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EVALUATION OF SURFACED-ATTACHED THERMOCOUPLES
DURING FORCED CONVECTION HEAT TRANSFER

MASTER

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US ATOMIC ENERGY COMMISSION

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ABSTRACT

Metal-clad thermocouples with a flat (spade) tip were used to measure the temperature of a 0.030-in.-thick metal plate acting as a forced convection heat transfer surface. The thermocouples were found to change the temperature of the plate at the point of attachment by 40 percent of the temperature difference between fluid and plate. This value was found to be independent of fluid velocity, heat flux, and fluid temperature. A heat transfer model of the thermocouple was developed and analyzed to determine the "effective fin height" of the thermocouple at four test conditions. A correlation is presented between the average heat transfer coefficient of the system and the "effective fin height" of the thermocouple. The model and the correlation may be used to predict the calibration factor for other systems of similar thermocouples during either heating or cooling if the heat transfer coefficient is known.

An evaluation of brazing and resistance spot welding for attaching the thermocouples to the plate was made. Resistance spot welding was found to give a weak attachment with poor thermal contact between plate and thermocouple. Brazing was found to give a strong attachment with excellent thermal contact between plate and thermocouple.

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I. INTRODUCTION

When a thermocouple is used to measure the temperature of a surface, the validity of the measurement depends on three factors:

- (1) The accuracy of the thermocouple
- (2) The difference between the temperature indicated by the thermocouple and the true surface temperature at the point of attachment
- (3) The difference between the true surface temperature at the point of attachment and the surface temperature that would occur in the absence of the thermocouple (temperature perturbation)

For surfaces near ambient temperature, and for rough measurements, the temperature perturbation can often be neglected. However, for surface temperatures appreciably different from ambient conditions and for precise measurements, the temperature perturbation becomes important and a thermocouple calibration factor must be determined.

This study presents an analysis of experimentally determined calibration data for a thermocouple selected to measure the surface temperature of a nuclear reactor fuel plate. The effect of the method of attachment on the indicated temperature is shown and an attachment method recommended that results in a small difference between indicated and true plate temperature. A heat transfer model of the thermocouple is developed and correlated with the experimental data. The correlation and model may be used to predict the temperature perturbation caused by thermocouples of a similar design on other forced convection heat transfer surfaces during either heating or cooling.

II. STATEMENT OF PROBLEM

A thermocouple suitable for measuring the surface temperature of fuel plates in the Experimental Organic Cooled Reactor (EOCR) was required. The EOCR fuel plates are 0.030 in. thick, stainless steel clad, and are separated by 0.100-in.-wide channels through which flows the organic liquid coolant. Nominal plate operating conditions are:

Surface temperature - 800°F

Coolant temperature - 515°F

Coolant velocity range - 8-18 ft/sec

A review of the literature showed that most of the work on thermocouple-induced temperature perturbations has been on air-cooled systems. A report [1] on the instrumentation for the Organic Moderated Reactor Experiment (OMRE), however, contains calibration data for a thermocouple used to measure the temperature of a liquid-cooled surface. In the OMRE, thermocouple junctions were formed by welding uninsulated 0.005-in.-o.d. Chromel and Alumel wires to the plate surfaces. The difference between unperturbed and indicated temperatures was reported to be thirty-five percent of the plate to coolant temperature drop.

In an attempt to reduce the temperature perturbation caused by the OMRE design, and to improve the strength of the attachment, metal-clad thermocouples were chosen for use in the EOCR. A 0.062-in.-o.d. thermocouple was specified for strength and a flattened (spade) tip designed to minimize the temperature perturbation. Figure 1 shows the details of the thermocouple design and two different lead-in arrangements. Figure 2 compares the 0.062-in. size chosen with alternate 0.040- and 0.025-in. sizes that were considered.

LEADOUT DESIGN I

LEADOUT DESIGN II

FIGURE 1. THERMOCOUPLE TIP AND LEADOUT DESIGN.

FIGURE 2. THERMOCOUPLES (0.025, 0.040, AND 0.062 IN. OD).

To determine the suitability of the metal-clad thermocouple for use in the EOCR the following information was required:

- (1) The method of attaching the thermocouple to the fuel plate surface
- (2) The difference between indicated and true plate temperature
- (3) The temperature perturbation caused by the attachment of the thermocouples
- (4) A correlation relating the variables that affect the temperature measurement to readily determined system parameters

III. EXPERIMENTAL

THERMOCOUPLE ATTACHMENT

Brazing and resistance welding are two suitable methods for attaching metal-clad thermocouples to reactor fuel plates. A study was made to develop and evaluate the attachment of metal-clad thermocouples by both methods.

Brazing Method. A complete report [2] on the development of a procedure for brazing a spade-tip thermocouple has been published. It shows that Nicrobraz 30, which has been used in the missile industry for brazing thin layers of stainless steel, is suitable for bonding the thin sheath of the thermocouple to thin plates. The thermocouple and plate were mounted in a pressure jig and brazed at $2175 \pm 25^{\circ}\text{F}$ in a hydrogen atmosphere. Under these conditions the Nicrobraz 30 flowed freely between the thermocouple and the plate causing the thermocouple tip to become an integral part of the plate surface. X-ray examination of the resulting bond showed little penetration of the brazing compound into the two surfaces and little evidence of erosion. The strength of the bond was found to be stronger than the thermocouple. Figure 3 shows a thermocouple attached to a plate by brazing.

Resistance Spot Welding Method. Welding of the thermocouples was considered because of the relative cheapness of the method compared to brazing. In addition, welding can be accomplished in the field, thus saving time and giving more flexibility to thermocouple placement. The resistance spot welding study, however, failed to produce an attachment with the strength of the brazing method. A Hughes Model VTW-32 welder was used for the study. The study showed that weld energies had to be limited to 80 watt-seconds at 5 pounds

FIGURE 3, THERMOCOUPLE BRAZED TO PLATE.

pressure, otherwise the penetration of the thermocouple sheath could not be avoided. Figure 4 shows a thermocouple attached to a plate by spot welding.

The length of metal at the thermocouple tip was extended to one-eighth inch (Figure 5) in an attempt to improve the welds. This change allowed an increase in weld energy to 140 watt-seconds at 5 pounds pressure. Better strength characteristics were achieved, but the strength of the welded attachment was still weaker than that for brazing. Thermocouples of the revised design were attached to plates by spot welds at the thermocouple tip and a strap as shown in Figure 6.

THERMOCOUPLE CALIBRATION

Test Loop. A high-temperature organic-liquid test loop was used to calibrate the thermocouples. Figure 7 is a schematic diagram of the loop, Figure 8 shows a view of the loop, and Figure 9 shows the loop control panel.

The loop was designed to operate at 800°F and 250 psig. Maximum loop flow rate was approximately 15 gal/min. The high-temperature low-pressure design of the loop was made possible by the use of organic liquids as the working fluid in the loop. The organic liquids also simulated the coolant used in the EOGR. The reported calibration runs were made with a eutectic mixture of biphenyl and terphenyls. The eutectic was used because it is liquid at room temperature, whereas the mixture of terphenyls used in the EOGR melts at approximately 300°F.

All wetted surfaces were stainless steel to prevent the formation of corrosion products in the loop. Leakage was minimized by seal welding all screwed connections and by using canned rotor pumps. Leakage past valve stem packing proved to be a major problem in this loop design.

FIGURE 4. THERMOCOUPLE WELDED TO PLATE.

FIGURE 5. REVISED THERMOCOUPLE DESIGN.

FIGURE 6. REVISED THERMOCOUPLE DESIGN WELDED TO PLATE.

FIGURE 7. FLOW DIAGRAM OF TEST LOOP.

FIGURE 8. VIEW OF TEST LOOP.

FIGURE 9. CONTROL PANEL OF TEST LOOP.

Test Sections. Test sections for calibrating thermocouples which were attached by the two methods were fabricated out of 1/2- x 2-in. stainless steel bar stock as shown in Figures 10 and 11. The thermocouples to be calibrated were attached to 1.25- x 36- x 0.030-in. stainless steel plates (Figure 12) and the leads run through leadout holes in the test section. The leads were sealed with Conax fittings mounted in bosses (Figure 13) attached to the back of the test section. The plates were seal-welded to the bar stock to form a mock-up of an instrumented EOCR fuel plate and coolant channel. A temperature driving force was imposed across the instrumented plate surface by circulating hot eutectic through the channel and cooling the exterior surface of the plate.

Initially a 1/4- x 1-1/2-in. water channel over the plate was used for cooling. Data were difficult to obtain with this method because of fluctuating water flow. In addition, the heater capacity of the loop was not sufficient to maintain the eutectic at the desired 500°F inlet temperature at high flow rates. To overcome these problems a boiling-water heat sink was designed. The depth of the water channel was increased to one inch and the channel used as a pool boiler. The steam produced was condensed in a cooler as shown in Figure 14 and returned to the pool. The boiling-water heat sink increased the operating temperature of the loop over 130°F and eliminated the problem of fluctuating water flow. Allowable heat flux, however, was limited to levels which would not steam blanket the water side of the plate.

Instrumentation. Figure 7 shows the instrumentation installed in the loop. Water temperatures in and out of the cold-water heat sink design also were measured. Thermocouple outputs were measured with a Rubicon potentiometer using an internally compensated cold junction. Leeds and Northrup rotary silver

FIGURE 10. ORGANIC CHANNEL DESIGN.

FIGURE 11. ORGANIC CHANNEL AND THERMOCOUPLE LEADOUT HOLES.

FIGURE 12, PLATE WITH BRAZED THERMOCOUPLES,

FIGURE 13, THERMOCOUPLE LEADOUT BOSSES.

FIGURE 14. BOILING-WATER HEAT SINK.

contact switches were used to change thermocouple inputs to the potentiometer.

A test section was instrumented (Figure 15) to measure the surface temperature of the water side of the plate. Metal-clad thermocouples (0.025 in. o.d.) were attached to the surface with silver solder (Figure 16). The silver solder was polished to form a smooth transition on the surface. Since the water-film resistance is uniform over the entire plate surface, the temperature at the thermocouple junction will differ from the actual plate surface temperature only by the temperature drop through the silver solder. This temperature drop was estimated to be less than 2°F. The test section so instrumented was used with the revised design resistance-welded thermocouples only.

EXPERIMENTAL PROCEDURE

The operation of the loop and the recording of the test data at each experimental point followed a simple procedure. At the start of each day's testing the nitrogen blanket in the loop surge tank was pressurized to 50 psig to prevent cavitation in the pump. For all calibration runs the primary coolant pump was used. The circulation heaters were then energized and the pump vented. During the heat-up of the eutectic, which took several hours, the temperature-measuring equipment was checked for proper operation. When the eutectic reached approximately 400°F, the loop flow rate was set at the desired value, and cooling water was admitted to the test section. System temperatures were then monitored until steady-state conditions were reached. At this point the flow rate was readjusted if necessary, system temperatures were rechecked, and then a minimum of three sets of data was recorded. If any instrument indicated a departure from steady-state conditions, the recording of test data was suspended until steady-state conditions were again reached and checked.

FIGURE 15. WATER SIDE OF PLATE WITH 0.025-IN.-OD THERMOCOUPLES.

FIGURE 16, THERMOCOUPLE SILVER-SOLDERED TO WATER SIDE OF PLATE.

IV. DISCUSSION OF RESULTS

GENERAL

Each of the attachment methods [(a) brazing, (b) resistance welding (standard design), and (c) resistance welding (revised design)] was evaluated in a test section. Cold water was used to cool the test sections for (a) and (b). The regular laboratory water supply which furnished the coolant was found to cause erratic fluctuations in the water flow. Numerous delays in testing resulted from waiting for the system to regain steady-state conditions. The consistency of the data from run to run for methods (a) and (b), however, indicated that the calibration data were obtained at the required steady-state conditions. The calibration data for the brazed thermocouples (Runs 1-19) were checked by a second calibration test (Runs 20-39) one week later. The two sets of data were found to agree. The high heat flux reached in the two test sections and the large heat transfer area taxed the capacity of the circulation heaters and limited inlet organic liquid temperature to 300-400°F.

The calibration of the resistance welding (standard design) was not completed. The data showed that only two thermocouples out of nine remained attached to the test plate after assembly of the test section and these indicated the temperature of the eutectic.

The boiling-water heat sink system was used for calibrating method (c). The initial calibration run with seven resistance-welded (revised design) thermocouples showed the welded thermocouples again to be indicating the temperature of the eutectic. Since welded thermocouples proved unsatisfactory mechanically and gave poor indication of the plate temperature, this portion of the program was terminated.

Appendix A contains the calibration data obtained for the braze-attached thermocouples. Runs which were determined to be at unsteady-state conditions, and runs during which the thermocouples were inter-calibrated, have been omitted. A maximum difference of 1°F was found between the thermocouples. All presented data have been corrected for this difference. No data are presented for welded thermocouples because all read essentially the temperature of the eutectic.

CALCULATION OF UNPERTURBED PLATE TEMPERATURES

The heat absorbed in the water was used to determine unperturbed plate temperatures for (a) and (b) as shown in Appendix B. Specific heat data for the eutectic were estimated from data listed in [3] and used to calculate the heat lost by the eutectic as a check on the water side calculation. The two values for heat absorbed and heat lost normally showed close agreement. The small difference calculated for each run, and listed in Appendix A, can reasonably be considered the amount of heat lost to the ambient air. Because the water temperature was close to ambient, the amount of heat lost was considered not to have passed through the plate. Therefore, heat flux calculations based on the heat absorbed in the water were considered more accurate than calculations based on the heat lost by the eutectic.

To determine the heat flux at the centerline of the plate from the overall power absorbed in the water, the amount of heat transferred to the water through the edge of the test section and the temperature profile across the plate must be estimated. A two-dimensional relaxation calculation of the temperature distribution around the edge of the plate (Figure 17) was made to estimate the edge effect and plate temperature profile. This analysis gave a

$$h_w = 1000 \frac{\text{BTU}}{\text{hr-ft}^2-\text{°F}}$$

$$h_o = 1000 \frac{\text{BTU}}{\text{hr-ft}^2-\text{°F}}$$

$$K_p = 10 \frac{\text{BTU}}{\text{hr-ft} - ^\circ\text{F}}$$

$$\phi_L = 1.27 \times 10^5 \frac{\text{BTU}}{\text{hr-ft}^2}$$

ALL POINTS ARE GIVEN IN °F

() DENOTES ASSIGNED BOUNDARY TEMP.

FIGURE 17. TEMPERATURE FIELD AT PLATE EDGE.

value of 0.77 for the ratio of the centerline heat flux to the average heat flux. The average heat flux is the total heat gained by the water divided by the area of the plate.

The water channel heat transfer coefficient (h_w) was calculated by the Dittus-Boelter equation [4] with a heating exponent of 0.4 on the Prandtl number. The temperature drop across the water film was then found. The temperature drop through the plate was calculated from measured plate thickness and a handbook value of thermal conductivity. Adding the sum of these temperature differences to inlet and outlet water temperatures gave the values of unperturbed temperature at the plate ends. The unperturbed temperatures at the thermocouple locations (Table I) were calculated by interpolating the inlet and outlet unperturbed surface temperature as shown in Appendix B.

TABLE I

BRAZED THERMOCOUPLE LOCATIONS ON PLATE

<u>Thermocouple No.</u>	<u>Tip Location* (in.)</u>
1	28.4
2	25.4
3	22.4
4	19.4
5	16.3
6	13.4
7	10.3

*From inlet end of channel, overall channel length was 36 in.

The use of the reference thermocouples described in Section III required the calculation of only the plate-temperature drop to determine unperturbed plate temperatures.

BRAZING METHOD

Bond Strength. The brazing operation results in the thermocouple becoming an integral part of the plate surface. As such, the braze attachment strength is limited by the ruggedness of the thermocouple. No detrimental effects from the brazing operation were noticed. This method is recommended for high-strength attachments such as are required in nuclear reactors.

Calibration. Seven brazed thermocouples were calibrated at 7.6, 18, and 30 fps eutectic velocity. To allow the results of each run to be compared, the data have been expressed in terms of a dimensionless calibration factor which is defined as:

$$f = \frac{T_{t/c} - T_o}{T_p - T_o}$$

All the valid data points have been summarized as f values in Figures 18 and 19. Figure 18 shows the average calibration factor for each thermocouple at the three flow rates. Even though flow rate was varied by a factor of four, heat flux by a factor of 2, and temperature by approximately 100°F, the calibration factor remained essentially constant. The average of all the values was 0.60 and all values fell within a ± 0.14 band. Considering that unperturbed plate temperatures were calculated by an indirect method, this is considered good agreement between values. The spread of data for each test point is shown in Figure 19.

FIGURE 18. BRAZED THERMOCOUPLE CALIBRATION.

FIGURE 19. BRAZED THERMOCOUPLE CALIBRATION - DATA SCATTER.

To estimate the difference between the true plate temperature and the temperature indicated by the thermocouple junction, a one-dimensional fin calculation was made for the temperature gradient at the tip of the thermocouple using the method given in [5]. This calculation showed a temperature difference of less than five degrees. The difference between indicated and unperturbed temperature was considered the temperature perturbation caused by the attachment of the thermocouple to the plate.

RESISTANCE WELDING

All the resistance-welded thermocouples were found to be unsatisfactory for one of the following three reasons:

1. Weld failure during test section assembly
2. Weld failure during testing
3. Thermocouple indicated eutectic temperature.

The resistance-welding program was terminated as discussed at the beginning of this section.

V. HEAT TRANSFER MODEL OF THERMOCOUPLE

For analysis, a thermocouple was considered as a hollow fin (Figure 20). The total cross sectional area of the fin was made equal to the plate area covered by the thermocouple (A'). The cross sectional area of the fin wall (A) was made equal to the thickness of the thermocouple sheath. The temperature indicated by the thermocouple junction was considered to be the temperature at the base of the fin as discussed in Section III.

The power balance across a differential length of fin may be written as follows:

$$h_o C (T_o - T) dx + KA \left(\frac{dT}{dx} + \frac{d^2T}{dx^2} dx \right) - KA \frac{dT}{dx} = 0 \quad (1)$$

Combining terms and dividing by dx results in:

$$h_o C (T_o - T) + KA \frac{d^2T}{dx^2} = 0 \quad (2)$$

Equation (2) has a solution of the form:

$$\theta = Me^{-mx} + Ne^{mx} \quad (3)$$

where

$$\theta = T_o - T \quad \text{and} \quad m = \sqrt{\frac{h_o C}{KA}}$$

Equation (3) may be solved by applying the following boundary conditions to determine M and N :

$$(a) \quad x = 0, \quad \theta = T_o - T_{t/c}$$

$$(b) \quad x = 0, \quad \frac{d\theta}{dx} = \frac{\Phi_{t/c}}{K} \cdot \frac{A'}{A}$$

THERMOCOUPLE ATTACHED TO PLATE AND ACTING AS
A HEAT GATHERING FIN

HEAT FLOW PATH BETWEEN THERMOCOUPLE SHEATH
AND PLATE

HOLLOW FIN MODEL OF THERMOCOUPLE SHOWING HEAT
BALANCE AROUND A SECTION OF DIFFERENTIAL HEIGHT

NOTE:

→ INDICATES HEAT FLOW

FIGURE 20, HEAT TRANSFER MODEL OF THERMOCOUPLE.

Since both T_o and $T_{t/c}$ are measured, boundary condition (a) can be evaluated. Boundary condition (b) can be evaluated by considering that $\Phi_{t/c}$ can be expressed as:

$$\Phi_{t/c} = \frac{T_{t/c} - T_w}{\frac{t}{K} + \frac{1}{h_w}} \quad (4)$$

All terms in Equation (4) with the exception of h_w , which is calculated as shown in Section IV, are either system properties or measured.

Multiplying Equation (3) by dx , and integrating between 0 and ℓ (where ℓ is the effective length of the fin) yields:

$$\int_0^\ell \theta \, dx = \frac{1}{m} \left[(N e^{m\ell} - M e^{-m\ell}) - (N - M) \right] \quad (5)$$

Now note that $Q_{t/c}$ may be obtained by multiplying Equation (4) by A' , or by multiplying Equation (5) by $h_o C$:

$$Q_{t/c} = \Phi_{t/c} \cdot A' = \frac{h_o C}{m} \left[(N e^{m\ell} - M e^{-m\ell}) - (N - M) \right] \quad (6)$$

The effective length of the fin may now be calculated by a trial-and-error solution of Equation (6).

For calculational purposes the data tabulated in Appendix A has been divided into four groups based on average eutectic heat transfer coefficient (Table II). The heat transfer coefficient tabulated for each run was calculated from the centerline heat flux listed in Appendix A and the eutectic-plate temperature difference at the midpoint of the plate. The data for all the runs in each group have been averaged and listed in Table III. The runs included within each group are as follows:

TABLE II

EUTECTIC HEAT TRANSFER COEFFICIENTS

Run No.	$h\text{-Btu/hr-ft}^2\text{-}^\circ\text{F}$	Run No.	$h\text{-Btu/hr-ft}^2\text{-}^\circ\text{F}$
4	1.8×10^3	26	0.38×10^3
5	1.8×10^3	27	0.42×10^3
6	1.6×10^3	28	0.37×10^3
7	1.8×10^3	29	0.41×10^3
8	1.8×10^3	30	0.41×10^3
9	1.6×10^3	31	0.85×10^3
10	1.9×10^3	32	0.83×10^3
12	0.40×10^3	33	0.82×10^3
13	0.40×10^3	34	0.83×10^3
14	0.37×10^3	35	0.83×10^3
15	0.32×10^3	36	0.83×10^3
16	0.36×10^3	37	1.1×10^3
17	0.74×10^3	38	1.2×10^3
18	0.59×10^3	39	1.2×10^3
19	0.87×10^3		

Group I (Average $h = 0.38 \times 10^3$)

Run No. 12, 13, 14, 15, 16, 26, 27, 28, 29, 30

Group II (Average $h = 0.80 \times 10^3$)

Run No. 17, 18, 19, 31, 32, 33, 34, 35, 36

Group III (Average $h = 1.2 \times 10^3$)

Run No. 37, 38, 39

Group IV (Average $h = 1.8 \times 10^3$)

Run No. 4, 5, 6, 7, 8, 9, 10

TABLE III
AVERAGED CALIBRATION DATA

	<u>Group I</u>	<u>Group II</u>	<u>Group III</u>	<u>Group IV</u>
$h_o \left(10^3 \frac{\text{Btu}}{\text{hr-ft}^2-\text{°F}}\right)$	0.38	0.80	1.2	1.8
$T_o \text{ (°F)}$	362	311	292	308
$T_p \text{ (°F)}$	141	166	191	225
$T_o - T_p \text{ (°F)}$	221	145	101	83
$T_{t/c} \text{ (°F)}$	230	224	231	258
$T_o - T_{t/c} \text{ (°F)}$	132	87	61	50
$T_w \text{ (°F)}$	65	66	67	71
$T_{t/c} - T_w \text{ (°F)}$	165	158	164	187
$T_p - T_w \text{ (°F)}$	76	100	124	154
$\Phi_e \left(10^5 \frac{\text{Btu}}{\text{hr-ft}^2}\right)$	0.85	1.2	1.2	1.5
$\Phi_{t/c} \left(10^5 \frac{\text{Btu}}{\text{hr-ft}^2}\right)$	1.8	1.9	1.6	1.8
$A' \left(10^{-4} \text{ ft}^2\right)$	2.4	2.4	2.4	2.4
$\Phi_{t/c} \cdot A' \left(\frac{\text{Btu}}{\text{hr}}\right)$	43	46	38	43

The following calculation of the effective fin height for the data listed in Table III (Group I) will serve as an example of the calculations that were made for all groups to determine an effective fin height (l):

$$Q_{t/c} = \frac{h_o C}{m} \left[(N e^{m l} - M e^{-m l}) - (N - M) \right]$$

where

$$Q_{t/c} = 43 \frac{\text{Btu}}{\text{hr}}$$

$$h_o = 0.38 \times 10^3 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}$$

$$C = 7.8 \times 10^{-2} \text{ ft}$$

$$K = 9.4 \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}$$

$$A = 6.5 \times 10^{-5} \text{ ft}^2$$

$$m = \sqrt{\frac{h_o C}{K A}} = 2.2 \times 10^2 \text{ ft}^{-1}$$

using boundary condition (a):

$$M + N = T_o - T_{t/c} = 132^\circ\text{F}$$

using boundary condition (b):

$$N - M = \frac{\Phi_{t/c}}{mK} \cdot \frac{A'}{A} = 322^\circ\text{F}$$

therefore:

$$M = -95^\circ\text{F}$$

$$N = 227^\circ\text{F}$$

Assuming $\ell = 0.054 \text{ in. } (4.5 \times 10^{-3} \text{ ft})$ and substituting into the equation:

$$\begin{aligned} 43 \frac{\text{Btu}}{\text{hr}} &= \frac{0.38 \times 10^3 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}} \cdot 7.8 \times 10^{-2} \text{ ft}}{2.2 \times 10^2 \text{ ft}^{-1}} \\ &\quad \left[\left(227^\circ\text{F} e^{2.2 \times 10^2 \text{ ft}^{-1} \cdot 4.5 \times 10^{-3} \text{ ft}} \right. \right. \\ &\quad \left. \left. + 95^\circ\text{F} e^{-2.2 \times 10^2 \text{ ft}^{-1} \cdot 4.5 \times 10^{-3} \text{ ft}} \right) \right. \\ &\quad \left. - (227^\circ\text{F} + 95^\circ\text{F}) \right] = 44 \frac{\text{Btu}}{\text{hr}} \end{aligned}$$

VI. UTILIZATION AND CORRELATION OF DATA

The calibration factor, f , determined for the metal-clad thermocouples used in this study was practically independent of flow rate, heat flux, and temperature. The heat transfer model developed to represent the thermocouple accounted for the constancy of the calibration factor by showing the thermocouple to be acting as a variable-height fin. To apply this information to other systems instrumented with similar thermocouples, a method is required to predict effective fin height for the system. The equations used in Section V to calculate fin height can then be used to calculate the temperature perturbation to be expected.

Attempts to correlate the calculated fin heights with fluid velocity, heat flux, and temperature did not reveal any particular relationships. However, when correlated against the heat transfer coefficients of the data groups, as shown in Figure 21, the effective fin heights were found to fall along a straight line. Considering that the range of heat transfer coefficients covered by the correlations presented in Figure 21 includes values frequently encountered in heat transfer calculations, the correlation and calculational method suggested should prove helpful in estimating the temperature perturbation for other heat transfer surfaces instrumented with similar thermocouples. This method is applicable to both heating and cooling.

FIGURE 21, CORRELATION OF FIN HEIGHT.

VII. CONCLUSIONS

In order for a thermocouple to measure the temperature of a surface, good thermal contact must be made between the surface and the thermocouple. The data showed that brazing of metal-clad thermocouples to metal surfaces results in a good thermal bond, while resistance spot welding does not give an adequate thermal bond. In addition, resistance spot welding results in a weak bond unsuitable for attaching thermocouples to reactor fuel plates. Brazing, however, produces a bond as strong as the thermocouple.

The calibration of braze-attached thermocouples in a mocked-up EOOR coolant channel showed that the thermocouples perturbed the surface temperature of the plate by 40 percent of the temperature drop through the fluid. This factor was found to be constant over a wide range of operating conditions. The constancy of the perturbation was accounted for by showing the thermocouple to be acting as a variable-height fin. The effective height of the fin was found to correlate with the heat transfer coefficient of the system. The temperature perturbation in other systems caused by the attachment of similar metal-clad thermocouples can be estimated using the correlation and calculational method presented. This estimate can be made for both heated and cooled surfaces.

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LIST OF REFERENCES

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LIST OF NOMENCLATURE

LIST OF NOMENCLATURE

SYMBOL	DESCRIPTION	UNITS
A	Cross sectional area of fin wall	ft ²
A'	Area of plate in contact with fin	ft ²
A _p	Total area of plate	ft ²
C	Circumference of fin	ft
C _p	Heat capacity	Btu/lb-°F
CF	Correction factor	—
d	Hydraulic diameter	ft
F	Flow rate	gal/min
°F	Degrees Fahrenheit	—
f	Calibration factor	—
ft	Feet	—
G	Mass flow rate	lb/hr-ft ²
gal	Gallon	—
h	Heat transfer coefficient	Btu/hr-ft ² -°F
in.	Inch	—
K	Thermal conductivity	Btu/hr-ft-°F
ℓ	Effective length of fin	ft or in.
min	Minute	—
o.d.	Outside diameter	in.
Q	Power	Btu/hr
sec	Second	—
T	Temperature	°F

SYMBOL	DESCRIPTION	UNITS
t	Thickness of plate	ft
t/c	Thermocouple	—
T_{in}	Inlet temperature	$^{\circ}\text{F}$
T_{out}	Outlet temperature	$^{\circ}\text{F}$
W	Flow rate	lb/hr
GREEK		
Φ	Heat flux	Btu/hr-ft ²
ρ	Density	lb/gal
μ	Viscosity	lb/ft-hr
SUBSCRIPTS		
f	Fin	
ϕ	Centerline	
o	Organic fluid	
t/c	Thermocouple	
w	Water	
wf	Water film	
p	Plate surface in contact with organic fluid	

APPENDIXES

APPENDIX A

CALIBRATION DATA FOR BRAZE-ATTACHED THERMOCOUPLES

RUN NUMBER 4

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	316	62
T _{out} (°F)	294	80
ΔT (°F)	22	18
Flow rate (gal/min)	9.45	5.25
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10 ⁵ Btu/hr)	0.47	- - -
Heat gained (10 ⁵ Btu/hr)	- - -	0.47
Heat lost to ambient (10 ⁵ Btu/hr)	0.00	
Centerline heat flux (10 ⁵ Btu/hr-sq ft)	1.4	

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	258°F	0.39
2	257°F	0.42
3	247°F	0.68
4	262°F	0.52
5	240°F	0.81
6	252°F	0.68
7	253°F	0.69

RUN NUMBER 5

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	317	62
T _{out} (°F)	295	80
ΔT (°F)	22	18
Flow rate (gal/min)	9.45	5.25
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10^5 Btu/hr)	0.47	- - -
Heat gained (10^5 Btu/hr)	- - -	0.47
Heat lost to ambient (10^5 Btu/hr)		0.00
Centerline heat flux (10^5 Btu/hr-sq ft)		1.4

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	259°F	0.50
2	258°F	0.53
3	249°F	0.66
4	263°F	0.51
5	242°F	0.78
6	254°F	0.66
7	245°F	0.79

RUN NUMBER 6

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	319	62
T_{out} ($^{\circ}F$)	296	80
ΔT ($^{\circ}F$)	23	18
Flow rate (gal/min)	9.45	4.95
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10^5 Btu/hr)	0.49	- - -
Heat gained (10^5 Btu/hr)	- - -	0.44
Heat lost to ambient (10^5 Btu/hr)		0.05
Centerline heat flux (10^5 Btu/hr-sq ft)		1.4

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	260 $^{\circ}F$	0.49
2	259 $^{\circ}F$	0.52
3	250 $^{\circ}F$	0.64
4	264 $^{\circ}F$	0.50
5	244 $^{\circ}F$	0.75
6	255 $^{\circ}F$	0.64
7	255 $^{\circ}F$	0.65

RUN NUMBER 7

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	319	62
T_{out} ($^{\circ}F$)	297	80
ΔT ($^{\circ}F$)	22	18
Flow rate (gal/min)	9.45	5.25
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10^5 Btu/hr)	0.47	- - -
Heat gained (10^5 Btu/hr)	- - -	0.47
Heat lost to ambient (10^5 Btu/hr)		0.00
Centerline heat flux (10^5 Btu/hr-sq ft)		1.4

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	260 $^{\circ}F$	0.52
2	260 $^{\circ}F$	0.55
3	250 $^{\circ}F$	0.67
4	265 $^{\circ}F$	0.52
5	244 $^{\circ}F$	0.79
6	255 $^{\circ}F$	0.67
7	256 $^{\circ}F$	0.68

RUN NUMBER 8

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	320	62
T _{out} (°F)	297	80
ΔT (°F)	23	18
Flow rate (gal/min)	9.45	5.16
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10 ⁵ Btu/hr)	0.49	- - -
Heat gained (10 ⁵ Btu/hr)	- - -	0.46
Heat lost to ambient (10 ⁵ Btu/hr)	0.03	
Centerline heat flux (10 ⁵ Btu/hr-sq ft)	1.4	

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	261°F	0.52
2	260°F	0.54
3	250°F	0.68
4	265°F	0.52
5	244°F	0.80
6	255°F	0.68
7	255°F	0.70

RUN NUMBER 9

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	320	62
T _{out} (°F)	298	80
ΔT (°F)	22	18
Flow rate (gal/min)	9.45	5.04
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10 ⁵ Btu/hr)	0.47	- - -
Heat gained (10 ⁵ Btu/hr)	- - -	0.45
Heat lost to ambient (10 ⁵ Btu/hr)		0.02
Centerline heat flux (10 ⁵ Btu/hr-sq ft)		1.4

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	261°F	0.48
2	260°F	0.51
3	251°F	0.62
4	265°F	0.49
5	243°F	0.76
6	255°F	0.64
7	256°F	0.65

RUN NUMBER 10

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	321	62
T_{out} ($^{\circ}F$)	298	80
ΔT ($^{\circ}F$)	23	18
Flow rate (gal/min)	9.45	5.25
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10^5 Btu/hr)	0.49	- - -
Heat gained (10^5 Btu/hr)	- - -	0.47
Heat lost to ambient (10^5 Btu/hr)		0.02
Centerline heat flux (10^5 Btu/hr-sq ft)		1.4

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	261 $^{\circ}F$	0.51
2	260 $^{\circ}F$	0.55
3	251 $^{\circ}F$	0.67
4	265 $^{\circ}F$	0.52
5	244 $^{\circ}F$	0.80
6	255 $^{\circ}F$	0.68
7	257 $^{\circ}F$	0.68

RUN NUMBER 12

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	389	63
T_{out} ($^{\circ}F$)	327	71
ΔT ($^{\circ}F$)	62	8
Flow rate (gal/min)	2.36	6.88
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.33	- - -
Heat gained (10^5 Btu/hr)	- - -	0.28
Heat lost to ambient (10^5 Btu/hr)		0.05
Centerline heat flux (10^5 Btu/hr-sq ft)		0.86

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	229 $^{\circ}F$	0.56
2	222 $^{\circ}F$	0.60
3	214 $^{\circ}F$	0.65
4	236 $^{\circ}F$	0.56
5	206 $^{\circ}F$	0.71
6	228 $^{\circ}F$	0.62
7	220 $^{\circ}F$	0.66

RUN NUMBER 13

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	385	63
T_{out} ($^{\circ}F$)	324	71
ΔT ($^{\circ}F$)	61	8
Flow rate (gal/min)	2.36	6.88
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.32	- - -
Heat gained (10^5 Btu/hr)	- - -	0.28
Heat lost to ambient (10^5 Btu/hr)		0.04
Centerline heat flux (10^5 Btu/hr-sq ft)		0.86

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	227 $^{\circ}F$	0.58
2	220 $^{\circ}F$	0.62
3	212 $^{\circ}F$	0.67
4	232 $^{\circ}F$	0.58
5	206 $^{\circ}F$	0.70
6	225 $^{\circ}F$	0.63
7	214 $^{\circ}F$	0.69

RUN NUMBER 14

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	382	63
T _{out} (°F)	322	70
ΔT (°F)	60	7
Flow rate (gal/min)	2.36	6.82
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.32	- - -
Heat gained (10^5 Btu/hr)	- - -	0.24
Heat lost to ambient (10^5 Btu/hr)	0.08	
Centerline heat flux (10^5 Btu/hr-sq ft)	0.74	

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	220°F	0.59
2	217°F	0.61
3	209°F	0.67
4	232°F	0.57
5	203°F	0.71
6	224°F	0.62
7	213°F	0.68

RUN NUMBER 15

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	382	63
T _{out} (°F)	322	70
ΔT (°F)	60	7
Flow rate (gal/min)	2.36	6.75
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10 ⁵ Btu/hr)	0.32	- - -
Heat gained (10 ⁵ Btu/hr)	- - -	0.23
Heat lost to ambient (10 ⁵ Btu/hr)		0.09
Centerline heat flux (10 ⁵ Btu/hr-sq ft)		0.71

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	224°F	0.53
2	217°F	0.58
3	209°F	0.58
4	232°F	0.53
5	204°F	0.66
6	225°F	0.59
7	213°F	0.65

RUN NUMBER 16

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}\text{F}$)	382	63
T_{out} ($^{\circ}\text{F}$)	322	70
ΔT ($^{\circ}\text{F}$)	60	7
Flow rate (gal/min)	2.36	6.88
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.32	- - -
Heat gained (10^5 Btu/hr)	- - -	0.24
Heat lost to ambient (10^5 Btu/hr)		0.08
Centerline heat flux (10^5 Btu/hr-sq ft)		0.74

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	225 $^{\circ}\text{F}$	0.55
2	219 $^{\circ}\text{F}$	0.59
3	210 $^{\circ}\text{F}$	0.64
4	233 $^{\circ}\text{F}$	0.54
5	206 $^{\circ}\text{F}$	0.68
6	227 $^{\circ}\text{F}$	0.59
7	215 $^{\circ}\text{F}$	0.66

RUN NUMBER 17

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	326	63
T_{out} ($^{\circ}F$)	295	74
ΔT ($^{\circ}F$)	31	11
Flow rate (gal/min)	5.60	6.54
Flow velocity (ft/sec)	18.0	- - -
Heat lost (10^5 Btu/hr)	0.39	- - -
Heat gained (10^5 Btu/hr)	- - -	0.36
Heat lost to ambient (10^5 Btu/hr)		0.03
Centerline heat flux (10^5 Btu/hr-sq ft)		1.1

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	241 $^{\circ}F$	0.42
2	240 $^{\circ}F$	0.44
3	232 $^{\circ}F$	0.51
4	251 $^{\circ}F$	0.40
5	222 $^{\circ}F$	0.60
6	235 $^{\circ}F$	0.53
7	233 $^{\circ}F$	0.56

RUN NUMBER 18

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	326	64
T_{out} ($^{\circ}F$)	295	73
ΔT ($^{\circ}F$)	31	9
Flow rate (gal/min)	5.60	6.82
Flow velocity (ft/sec)	18.0	- - -
Heat lost (10^5 Btu/hr)	0.39	- - -
Heat gained (10^5 Btu/hr)	- - -	0.31
Heat lost to ambient (10^5 Btu/hr)		0.08
Centerline heat flux (10^5 Btu/hr-sq ft)		0.95

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	239 $^{\circ}F$	0.41
2	235 $^{\circ}F$	0.45
3	228 $^{\circ}F$	0.50
4	247 $^{\circ}F$	0.40
5	220 $^{\circ}F$	0.57
6	236 $^{\circ}F$	0.48
7	234 $^{\circ}F$	0.51

RUN NUMBER 19

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	325	62
T _{out} (°F)	293	73
ΔT (°F)	32	11
Flow rate (gal/min)	5.60	6.88
Flow velocity (ft/sec)	18.0	- - -
Heat lost (10 ⁵ Btu/hr)	0.40	- - -
Heat gained (10 ⁵ Btu/hr)	- - -	0.38
Heat lost to ambient (10 ⁵ Btu/hr)	0.02	
Centerline heat flux (10 ⁵ Btu/hr-sq ft)	1.2	

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	237°F	0.46
2	236°F	0.49
3	227°F	0.57
4	246°F	0.44
5	218°F	0.65
6	235°F	0.54
7	233°F	0.57

RUN NUMBER 26

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}\text{F}$)	399	60
T_{out} ($^{\circ}\text{F}$)	314	69
ΔT ($^{\circ}\text{F}$)	85	9
Flow rate (gal/min)	2.36	6.75
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.45	- - -
Heat gained (10^5 Btu/hr)	- - -	0.30
Heat lost to ambient (10^5 Btu/hr)		0.15
Centerline heat flux (10^5 Btu/hr-sq ft)		0.92

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	230°F	0.52
2	223°F	0.58
3	215°F	0.63
4	236°F	0.55
5	208°F	0.69
6	233°F	0.59
7	232°F	0.61

RUN NUMBER 27

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	404	60
T_{out} ($^{\circ}F$)	334	69
ΔT ($^{\circ}F$)	70	9
Flow rate (gal/min)	2.36	6.88
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.37	- - -
Heat gained (10^5 Btu/hr)	- - -	0.31
Heat lost to ambient (10^5 Btu/hr)		0.06
Centerline heat flux (10^5 Btu/hr-sq ft)		0.95

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	234 $^{\circ}F$	0.56
2	228 $^{\circ}F$	0.60
3	218 $^{\circ}F$	0.66
4	240 $^{\circ}F$	0.57
5	212 $^{\circ}F$	0.71
6	237 $^{\circ}F$	0.61
7	226 $^{\circ}F$	0.67

RUN NUMBER 28

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	409	60
T_{out} ($^{\circ}F$)	334	68
ΔT ($^{\circ}F$)	75	8
Flow rate (gal/min)	2.36	6.75
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.27
Heat lost to ambient (10^5 Btu/hr)		0.13
Centerline heat flux (10^5 Btu/hr-sq ft)		0.83

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	213 $^{\circ}F$	0.64
2	206 $^{\circ}F$	0.69
3	198 $^{\circ}F$	0.74
4	219 $^{\circ}F$	0.66
5	192 $^{\circ}F$	0.78
6	216 $^{\circ}F$	0.69
7	206 $^{\circ}F$	0.74

RUN NUMBER 29

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	410	59
T _{out} (°F)	337	68
ΔT (°F)	73	9
Flow rate (gal/min)	2.36	6.81
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10 ⁵ Btu/hr)	0.39	- - -
Heat gained (10 ⁵ Btu/hr)	- - -	0.31
Heat lost to ambient (10 ⁵ Btu/hr)	0.08	
Centerline heat flux (10 ⁵ Btu/hr-sq ft)	0.95	

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	213°F	0.66
2	206°F	0.71
3	198°F	0.75
4	219°F	0.67
5	191°F	0.81
6	215°F	0.71
7	205°F	0.76

RUN NUMBER 30

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}\text{F}$)	410	59
T_{out} ($^{\circ}\text{F}$)	336	68
ΔT ($^{\circ}\text{F}$)	74	9
Flow rate (gal/min)	2.36	6.88
Flow velocity (ft/sec)	7.56	- - -
Heat lost (10^5 Btu/hr)	0.39	- - -
Heat gained (10^5 Btu/hr)	- - -	0.31
Heat lost to ambient (10^5 Btu/hr)		0.08
Centerline heat flux (10^5 Btu/hr-sq ft)		0.95

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	236 $^{\circ}\text{F}$	0.57
2	228 $^{\circ}\text{F}$	0.62
3	221 $^{\circ}\text{F}$	0.68
4	241 $^{\circ}\text{F}$	0.60
5	215 $^{\circ}\text{F}$	0.73
6	234 $^{\circ}\text{F}$	0.66
7	226 $^{\circ}\text{F}$	0.70

RUN NUMBER 31

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	331	60
T _{out} (°F)	299	71
ΔT (°F)	32	11
Flow rate (gal/min)	5.67	6.80
Flow velocity (ft/sec)	18.2	- - -
Heat lost (10^5 Btu/hr)	0.41	- - -
Heat gained (10^5 Btu/hr)	- - -	0.37
Heat lost to ambient (10^5 Btu/hr)		0.04
Centerline heat flux (10^5 Btu/hr-sq ft)		1.1

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	236°F	0.49
2	233°F	0.52
3	225°F	0.59
4	242°F	0.48
5	218°F	0.65
6	235°F	0.54
7	232°F	0.58

RUN NUMBER 32

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T _{in} (°F)	328	60
T _{out} (°F)	297	71
ΔT (°F)	31	11
Flow rate (gal/min)	5.67	6.88
Flow velocity (ft/sec)	18.2	- - -
Heat lost (10 ⁵ Btu/hr)	0.40	- - -
Heat gained (10 ⁵ Btu/hr)	- - -	0.38
Heat lost to ambient (10 ⁵ Btu/hr)		0.02
Centerline heat flux (10 ⁵ Btu/hr-sq ft)		1.2

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	235°F	0.49
2	232°F	0.52
3	226°F	0.59
4	241°F	0.48
5	219°F	0.65
6	234°F	0.55
7	231°F	0.59

RUN NUMBER 33

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	328	59
T_{out} ($^{\circ}F$)	297	70
ΔT ($^{\circ}F$)	31	11
Flow rate (gal/min)	5.67	6.88
Flow velocity (ft/sec)	18.2	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.38
Heat lost to ambient (10^5 Btu/hr)		0.02
Centerline heat flux (10^5 Btu/hr-sq ft)		1.2

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	$234^{\circ}F$	0.50
2	$232^{\circ}F$	0.53
3	$224^{\circ}F$	0.59
4	$240^{\circ}F$	0.49
5	$216^{\circ}F$	0.66
6	$232^{\circ}F$	0.57
7	$230^{\circ}F$	0.59

RUN NUMBER 34

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	327	58
T_{out} ($^{\circ}F$)	296	69
ΔT ($^{\circ}F$)	31	11
Flow rate (gal/min)	5.67	6.80
Flow velocity (ft/sec)	18.2	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.37
Heat lost to ambient (10^5 Btu/hr)		0.03
Centerline heat flux (10^5 Btu/hr-sq ft)		1.1

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	234 $^{\circ}F$	0.49
2	232 $^{\circ}F$	0.52
3	225 $^{\circ}F$	0.58
4	240 $^{\circ}F$	0.49
5	215 $^{\circ}F$	0.67
6	232 $^{\circ}F$	0.56
7	229 $^{\circ}F$	0.60

RUN NUMBER 35

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	327	59
T_{out} ($^{\circ}F$)	296	70
ΔT ($^{\circ}F$)	31	11
Flow rate (gal/min)	5.67	6.88
Flow velocity (ft/sec)	18.2	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.38
Heat lost to ambient (10^5 Btu/hr)		0.02
Centerline heat flux (10^5 Btu/hr-sq ft)		1.2

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	233 $^{\circ}F$	0.50
2	231 $^{\circ}F$	0.53
3	223 $^{\circ}F$	0.60
4	239 $^{\circ}F$	0.50
5	216 $^{\circ}F$	0.66
6	232 $^{\circ}F$	0.57
7	230 $^{\circ}F$	0.59

RUN NUMBER 36

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	327	59
T_{out} ($^{\circ}F$)	296	70
ΔT ($^{\circ}F$)	31	11
Flow rate (gal/min)	5.67	6.88
Flow velocity (ft/sec)	18.2	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.38
Heat lost to ambient (10^5 Btu/hr)		0.02
Centerline heat flux (10^5 Btu/hr-sq ft)		1.2

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	234 $^{\circ}F$	0.50
2	232 $^{\circ}F$	0.52
3	224 $^{\circ}F$	0.61
4	240 $^{\circ}F$	0.49
5	217 $^{\circ}F$	0.66
6	234 $^{\circ}F$	0.56
7	231 $^{\circ}F$	0.58

RUN NUMBER 37

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	300	59
T_{out} ($^{\circ}F$)	281	73
ΔT ($^{\circ}F$)	19	14
Flow rate (gal/min)	9.45	5.16
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.36
Heat lost to ambient (10^5 Btu/hr)		0.04
Centerline heat flux (10^5 Btu/hr-sq ft)		1.1

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	$240^{\circ}F$	0.44
2	$237^{\circ}F$	0.48
3	$231^{\circ}F$	0.56
4	$241^{\circ}F$	0.47
5	$226^{\circ}F$	0.62
6	$235^{\circ}F$	0.55
7	$236^{\circ}F$	0.55

RUN NUMBER 38

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	302	60
T_{out} ($^{\circ}F$)	283	75
ΔT ($^{\circ}F$)	19	15
Flow rate (gal/min)	9.45	5.09
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.38
Heat lost to ambient (10^5 Btu/hr)		0.02
Centerline heat flux (10^5 Btu/hr-sq ft)		1.2

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	240 $^{\circ}F$	0.47
2	238 $^{\circ}F$	0.50
3	230 $^{\circ}F$	0.59
4	242 $^{\circ}F$	0.49
5	224 $^{\circ}F$	0.67
6	236 $^{\circ}F$	0.57
7	237 $^{\circ}F$	0.58

RUN NUMBER 39

HEAT BALANCE DATA

<u>Quantity Measured</u>	<u>Organic Stream</u>	<u>Water Stream</u>
T_{in} ($^{\circ}F$)	302	60
T_{out} ($^{\circ}F$)	283	74
ΔT ($^{\circ}F$)	19	14
Flow rate (gal/min)	9.45	5.30
Flow velocity (ft/sec)	30.3	- - -
Heat lost (10^5 Btu/hr)	0.40	- - -
Heat gained (10^5 Btu/hr)	- - -	0.37
Heat lost to ambient (10^5 Btu/hr)		0.03
Centerline heat flux (10^5 Btu/hr-sq ft)		1.1

THERMOCOUPLE DATA

<u>Thermocouple Number</u>	<u>Temperature</u>	<u>Calibration Factor</u>
1	240 $^{\circ}F$	0.50
2	237 $^{\circ}F$	0.54
3	230 $^{\circ}F$	0.61
4	243 $^{\circ}F$	0.51
5	224 $^{\circ}F$	0.70
6	235 $^{\circ}F$	0.61
7	235 $^{\circ}F$	0.62

APPENDIX B
SAMPLE CALCULATIONS - RUN NO. 6

APPENDIX BSAMPLE CALCULATIONS - RUN NO. 6

I. HEAT BALANCE

Heat Gained by Water

$$Q_w = W_w \left| \Delta T_w \right| C_{p_w}$$

$$F_w = 4.95 \frac{\text{gal}}{\text{min}}$$

$$\rho_w = 8.33 \frac{\text{lb}}{\text{gal}}$$

$$\Delta T_w = 18^\circ\text{F}$$

$$C_{p_w} = 1 \frac{\text{Btu}}{\text{lb-}^\circ\text{F}}$$

$$Q_w = \frac{4.95 \text{ gal}}{\text{min}} \left| \frac{8.33 \text{ lb}}{\text{gal}} \right| \frac{60 \text{ min}}{\text{hr}} \left| \frac{1 \text{ Btu}}{\text{lb-}^\circ\text{F}} \right| 18^\circ\text{F}$$

$$= 0.44 \times 10^5 \frac{\text{Btu}}{\text{hr}}$$

Heat Lost by Organic

$$Q_o = W_o \left| \Delta T_o \right| C_{p_o}$$

$$F_o = 9.45 \frac{\text{gal}}{\text{min}}$$

$$\rho_o = 8.08 \frac{\text{lb}}{\text{min}}$$

$$\Delta T_o = 23^\circ\text{F}$$

$$C_{p_o} = 0.45 \frac{\text{Btu}}{\text{lb-}^\circ\text{F}}$$

Heat Lost by Organic (continued)

$$\begin{aligned}
 Q_o &= \frac{9.45 \text{ gal}}{\text{min}} \left| \frac{8.08 \text{ lb}}{\text{gal}} \right| \frac{60 \text{ min}}{\text{hr}} \left| \frac{0.45 \text{ Btu}}{\text{lb-}^\circ\text{F}} \right| 23^\circ\text{F} \\
 &= 0.47 \times 10^5 \frac{\text{Btu}}{\text{hr}}
 \end{aligned}$$

Heat Lost to Ambient

$$\begin{aligned}
 Q(\text{lost}) &= Q_o - Q_w \\
 &= 0.47 \times 10^5 \frac{\text{Btu}}{\text{hr}} - 0.44 \times 10^5 \frac{\text{Btu}}{\text{hr}} \\
 &= 0.03 \times 10^5 \frac{\text{Btu}}{\text{hr}}
 \end{aligned}$$

II. CENTERLINE HEAT FLUX

$$\phi_c = \frac{Q_w}{A_p} \left| \text{CF} \right|$$

$$Q_w = 0.44 \times 10^5 \frac{\text{Btu}}{\text{hr}}$$

$$A_p = 0.25 \text{ ft}^2$$

$$\text{CF} = 0.77$$

$$\phi_c = \frac{0.44 \times 10^5 \frac{\text{Btu}}{\text{hr}}}{0.25 \text{ ft}^2} \left| 0.77 \right|$$

$$= 1.4 \times 10^5 \frac{\text{Btu}}{\text{hr-ft}^2}$$

III. UNPERTURBED PLATE TEMPERATURE

Water Film Temperature Drop

$$\Delta T_{wf} = \frac{\Phi_{\ell}}{h}$$

$$\Phi_{\ell} = 1.4 \times 10^5 \frac{\text{Btu}}{\text{hr-ft}^2}$$

$$h = 0.023 \frac{k}{d} \left(\frac{dG}{\mu} \right)^{0.8} \left(\frac{C_p \mu}{k} \right)^{0.4}$$

$$k = 0.35 \frac{\text{Btu}}{\text{ft-}^{\circ}\text{F-hr}}$$

$$d = 0.032 \text{ ft}$$

$$G = 0.95 \times 10^6 \frac{\text{lb}}{\text{hr-ft}^2}$$

$$\mu = 2.28 \frac{\text{lb}}{\text{ft-hr}}$$

$$C_p = 1 \frac{\text{Btu}}{\text{lb-}^{\circ}\text{F}}$$

$$h = \frac{0.023}{\left| \frac{0.035 \text{ Btu}}{\text{ft-hr-}^{\circ}\text{F}} \right| \left| 0.032 \text{ ft} \right|}$$

$$\left(\frac{0.032 \text{ ft}}{\left| \frac{\text{ft-hr}}{2.28 \text{ lb}} \right| \left| \frac{0.95 \times 10^6 \text{ lb}}{\text{hr-ft}^2} \right|} \right)^{0.8}$$

$$\left(\frac{1 \text{ Btu}}{\left| \frac{\text{lb-}^{\circ}\text{F}}{2.28 \text{ lb}} \right| \left| \frac{\text{ft-hr-}^{\circ}\text{F}}{0.35 \text{ Btu}} \right|} \right)^{0.4}$$

$$= 1.1 \times 10^3 \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^{\circ}\text{F}}$$

$$\Delta T_{wf} = \frac{1.4 \times 10^5 \text{ Btu}}{\left| \frac{\text{hr-ft}^2}{1.1 \times 10^3 \text{ Btu}} \right|} = 127^{\circ}\text{F}$$

Plate Temperature Drop

$$\Delta T_p = \frac{\phi_c}{k} \left| \frac{t}{k} \right|$$

$$\phi_c = 1.4 \times 10^5 \frac{\text{Btu}}{\text{hr-ft}^2}$$

$$t = 2.5 \times 10^{-3} \text{ ft}$$

$$k = 9.4 \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}$$

$$\Delta T_p = \frac{1.4 \times 10^5 \text{ Btu}}{\text{hr-ft}^2} \left| \frac{0.25 \times 10^{-3} \text{ ft}}{9.4 \text{ Btu}} \right| \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} = 37^\circ\text{F}$$

Inlet End Temperature

$$\begin{aligned} T_p &= T_{out_w} + \Delta T_{wf} + \Delta T_p \\ &= 80 + 127 + 37 = 244^\circ\text{F} \end{aligned}$$

Outlet End Temperature

$$\begin{aligned} T_p &= T_{in_w} + \Delta T_{wf} + \Delta T_p \\ &= 62 + 127 + 37 = 226^\circ\text{F} \end{aligned}$$

IV. CALIBRATION FACTOR

$$f(t/c-1) = \frac{T_o - T_{t/c}}{T_o - T_p}$$

$$T_o = 319^{\circ}\text{F} - \frac{28.4 \text{ inches } (319^{\circ}\text{F} - 296^{\circ}\text{F})}{36 \text{ inches}} = 301^{\circ}\text{F}$$

$$T_{t/c} = 255^{\circ}\text{F}$$

$$T_p = 244^{\circ}\text{F} - \frac{28.4 \text{ inches } (244^{\circ}\text{F} - 226^{\circ}\text{F})}{36 \text{ inches}} = 230^{\circ}\text{F}$$

$$f(t/c-1) = \frac{301^{\circ}\text{F} - 255^{\circ}\text{F}}{301^{\circ}\text{F} - 230^{\circ}\text{F}} = 0.65^{\circ}\text{F}$$