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SUBJECT: **Calibration of OMRE Fuel-Element Surface Thermocouple Assembly**

CONTENTS:

I. STATEMENT OF PROBLEM

Optimum operation of the OMRE at high power levels requires an accurate monitoring of the fuel-plate surface temperatures. These temperatures are being measured with 0.005-inch diameter chromel-alumel thermocouples attached to 0.005-inch thick fuel-plate cladding of Type 304 stainless steel. The thin cladding precludes the embedment of the thermocouple junction lead-wires and, consequently, these lead-wires are in contact with the coolant stream. Heat transfer from the thermocouple junction, by conduction along the lead-wires and by forced convection to the coolant, produces a lowering of the surface temperature in the region of the junction which results in an error in surface temperature measurement.

Thus, the mere presence of the thermocouple alters the temperature in the region being measured; the problem, then, is to determine what the actual surface temperature would be if the thermocouple were not present. In this report the term "actual surface temperature" will be used to indicate the surface temperature of the fuel plate in the absence of any thermocouple.

Theoretical analysis of the temperature error can only be made upon an idealized model; therefore, a calibration of the thermocouple assembly under simulated reactor conditions was required. An initial calibration of the OMRE surface thermocouples test results indicated a temperature-measurement error much larger than anticipated.[1] The temperature correction factors were found to be 0.44 and 0.50 for coolant temperatures of 600°F and 500°F, respectively. The calibration was based upon calculated reference surface temperatures utilizing experimental heat transfer coefficients; the accuracy of these coefficients was ±15%. Considering the magnitude of the temperature-measurement error, a significant error in thermocouple calibration was introduced by the method employed to determine the reference surface temperatures.

To obtain a more accurate thermocouple calibration a more direct method of determining the reference surface temperatures was needed. The calibration test reported herein utilized temperature measurements of the insulated side of the test plate as a means of determining these reference temperatures.

II. SUMMARY OF RESULTS AND RECOMMENDATIONS

A. Test Results

Experimental determinations of the errors in surface temperature measurements made with the OMRE fuel-element thermocouple assembly were obtained at the following simulated reactor conditions:

Coolant material	Santowax O-M
Coolant temperature	500°F and 600°F
Coolant velocity	12 and 15 ft/sec
Heat flux	70,000 - 170,000 Btu/(hr) (sqft)

1. For test conditions which were a combination of the maximum values of the above parameters and, therefore, most closely conforming to the actual reactor conditions, the observed surface temperature was lower than the actual surface temperature by 30% of the difference between the actual surface temperature and the coolant temperature. Under reactor conditions, for example, if the actual surface temperature is 750°F and coolant temperature is 600°F, the observed surface temperature will be 705°F.

2. For similar test conditions with the exception of the coolant temperature which was decreased to 500°F, the observed surface temperature was less than the actual surface temperature by 35% of the difference between the actual surface temperature and the coolant temperature. Under reactor conditions, for example, if the actual surface temperature is 750°F and coolant temperature is 500°F, the observed surface temperature will be 663°F.

3. Over the range of coolant velocities and heat fluxes investigated there was no significant effect of these parameters upon the magnitude of temperature error.

4. Switching the orientation of the separate chromel-steel and alumel-steel junctions of the thermocouple assembly from the design configuration and placing the chromel-steel junction upstream with respect to the coolant flow direction had no effect upon the magnitude of error in surface temperature measurement.

B. Recommendation

1. To obtain the actual surface temperature from the observed values during reactor operation, the following relationship should be used:

$$T_s = \frac{T_o - Z\, T_c}{1-Z}$$

where

T_s = actual surface temperature

T_o = observed surface temperature

T_c = bulk coolant temperature

Z = temperature correction factor

The temperature correction factors for two OMRE design conditions are tabulated below:

Coolant Temperature °F	Coolant Velocity Feet per Second	Z
500	>12	0.35
600	>12	0.30

III. DESCRIPTION OF EQUIPMENT

A. OMRE Thermocouple Assembly

The OMRE fuel-plate thermocouple assembly as simulated for the purpose of calibration is shown in Figure I. The thermocouple lead-wires of 0.005-inch chromel-alumel extend parallel 0.25 inches along the plate surface in a direction normal to the coolant flow. Quartz sleeves (0.007-inch I.D. with 0.003-inch wall) insulate the lead-wires from the Type 304 stainless steel surface. The parallel wires are individually spot-welded to the surface (approximately 0.010-inches apart) forming two separate junctions of chromel-steel and alumel-steel. The presence of the third metal, steel, does not alter the chromel-alumel emf if the two junctions are at the same temperature. Since the thermal gradient in the direction of flow is very small this thermocouple assembly has essentially a chromel-alumel junction.

B. Test Section

The test section, illustrated in Figure 2, contains a Type 304 stainless-steel plate which simulated an OMRE fuel plate and formed one wall of a rectangular coolant channel. This coolant channel simulated the coolant passage between two adjacent fuel plates in the OMRE fuel element. Six OMRE-type thermocouple assemblies were attached to the surface of the steel plate exposed to the circulating coolant. The opposite plate surface was insulated by the lavite plate-holder; six reference thermocouples, used to determine the actual plate temperature, were attached to this surface. The sheathed thermocouple lead wires, extending from the regions of attachment to an area outside of the test section, were contained in grooves cut into the lavite holder. The assembly of the test plate with attached thermocouples, all contained in the lavite holder, was housed in a rectangular stainless-steel duct. Two 250-watt strip heaters were attached to the external surfaces of the steel duct to serve as guard heaters. Location of the OMRE-type surface thermocouples and the reference thermocouples is shown in Figure 3.

C. Test Loop

A flow diagram of the test loop is shown in Figure 4. The loop consisted of a 120-gpm, 150-ft head, centrifugal process pump, a by-pass filter, a turbine-type flowmeter, the test section, an air-cooled heat exchanger, a surge tank, and a supply tank. Santowax O-M was the circulating fluid. The 3-inch loop ~~piping~~ was used as a one turn secondary in a transformer ~~to provide~~ resistance heating of the piping system. Large components such as the tank, test section, and valves were heated with strip heaters and heating cable. Flow control was provided by globe valves in the main circulating system and in the filter by-pass system.

D. Instrumentation

The test-plate temperatures and circulating fluid temperatures were measured with 36-gauge chrome-alumel thermocouples sheathed with stainless steel. The thermocouple emf's were measured with a Leeds and Northrup precision potentiometer with an ice bath reference junction. A bank of 10-point rotary selector switches was used to permit rapid readings. Calibration of the test-section thermocouples (OMRE-type, reference, coolant inlet, and coolant outlet) with reference to each other under isothermal conditions showed less than 0.3% deviation from the mean temperature.

Fluid flow rate was measured with a turbine flowmeter and recorded on a Foxboro circular-chart emf recorder. Accuracy was ±1/2 percent.

System pressures were indicated by Bourdon gauges located in the pump suction and discharge piping.

Power input to the test plate was determined with individual current and voltage measurements. A 0-5 ampere ammeter was used in conjunction with a 200:1 current transformer. The voltmeter range was 0-15 volts. The accuracy of current measurement was ±1%. Accuracy of voltage reading was ±2%

E. Test Section Power Supply

Alternating current was supplied to the test plate from a 240-volt supply through a regulating 15.7 KVA autotransformer and a step-down transformer. Test section power was limited by the autotransformer capacity to a maximum of 800 amperes at 14.9 volts.

IV. TEST PROCEDURE

Santowax O-M was circulated at constant flow rate and constant temperature. At a fixed power input to the test plate the system was allowed to reach equilibrium and the following measurements were taken:

1. Voltage drop across test plate.
2. Current through test plate.
3. Coolant flow rate.
4. Coolant inlet and exit temperatures.
5. Test-plate surface temperatures.
6. Test-plate reference temperatures.
7. Temperatures in lavite plate-holder.
8. Temperatures of outside surface of test section.

Two sets of measurements were taken for the same experimental conditions at a time interval of approximately five minutes.

For conditions of constant coolant temperature and constant flow rate, the heat input was varied over a range of heat flux from approximately 70,000 to 170,000 Btu/(hr)/(sq ft).

Data were obtained for coolant temperatures of approximately 500°F and 600°F and coolant velocities of 12 and 15 ft per sec.

The test-plate surface and reference thermocouples were calibrated in place by circulating the coolant at several temperatures with no power input to the test plate.

During installation of the test assembly into the test loop two reference thermocouples, R-4 and R-6, were broken. Since repair of these thermocouples would have caused extensive delay in the experimental program, the test was performed with insulated-surface temperature measurements taken at four positions; these measurements yielded adequate information to meet the test objectives.

V. DISCUSSION

A. Introduction

The need for calibration of the OMRE fuel-plate thermocouple assembly stems from the following reasons:

1. Presence of the thermocouple on the fuel plate produces local turbulence of the coolant stream which in turn increases the local heat transfer coefficient and results in a local lowering of the plate temperature.

2. Presence of the thermocouple lead-wires in the relatively cold temperature zone of the coolant stream induces loss of heat from the thermocouple junctions by conduction through the lead wires and convection to the coolant, the effect again being a local lowering of the fuel-plate temperature.

Thus the actual temperature of the fuel plate is decreased in the region of the thermocouple and the indicated plate temperature is too low.

Since the local lowering of the fuel-plate temperature is a function of the heat transfer properties of the reactor coolant, a determination of the extent of surface temperature measurement error requires test conditions which will simulate the reactor heat transfer characteristics. This was accomplished by circulating the reactor coolant, Santowax O-M, at the two design coolant temperatures of 500°F and 600°F, and at the design coolant velocity of 15 ft per sec.(also at 12 ft/sec to determine effect of coolant velocity).

B. <u>Method</u>

To calibrate the OMRE surface thermocouple assembly under simulated reactor conditions an electrically heated plate, insulated on one side and cooled on the other with circulating Santowax-O-M, was utilized. Specimens of the OMRE-type surface thermocouple assembly were attached to the cooled surface of the plate and the indicated plate-surface temperatures were recorded. Reference surface temperatures of the test plate were measured with thermocouples attached to the insulated surface of the plate, thus averting the source of temperature measurement error inherent in the OMRE surface thermocouple configuration; namely, exposure of the thermocouple to the coolant stream.

The reference thermocouples as shown in Figure 3 were not directly opposite of the associated OMRE thermocouples but were deliberately displaced 1 inch upstream. This was done to preclude measurement of a reference surface temperature which would be lowered by the local cooling of the plate caused by the OMRE thermocouples. Because of their location, therefore, the reference surface thermocouples furnished temperature data which had to be corrected for the temperature gradient through the plate and for the gradient parallel to the longitudinal axis of the plate; the corrected reference surface temperatures represented plate temperatures in the regions of the OMRE thermocouples that would exist were the thermocouples not present, i.e., the actual surface temperatures.

Calibration of the OMRE thermocouple was accomplished by comparison of the observed surface temperatures with the calculated actual surface temperatures under approximate reactor design conditions of heat flux and coolant velocity. The test data were obtained in two series of experimental runs; one series was with the coolant temperature maintained at 500°F and the other series was with the coolant temperature held at 600°F.

C. <u>Accuracy of Results</u>

The maximum probable error in actual OMRE surface temperatures due to correction of the observed temperatures by the recommended "Z" values is 2.3% for the conditions of 750°F true surface and 600° coolant and 2.8% for the condition of 750°F true surface and 500°F coolant (See Appendix). This estimate of error is based upon the probable error in experimentally determined temperature correction factors "Z" and the measurement errors associated with determining reactor coolant and observed plate temperatures.

The maximum probable errors in the experimentally determined temperature correction factors "Z" ranged from 13% to 20% (See Appendix).

To limit the maximum probable error in "Z" to 20%, data obtained at heat fluxes less than 100,000 But/(hr)(sq ft) were discarded. At the smaller heat fluxes the temperature difference between the test plate surface and the coolant was too small to yield accurate results because the instrumental temperature measurement errors were almost of the same order as the OMRE thermocouple error being determined.

An irregularity in test data was observed in the series of test runs made with the coolant temperature at 600°F. The extent of surface temperature measurement error occurring in each of the OMRE-type thermocouples located at station A was appreciably larger than the errors of the other four OMRE-type thermocouples. This behavior was not exhibited in the 500°F test runs. It was surmised that when the coolant temperature was at 600°F and the test plate temperature was around 700°F loss of heat from the edge of the plate close to station A, due to conduction through the copper terminal to the ambient atmosphere, produced a significant local cooling of the test plate. Since the temperatures indicated by the reference thermocouples at station A' did not deviate from the normal pattern, the local cooling of the plate did not extend along the plate far enough to be detected by the reference surface thermocouple. Consequently, the calculated actual surface temperatures at station A were too high and this resulted in the error determination of thermocouples at A, also being too high. Therefore, the temperature correction factors obtained with these two end thermocouples for the 600°F coolant test runs were discarded.

D. Comparison of Exp. and Reactor Conditions Affecting the Calibration

In the OMRE the fuel-plate surface thermocouple is attached to the fuel plate with the lead wires and their insulating quartz sleeves, the two junctions, and the steel hold-down straps all located upon the 0.005-inch cladding directly above the enriched uranium oxide fuel. The entire assembly is, therefore, located on a heat generating surface. In the calibration test this thermocouple configuration was simulated by attaching a duplicate of the thermocouple assembly to an electrically heated plate. The presence of the steel hold-down straps in the thermocouple assembly, however, produced a temperature perturbation effect under test conditions slightly different than their effect under reactor conditions.

The effect of the straps in the reactor thermocouple is to slightly cool an area of plate surface adjacent to the welded ends of the straps; the straps act as fins. This cooling effect of the straps was somewhat emphasized in this test since the 0.003 inch thick straps afforded a parallel path for the electric current which heated the test plate. Proportionately less heat was generated in the plate directly under the straps by the ratio of the plate thickness (0.020 inches) to the sum of plate and strap thickness (0.023 inches) However, the 13% loss in heat generation within the plate was offset, to an extent, by the resultant reduction in the fin cooling effect of the strap because of the heat generation within the strap. The overall effect upon the plate temperature at the thermocouple junctions, which were located approximately 0.010-inch away from the straps, is considered insignificant because of the relatively low thermal conductivity of stainless steel which was used for both fuel-plate cladding and test plate.

E. Comparison of Results with Previous Thermocouple Calibration Test

As stated earlier in this report, a calibration test of the OMRE fuel-plate thermocouple assembly was performed prior to the test being reported herein. In the first test an electrically heated plate containing four specimens of the subject thermocouple assembly was mounted in the center of a rectangular coolant channel, and with coolant flowing on both sides of the test it was impossible to measure a reference surface temperature. However, from a knowledge of the heat flux q/A, and coolant temperature, Tc, the reference temperature, Ts, was calculated by utilizing experimental heat transfer coefficients in the relation:

$$\frac{q}{A} = h(T_s - T_c)$$

At coolant temperatures of 600°F and 500°F, the temperature correction factors determined in this test were 0.30 and 0.35, respectively; whereas, in the previous test the values of "Z" were 0.44 and 0.50, respectively.

Although the results of the two tests do not agree as to the magnitude of temperature measurement error, there is approximate agreement as to the effect of coolant temperature upon the change in the error. Lowering the coolant temperature from 600°F to 500°F resulted in about the same percentage increase in the error for both calibration tests.

Since in this test the variables q/A, T_s, and T_c were measured quantities, the heat transfer coefficient, h, can be calculated. It is interesting to note that the calculated values of h determined in this experiment are approximately 50% higher than the heat transfer coefficients obtained by Silberberg and Huber.[2] Additional experimental heat transfer data, preferably obtained in rectangular coolant passages, may possibly explain the discrepancy in heat transfer coefficients.

VI. SAMPLE CALCULATIONS

Calculation of the Error in Surface Temperature Measurement

The following calculations are based upon data obtained in test run No. 15-20. Test conditions were:

Coolant temperature	= 600°F
Fluid velocity	= 15.0 ft/sec
Heat flux	= 165,000 Btu/(hr) (sq ft)

A. Calculation of Actual Surface Temperature (T_s).

The test section configuration is essentially equivalent to the case of a flat metal plate ideally insulated except on one surface. Heat is generated uniformly throughout the plate and is dissipated at the uninsulated surface by transfer to a liquid. Assuming the liquid temperature is constant over the entire surface of the plate, (a condition approximately satisfied in the test), the temperature drop from the insulated to the colder surface is found as follows:[3]

$$(1) \qquad q_x = q_t \frac{x}{x_t} = -kA\frac{dt}{dx}$$

where q_x = heat current at a distance x from adiabatic surface (Btu/hr).

q_t = total heat generation (Btu/hr).

x_t = distance from adiabatic surface to cooled surface (ft).

A = area of heat transfer surface (sq ft).

k = thermal conductivity of stainless steel plate (Btu/(hr)(°F)(sq ft)/ft.

integrating equation (1)

$$\frac{q_t}{x_t}\int_0^{x_t} x\,dx = -\,kA\int_{T_r}^{T_r'} dt$$

where T_r = temperature of insulated plate-surface

T_r' = temperature of cooled plate-surface (see Figure 2)

$$\frac{q_t x_t^2}{2x_t} = -kA\,(T_r' - T_r)$$

$$(2)\qquad T_r' - T_r = -\,\frac{q_t x_t}{2kA}$$

and $x_t = \frac{0.020 \text{ in}}{12 \text{ in/ft}} = 0.00167$ ft

$k = 12$ Btu/(hr)(^{o}F)(sq ft)/ft

$q_t = \left[3.413 \text{ Btu/(hr) (watt)}\right]\left[\text{EI (watts)}\right]$

$= 3.413 \quad 14.8 \times 800 = 40{,}400$ Btu/hr.

$A = \frac{17.875 \text{ in.} \times 1.977 \text{ in.}}{144 \text{ sq in/ sq ft}} = 0.245$ sq ft

Substituting into (2)

$$T_r' - T_r = \frac{40{,}400 \times 0.00167}{2 \times 12 \times 0.245} = -\,11^{o}F$$

Measured values of T_r were:

$T_{r1} = 703^{o}F$

$T_{r2} = 689^{o}F$

$T_{r3} = 707^{o}F$

$T_{r5} = 705^{o}F$

Note:

Second subscript indicates thermocouple position. (See Figure 3)

therefore, the reference temperatures adjusted for T through the plate, were:

$T_{r1}' = 692^{o}F$

$T_{r2}' = 678^{o}F$

$T_{r3}' = 696^{o}F$

$T'_{r5} = 694°F$

Assuming a linear variation in test-plate temperature between thermocouple stations A' and C', the actual surface temperatures at thermocouple stations A, B, and C were obtained as follows:

$$\frac{T'_{r3} - T'_{r1}}{\text{distance between thermocouples}} = \frac{4°F}{4 \text{ in}} = 1°F/\text{in.}$$

therefore, since T_s is 1-inch above the corresponding T'_r

$T_{s1} = 691°F$

$T_{s2} = 677°F$

$T_{s3} = 695°F$

$T_{s5} = 693°F$

Based upon the symetrical spacing of the pair of thermocouples at each reference thermocouple station and the small variation in plate surface temperature in the direction normal to the coolant flow, equality of calculated actual surface temperatures at each of the OMRE-type thermocouple stations is expected. Consequently, values of T_{r2} and, therefore, the derived values of T_{s2} were disregarded. Actual surface temperatures employed in subsequent calculations are:

$T_{s1} = T_{s4} = 691°F$

$T_{s2} = T_{s5} = 693°F$

$T_{s3} = T_{s6} = 695°F$

B. Difference Between Actual Surface Temperature and Observed Surface Temperature, $(T_s - T_o)$.

Observed surface temperatures were:

$T_{o1} = 661°F$

$T_{o2} = 666°F$

$T_{o3} = 671°F$

$T_{o4} = 660°F$

$T_{o5} = 667°F$

$T_{o6} = 669°F$

therefore

$T_{s1} - T_{o1} = 691 - 661 = 30°$

$T_{s2} - T_{o2} = 27°$

$T_{s3} - T_{o3} = 24°$

$T_{s4} - T_{o4} = 31°$

$T_{s5} - T_{o5} = 26°$

$T_{s6} - T_{o6} = 26°$

C. Local Coolant Temperature (Tc)

OMRE Thermocouple Station	Distance Downstream of Channel Entrance
A	16.75 inches
B	14.75 inches
C	12.75 inches

Total length of test channel = 17.88 inches

Assuming a linear increase in coolant temperature within the test channel, the coolant temperature in the regions of the surface thermocouples is obtained as follows:

At station A, $T_{cA} = \frac{16.75}{17.88} (\Delta T_c) + T_c$ inlet

$T_{cA} = 0.71 \times 9° + 600° = 606°F$

At station B, $T_{cB} = 607°F$

At station C, $T_{cC} = 608°F$

D. Difference Between Actual Surface Temperature and Local Coolant Temperature

$T_{s1} - T_{cA} = 691 - 606 = 85°F$

$T_{s2} - T_{cB} = 693 - 607 = 86°F$

$T_{s3} - T_{cC} = 695 - 606 = 89°F$

$T_{s4} - T_{cA} = 691 - 606 = 85°F$

$T_{s5} - T_{cB} = 693 - 607 = 86°F$

$T_{s6} - T_{cC} = 695 - 606 = 89°F$

E. Magnitude of Error in Surface Temperature Measurement

The magnitude of surface-temperature measurement error for the OMRE thermocouple assembly is best expressed as follows:

$$\% \text{ Error} = \frac{(T_s - T_o)\,100}{(T_s - T_c)}$$

Thus if $T_o = T_s$ = the error will be zero and if $T_o = T_c$ the error will be 100%.

a) Error in thermocouple assembly T_{o1}

$$\% \text{ Error} = \frac{30}{85}(100) = 35$$

b) Error in thermocouple assembly T_{o2}

$$\% \text{ Error} = \frac{27}{86}(100) = 31$$

c) Error in thermocouple assembly T_{o3}

$$\% \text{ Error} = \frac{24}{89}(100) = 27$$

d) Error in thermocouple assembly T_{o4}

$$\% \text{ Error} = \frac{31}{85}(100) = 36$$

e) Error in thermocouple assembly T_{o5}

$$\% \text{ Error} = \frac{26}{86}(100) = 30$$

f) Error in thermocouple assembly T_{o6}

$$\% \text{ Error} = \frac{26}{89}(100) = 29$$

F. Temperature Correction Factors (Z)

Z is defined as follows:

$$Z = \frac{T_s - T_o}{T_s - T_c}$$

Therefore, for the six test specimen thermocouples, the values of Z are:

$Z_1 = 0.35$

$Z_2 = 0.31$

$Z_3 = 0.27$

$Z_4 = 0.36$

$Z_5 = 0.30$

$Z_6 = 0.29$

G. <u>Heat Balance</u>

1. Heat input to test plate

$q_i = 3.413 \, EI$

$q_i = 3.41 \times 14.8 \times 800 = 40{,}400$ Btu/hr

2. Heat output to coolant

$q_o = wc_p \Delta T$

where w = mass flow rate, lb/hr

w = $AV\rho$

A = area of coolant channel, sq ft

V = coolant flow rate, ft/sec

ρ = density of Santowax O-M @ 600°F, lb/ft^3

$$w = \frac{(0.160 \text{ in})(1.977 \text{ in})(15 \text{ ft/sec})\, 3600 \text{ sec/Hr} (53.0 \text{ lb/cu ft})}{144 \text{ sq in/ sq ft}}$$

w = 6,270 lb/hr

$c_p = 0.000433T + 0.372$ (where T = temperature, °F)

$c_p = 0.000433 \times 600 + 0.372 = 0.631$ Btu/lb-°F

ΔT = temperature rise of coolant in test channel = 9°F

q_o = 6,270 lb/hr x 0.631 Btu/lb-°F x 9°F = 35,600 Btu/hr.

3. Heat loss from test section at zero power input

This quantity was determined with test conditions as previously indicated except for the coolant velocity which was 12.2 ft/sec instead of 15.0 ft/sec.

$q_1 = wc_p \Delta T$

$$q_1 = \left[\frac{(12.2 \text{ ft/sec})}{(15.0 \text{ ft/sec})} (6{,}270 \text{ lb/hr})\right] (0.631 \text{ Btu/lb-°F}) (2°\text{F})$$

$$q_1 = 6{,}440 \text{ Btu/hr}$$

4. Total heat output ($q_o + q_1$)

$$q_o + q_1 = 35{,}600 + 6{,}440 = 42{,}040 \text{ Btu/hr}$$

Comparing this value with the total heat input, a heat balance having reasonable agreement is obtained.

The heat loss by conduction from the test plate to the copper terminals at each end of the plate is minor because of the small cross-sectional area of the plate and is, therefore, disregarded in the heat balance calculation.

E. Heat Transfer Coefficient

$$h = \left(\frac{q}{A}\right)\left(\frac{1}{\Delta t}\right)$$

where $\frac{q}{A}$ = heat flux, Btu/(hr) (sq ft).

Δt = temperature difference between test-plate surface and bulk fluid (mean value), °F

$$h = (164{,}900)\left(\frac{1}{86}\right) = 1910 \text{ Btu/(hr) (sq ft) (°F)}$$

This value is 58% higher than the heat transfer coefficients[2] of 1200 Btu/(hr)(sq.ft) (°F) used in the previous calibration test cited in reference 1.

Original data for this report are recorded in Laboratory Notebook No. 3845.

VII. REFERENCES AND APPENDICES

A. References

1. TDR 2095, "Calibration of OMRE Fuel-Plate Thermocouple Assembly," S. Sudar, September 4, 1957.
2. IOL, D. Huber and M. Silberberg to D. W. Bareis, "Summary of Santowax O-M Heat Transfer Runs in the Laboratory Heat Transfer Loop," April 11, 1957.
3. McAdams, W. H., "Heat Transmission," McGraw-Hill Book Company, New York, 1954, 3rd Ed.

B. Appendix

__Maximum Probably Error in Determining OMRE Fuel-Plate Temperatures__

The relationship employed to determine the actual OMRE fuel-plate temperature is obtained from the expression for "Z" by solving for T_s and is

$$T_s = \frac{T_o - Z\, T_c}{1-Z}$$

Assuming that the quantities To and Tc are measured in the OMRE with reasonable accuracy (within 0.5%) the error in determining Ts is mainly a function of the accuracy of the experimentally determined quantity "Z". To determine the maximum probably error in Ts it is first necessary to determine the probable error in "Z".

1. Maximum probable error in "Z" (Data obtained in Run No. 15-20 for OMRE-type thermocouple specimen T_{o3}) as previously defined:

$$Z = \frac{T_s - T_o}{T_s - T_c}$$

The estimated maximum uncertainty in the measured quantities obtained in this experiment for actual surface temperature, observed surface temperature, and local coolant temperature were:

Quantity	Value at T/C Position T_{o3}	Maximum Uncertainty
T_s	695°F	$\Delta T_s = \pm 3°F$
T_o	671°F	$\Delta T_o = \pm 2°F$
T_c	607°F	$\Delta T_c = \pm 2°F$

In the above tabulation the uncertainty in Ts is increased over those for the other temperatures to account for the additional correction in Ts for position along the fuel element. By the method of partial derivatives the maximum probable error in "Z" is obtained as follows:

$$\Delta Z = \frac{\partial Z}{\partial T_s}(\Delta T_s) + \frac{\partial Z}{\partial T_o}(\Delta T_o) + \frac{\partial Z}{\partial T_c}(\Delta T_{cu})$$

where $$\frac{\partial Z}{\partial T_s} = \frac{T_o - T_c}{(T_s - T_c)^2}$$

$$\frac{\partial Z}{\partial T_o} = \frac{-1}{T_s - T_c}$$

$$\frac{\partial Z}{\partial T_c} = \frac{T_s - T_o}{(T_s - T_c)^2}$$

To obtain the maximum probable error, the absolute values of the partial derivatives are taken.

$$\Delta Z = \frac{(T_o - T_c)(\Delta T_s)}{(T_s - T_c)^2} + \frac{(1)(\Delta T_o)}{T_s - T_c} + \frac{(T_s - T_o)(\Delta T_c)}{(T_s - T_c)^2}$$

$$\Delta Z = \frac{(671-607)(3)}{(695-607)^2} + \frac{(1)(2)}{695-607} + \frac{(695-671)(2)}{(695-607)^2}$$

$$\Delta Z = 0.537$$

The maximum probable error in "Z" for the 600°F coolant condition is

$$\frac{\Delta Z}{Z} = \frac{0.0537}{0.27} \times 100 = \pm 20\%$$

2. Maximum probable error in actual OMRE fuel-plate surface temperature.

$$T_s = \frac{T_o - Z\,T_c}{1 - Z}$$

By the method of partial derivatives the maximum probable error in Ts is obtained as follows:

$$\Delta T_s = \frac{\partial T_s}{\partial T_o}(\Delta T_o) + \frac{\partial T_s}{\partial Z}(\Delta Z) + \frac{\partial T_s}{\partial T_c}(\Delta T_c)$$

where $\dfrac{\partial T_s}{\partial T_o} = \dfrac{1}{1-Z}$

$$\frac{\partial T_s}{\partial Z} = \frac{T_o - T_c}{(1-Z)^2}$$

$$\frac{\partial T_s}{\partial T_c} = \frac{Z}{1-Z}$$

and $\Delta T_s = \dfrac{(1)(\Delta T_o)}{1-Z} + \dfrac{(T_o - T_c)(\Delta Z)}{(1-Z)^2} + \dfrac{(Z)(\Delta T_c)}{1-Z}$

Approximate values of To, Tc and Z are 705°F, 600°F and 0.30 under OMRE design conditions of 750°F surface and 600°F coolant temperatures.

$$\Delta T_s = \frac{(1)(3)}{1-0.3} + \frac{(705-600)(0.0537)}{(1-0.30)^2} + \frac{(0.30)(3)}{1-0.30}$$

$$\Delta T_s = 4.3 + 11.5 + 1.3$$

$$\Delta T_s = \pm 17^\circ$$

$$\% \text{ Error} = \frac{(17)(100)}{750} = 2.3$$

C. Nomenclature

A = area sq ft

C_p = specific heat, Btu/(lb)(^oF)

E = electrical potential across test plate, volts

h = heat transfer coefficient Btu/(hr)(sq ft)(^oF)

I = current flowing in test plate, amperes

k = thermal conductivity, Btu/(hr)(sq ft)(^oF)/(ft)

q_i = heat generated within test plate, Btu/hr

q_l = heat loss from outside wall of test section, Btu/hr

q_o = heat input to coolant from test plate, Btu/hr

T_c = bulk coolant temperature, ^oF

T_o = surface temperature of test plate or OMRE fuel plate indicated by OMRE thermocouple assembly, ^oF

T_s = actual test plate or OMRE fuel-plate surface temperature, ^oF

T_r = reference surface temperature, ^oF

T_{cA} = local bulk coolant temperature at thermocouple station A, ^oF

T_{cB} = local bulk coolant temperature at thermocouple station B, ^oF

T_{cC} = local bulk coolant temperature at thermocouple station C, ^oF

T_r' = reference surface temperature adjusted for temperature drop through test plate

ΔT_c = temperature rise of coolant flowing through test section, ^oF

ΔT_o = uncertainty in measurement of observed surface temperature, ^oF

ΔT_s = uncertainty in measurement of actual surface temperature, ^oF

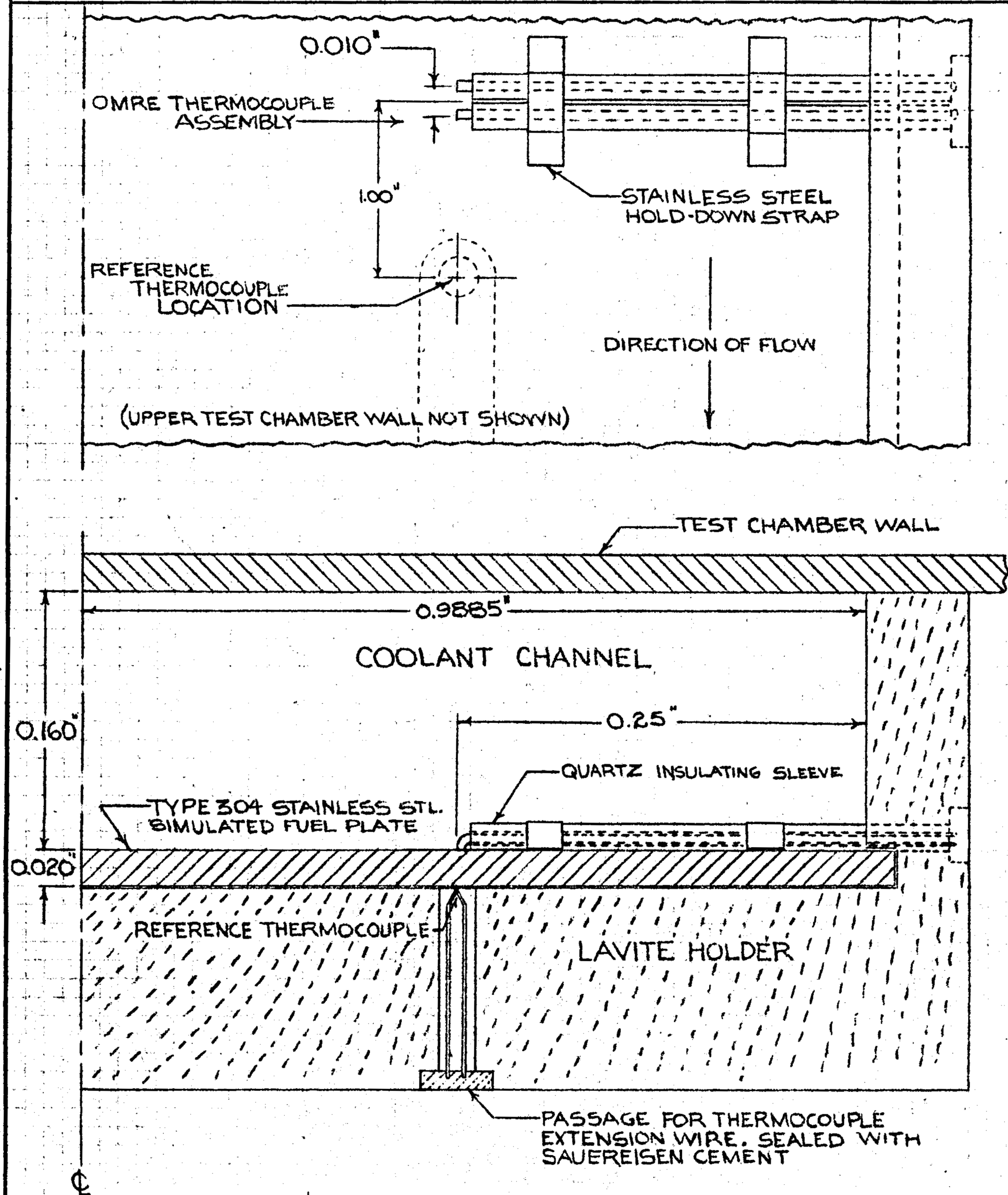
ΔT_{cu} = uncertainty in measurement of coolant temperature, ^oF

V = fluid velocity, average, ft/sec

w = mass rate of flow, lb/hr

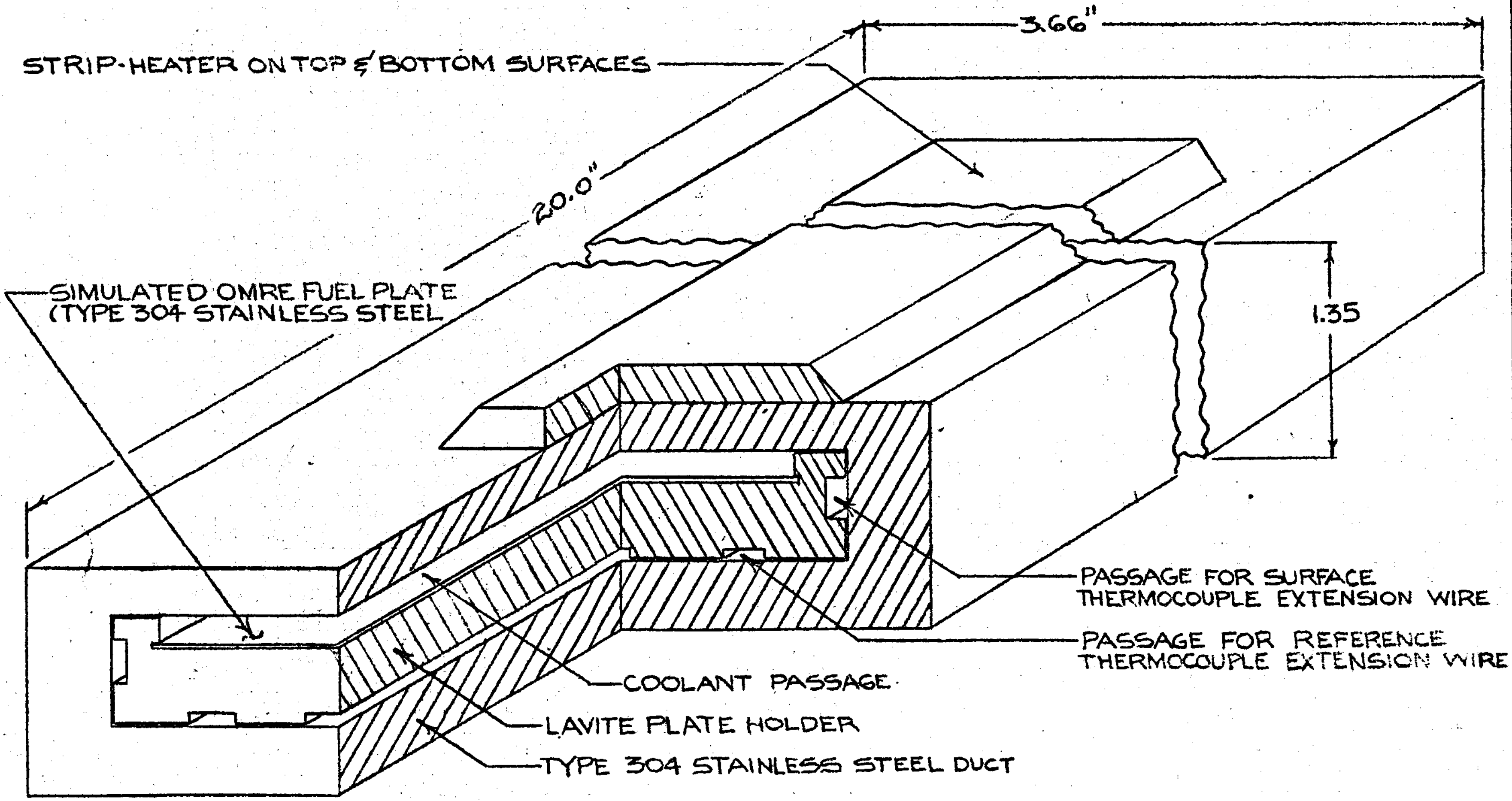
ρ = density of coolant, lb/(cu ft)

Subscripts: 1, 2, ... = identifying number of thermocouple specimen.



THERMOCOUPLE ASSEMBLY & COOLANT CHANNEL

TEST SECTION



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DATE: March 12, 1959

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Calibration of OMRE Fuel-Plate
Thermocouple Assembly Figure 2

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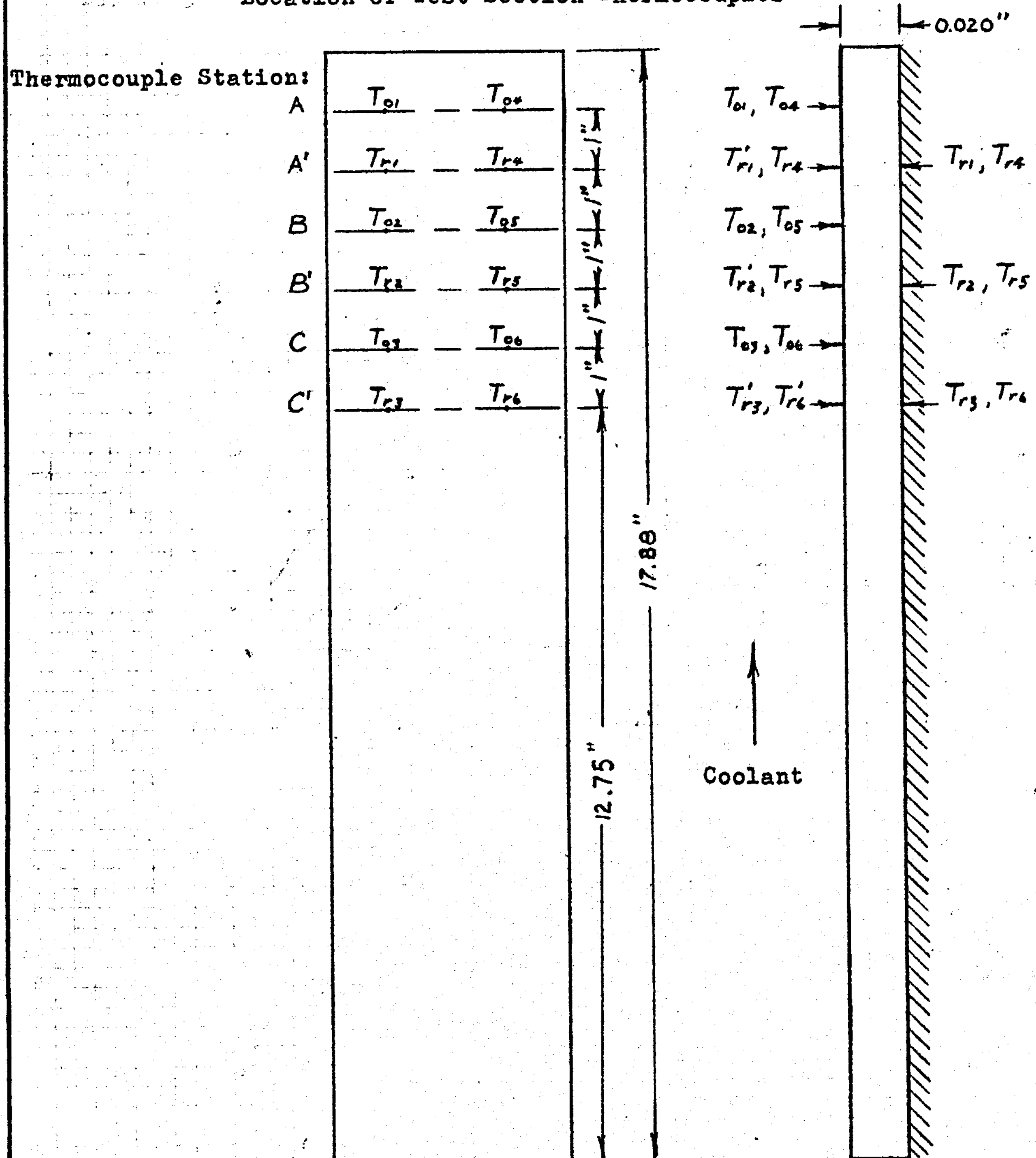
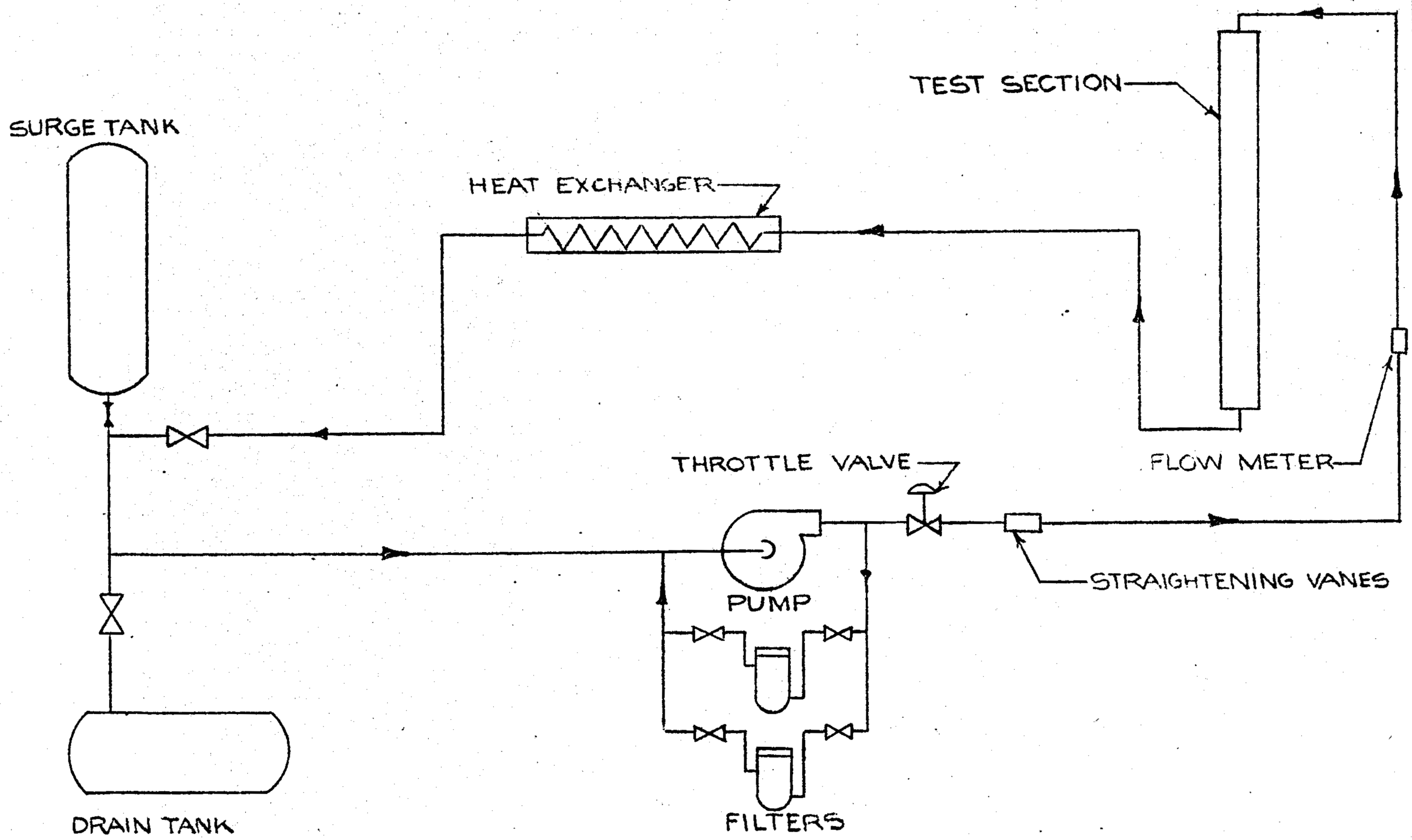
Location of Test Section Thermocouples



Key:

T_{o1} - T_{o6}	OMRE Surface Thermocouples
T_{r1} - T_{r6}	Reference Surface Thermocouples
T'_{r1} - T'_{r6}	Reference Temperatures Adjusted for ΔT Through Plate

SCHEMATIC FLOW DIAGRAM OF TEST LOOP



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Calibration of OMRE Fuel-Plate Thermocouple Assembly

Figure 4

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