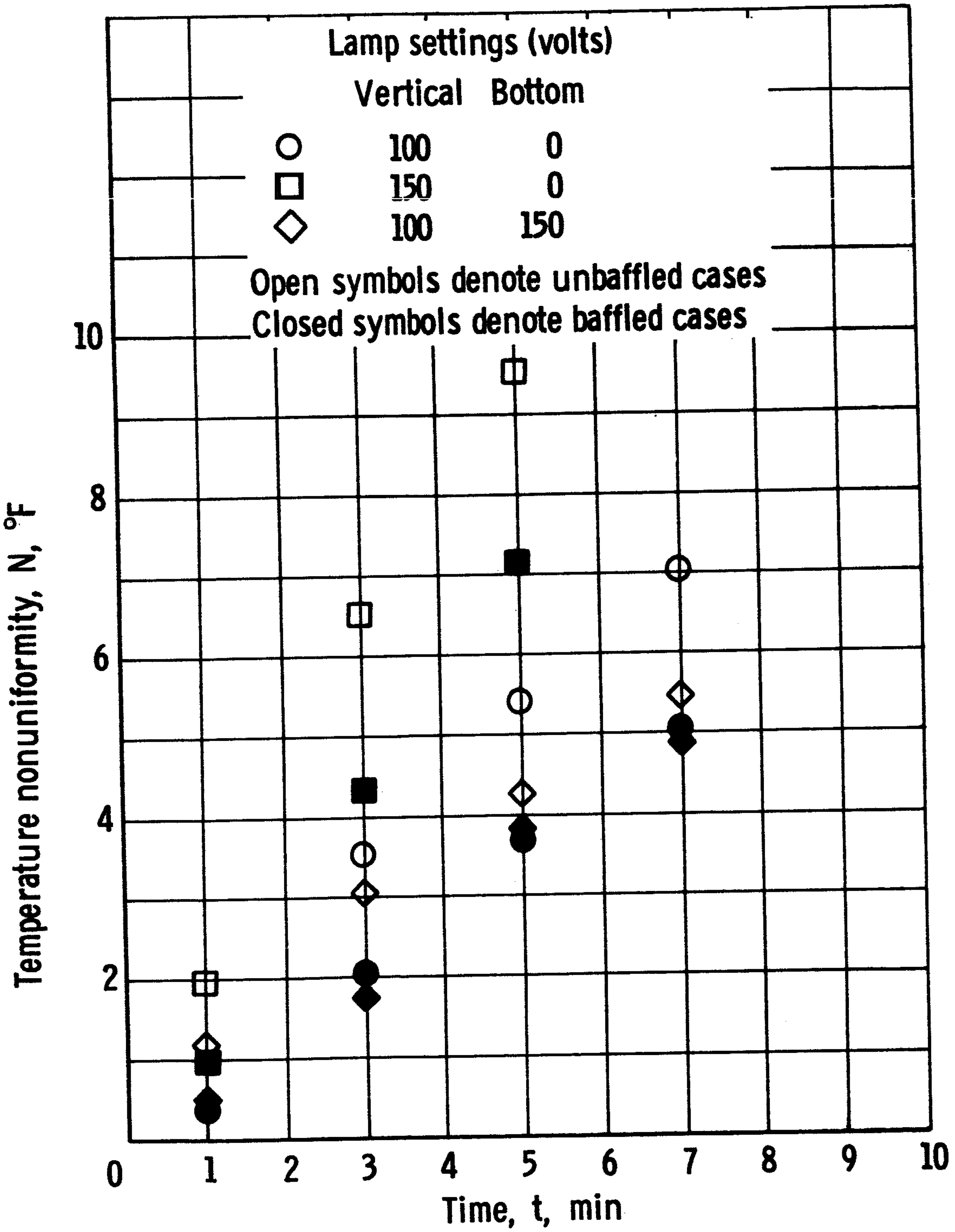

Figure 21. - Time history of temperature nonuniformity parameter for various runs.

values of N than the low wall heating rate did. The fractional decrease in temperature nonuniformity, $(N - N_b)/N$, was greater for the lower heating rate than for the higher heating rate. That is, baffles were more effective in bringing about temperature uniformity in the fluid at the lower heating rate. With nonuniform source heating (vertical lamp at 100 volts, bottom lamp at 150 volts) the fractional decrease in N was lower than it was in the absence of nonuniform source heating. Thus, baffles were less effective in the presence of nonuniform source heating.

Baffle Effectiveness Parameter

To provide an evaluation of the accuracy of the tests, the results were compared with those presented in Reference (4). Baffled and unbaffled tank runs for a vertical lamp setting of 100 volts and t = 3, 5, 7 and 10 minutes were selected and used to determine an effectiveness parameter. As presented in (4), this parameter is

$$E = \frac{M_T - \dfrac{\bar{\theta}_t \left(M_T\right)_b}{\left(\bar{\theta}_t\right)_b}}{M_T - \dfrac{\theta_t H^2}{2}} \qquad (5)$$

where

$$M_T = \int_0^H \theta_c X \, dX \qquad (5a)$$

H = height of liquid

θ_c = temperature rise (equation (1))

$\bar{\theta}_t$ = average temperature rise (equation (2))

To facilitate the integration of equation (5a), the temperature rise, θ_c, as a function of X (Figure 16) was fitted to a curve using a programming routine available on an IBM-7094 II computer. The resulting curve fit equations were in the form

$$\theta_{c,j} = \alpha_{1,j} + \alpha_{2,j}X + \alpha_{3,j}X^2 \qquad (6)$$

where

$$X_{j-1} \leq X \leq X_{j+1}$$

The resulting equation for M_T then becomes the sum of the integrals for each segment of the curve. That is,

$$M_T = \sum_{X=0}^{H} \int_{X_{j-1}}^{X_{j+1}} (\alpha_{1,j} + \alpha_{2,j}X + \alpha_{3,j}X^2)X\, dX \qquad (7)$$

Due to the lack of thermocouple data below $X = 3.0$ in., the temperature difference in this region was assumed to be equal to the temperature difference at 3.0 in. Calculations of E were carried out for four time values.

The four points calculated are shown plotted in Figure 22 using a curve similar to that shown in Reference (4). The ordinate, E, is the effectiveness parameter presented in equation (5). The abscissa, $(1 + 2.2\, e^{-0.15\, t/n})(B/W)^{0.5}(n)^{0.5}$, is a parameter developed in (4) to correlate the data. For the tests presented in this report B, the baffle width, was 1 in., W, the tank width was 8 in., n, the number of baffles was 2, and t was the time after initiation of heating, in this case 3, 5, 7 and 10 minutes. The deviations for $t = 3$ minutes and 5 minutes are approximately 15 percent, and for

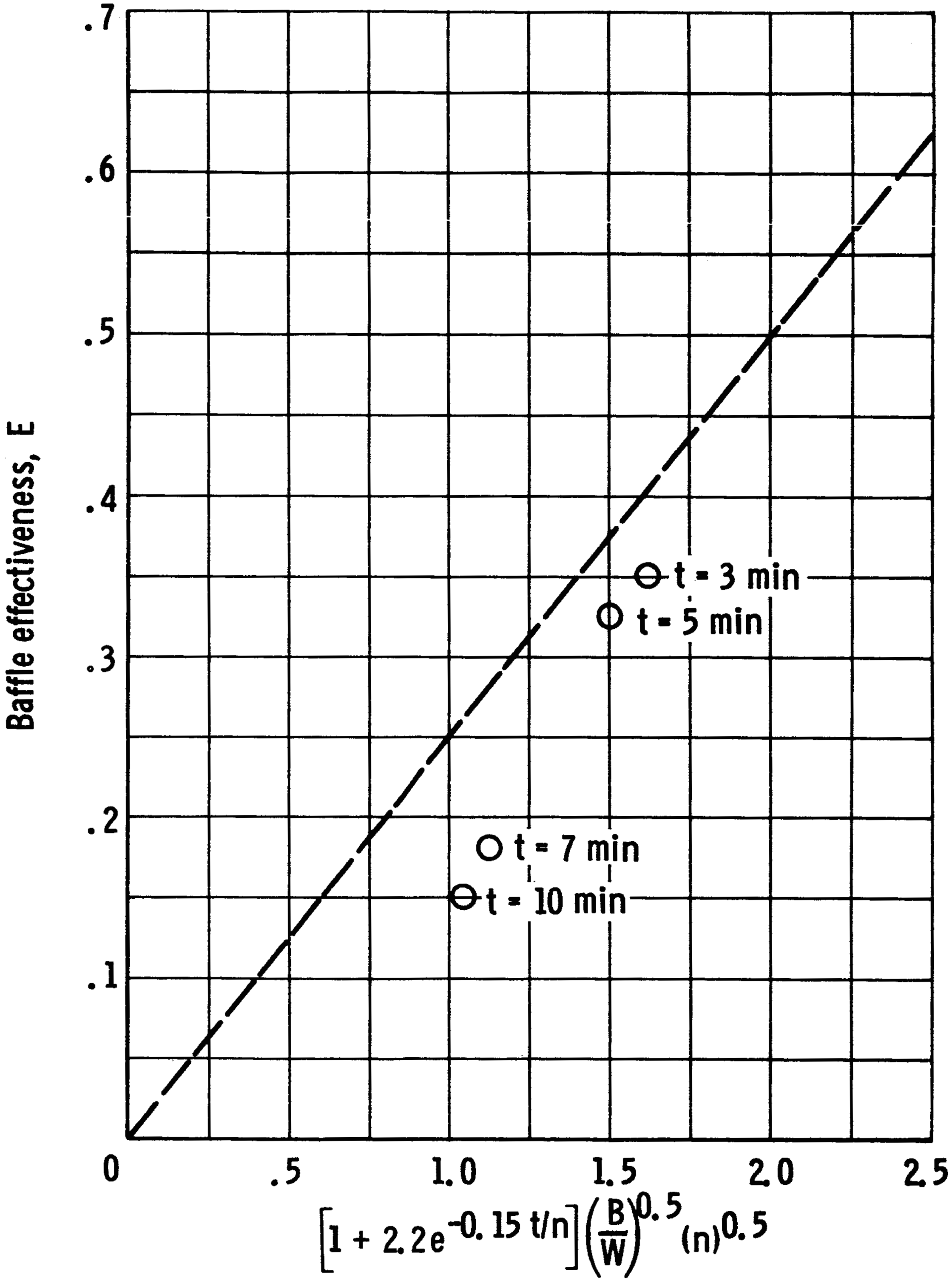

Figure 22. - Comparison of test data with baffle effectiveness correlation presented in Reference 4.

t = 7 and 10 minutes the deviations are about 40 percent (Figure 22). The agreement is favorable for the first two conditions and is reasonable for the last two when differences in the heating rates are considered. The heating rate used to correlate the data from Reference (4) was approximately 5 times higher than that used in the test runs presented.

Heat Transfer Coefficient

Heat transfer coefficients were calculated using fluid centerline temperatures and the temperatures recorded by the wall thermocouples. Favorable agreement between experimental and theoretical heat transfer coefficients was not obtained. This was due, principally, to the inability to determine a representative fluid bulk temperature in the stratified layer. One result of these heat transfer coefficient calculations is worthy of note, however. That result is associated with the critical length for transition from laminar to turbulent flow along the heated vertical wall. By using a modified Grashof number (6) at transition of approximately 10^{10} (see Reference (7)), the critical length was predicted. For a vertical lamp setting of 100 volts with no baffles present, the calculated critical length was 2.12 inches. With a lamp setting of 150 volts the critical length was 1.78 inches. Assuming that the boundary layer originated at the intersection of the vertical and inclined walls (X = 3.0 inches) the critical lengths from the tank bottom for 100 volt and 150 volt lamp settings are 5.12 and 4.78 inches, respectively.

In the presentation of the experimental heat transfer

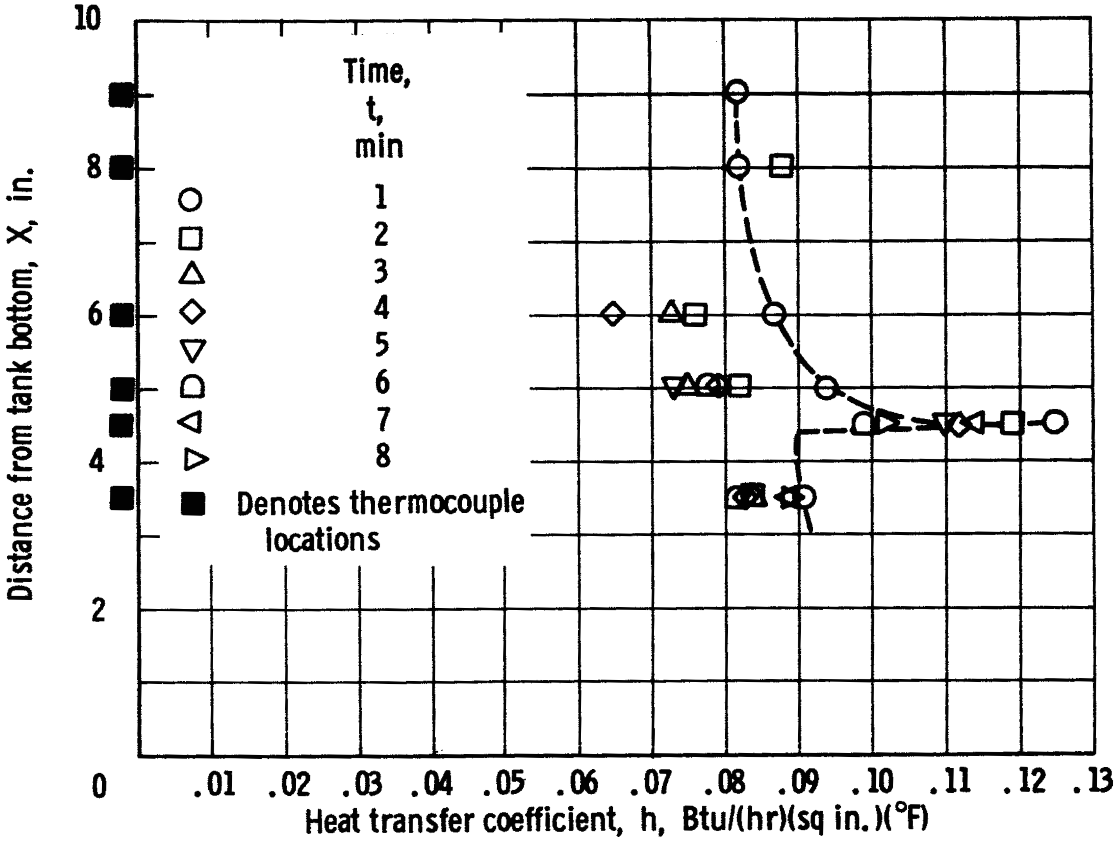

Figure 23. - Variation of heat transfer coefficient with time along a heated vertical wall (vertical lamps set at 100 volts).

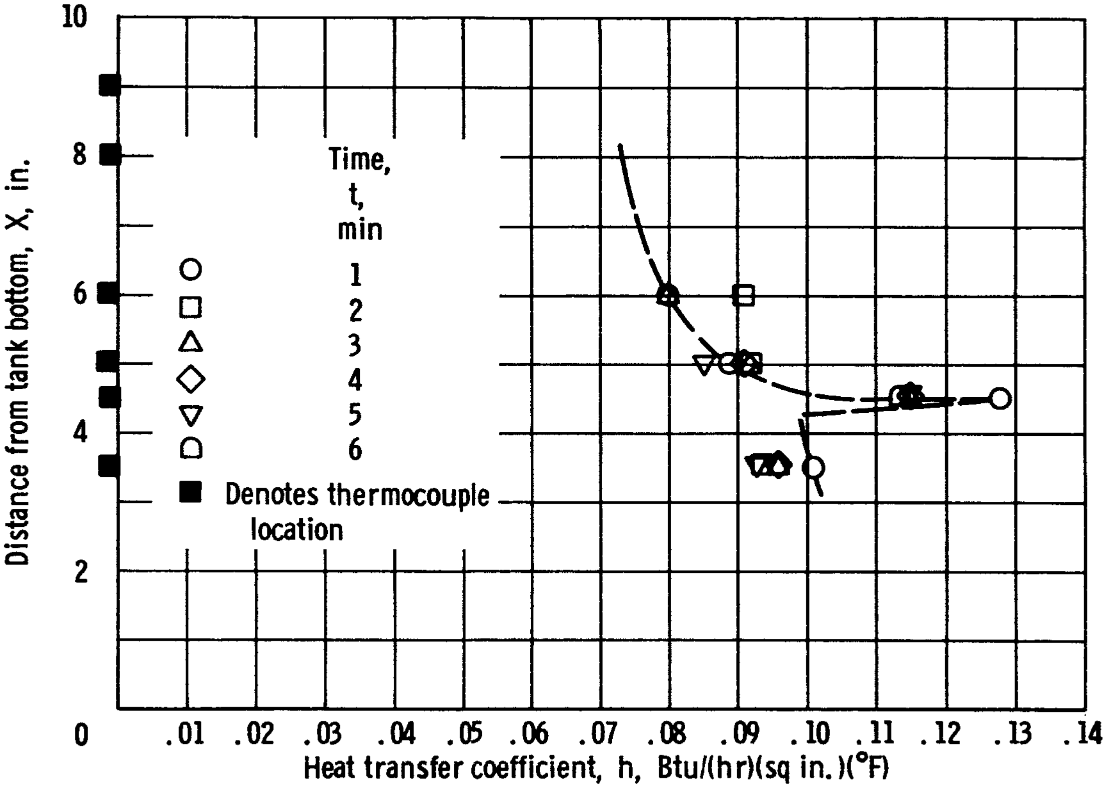

Figure 24. - Variation of heat transfer coefficient with time along a heated vertical wall (vertical lamps set at 150 volts).

coefficients for a vertical lamp settings of 100 volts (Figure 23) and 150 volts (Figure 24) a sharp peak can be observed at 4.5 inches. It appears evident that this peak corresponds to the location of the transition which occurred from laminar to turbulent flow in the experimental system. The observed transition points agreed with the predicted critical lengths within 12 percent for 100 volts and within 6 percent for 150 volts.

SUMMARY OF RESULTS

Two-dimensional viewing tanks, with and without baffles present, were subjected to wall heating, nonuniform source heating and a combination of both types of heating. The fluid behavior was studied and results were obtained by means of schlieren photographs, temperature measurements, and subsequent data reduction. The major conclusions are the following:

1. Baffles were found to be most effective during the early portion of each transient heating run when the stratified layer thickness was still small.

2. The boundary layer was deflected most effectively by the baffles at lower wall heating rates.

3. With nonuniform source heating present the effectiveness of the baffles was decreased as compared with their effectiveness under similiar conditions, but in the absence of source heating.

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BIBLIOGRAPHY

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