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REPORT RD-0008

HEAT-TRANSFER EXPERIMENTS ON A PROPOSED FUEL ASSEMBLY
FOR THE EXPERIMENTAL GAS COOLED REACTOR

SECTION II OF
FUEL-ASSEMBLY HEAT-TRANSFER AND CHANNEL PRESSURE-DROP EXPERIMENT
FOR THE EGCR RESEARCH AND DEVELOPMENT PROGRAM

April 12, 1960

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REPORT RD-0008

HEAT-TRANSFER EXPERIMENTS

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FOREWORD

The data described in this report were obtained between July and December, 1959, pursuant to Modification IV of Contract No. AT(10-1)-925.

A second and final phase of testing will be reported in a separate report should the final design differ significantly from the Title I design. The work will be performed under Modification IX of Contract AT(10-1)-925.

ABSTRACT

Heat-transfer data are presented for the Experimental Gas Cooled Reactor Title I seven-rod fuel-assembly design of the Allis-Chalmers Manufacturing Company (References 6 and 7). The effect on heat transfer of (1) the radial location of the outer six rods of the seven-fuel-rod cluster and of (2) the addition of helical-finned spacers at the mid-point of each of the seven fuel rods is discussed. The heat-transfer data were obtained to verify preliminary general assumptions pertaining to the heat-transfer characteristics of the seven-rod fuel-assembly design and to obtain local heat-transfer correlations. The heat-transfer tests were performed at near-atmospheric pressure using air as the coolant medium. Plots and equations of heat-transfer correlations over a Reynolds Number range from 12,000 to 60,000 are included. The test set-up and test procedure are also described.

I. INTRODUCTION

A factor of primary concern in the design of the Experimental Gas Cooled Reactor is knowledge of the maximum surface temperature of the fuel elements. The surface temperature of the fuel elements can be calculated once the helium-coolant flow and temperature are established, provided the proper correlations for heat-transfer coefficients are available. General heat-transfer correlations are available for predicting average heat-transfer coefficients for certain geometries. However, heat-transfer tests are required because of inaccuracy and uncertainty accompanying any extrapolation of existing heat-transfer correlations to the exact geometry of the given fuel-element design. Heat-transfer tests are also necessary in order to obtain data on the circumferential and axial temperature variation of the fuel elements. This data is required to evaluate the mechanical design of the fuel element and to provide a basis for prediction of the maximum fuel-element temperature.

The heat-transfer tests were performed in an atmospheric air loop. The relative merits of performing the heat-transfer tests in an atmospheric air loop rather than in a pressurized helium loop are discussed in R & D Report 0001.

This report presents the results of a heat-transfer program, using near-atmospheric air as the coolant medium, performed on full-scale test specimens of the proposed fuel assembly for the Experimental Gas Cooled Reactor. The results are in the form of plots and equations of heat-transfer correlations over a Reynolds Number range from 12,000 to 60,000.

II. OBJECTIVE

The objective of the heat-transfer test program was to obtain and to analyze experimental data on local heat transfer from fuel elements having a geometry identical with that of the Experimental Gas Cooled Reactor design. The results of the heat-transfer test program are intended to be used to determine the maximum Experimental Gas Cooled Reactor fuel-element surface temperature and the temperature variation around the circumference of the fuel elements.

A secondary objective of the heat-transfer test program was to provide axial surface-temperature profiles of the fuel elements, which will be useful in the determination of thermal stresses and stability of the fuel elements under reactor operating conditions.

III. SCOPE

The heat-transfer tests were performed, using the seven-rod fuel-element cluster, for combinations of one fuel-sleeve inside diameter and two fuel-rod spacings. Two tests with helical-finned spacers at the fuel-element mid-point were performed for one sleeve inside diameter and one spacing of outer fuel rods only.

Heat-transfer data were obtained over a range of Reynolds Numbers extending from approximately 12,000 to 60,000. At design conditions, the flow in the middle fuel assembly of the Experimental Gas Cooled Reactor core central fuel channel will result in a Reynolds Number of approximately 50,000.

IV. RESULTS

The results of the heat-transfer test program are presented for four combinations of sleeve diameter, spacing of the outer six fuel-element tubes, inclusion of spacers at the fuel-element mid-point, and fuel-assembly sleeve material. The combinations are tabulated below:

<u>Test Set-Up</u>	<u>Sleeve ID, in.</u>	<u>Tube Spacing Bolt Circle Dia. in.</u>	<u>Center Support Spacers</u>	<u>Fuel-Assembly Sleeve Material</u>
1	3.000	2.100	None	Carbon Steel
2	3.000	2.000	None	Carbon Steel
3	3.000	2.000	6-fin	Carbon Steel
4	3.000	2.000	6-fin	Glass

The results for all test runs are presented in the form of two heat-transfer correlations. The heat-transfer correlations selected are:

$$(1) \quad N_{Nu} = C (N_{Pr})^{0.4} (N_{Re})^x$$

$$(2) \quad N_{Nu} = C (N_{Pr})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575} (N_{Re})^x$$

and are plotted as ratios, $N_{Nu} / (N_{Pr})^{0.4} = Y_1$ and $N_{Nu} (N_{Pr})^{0.33}$

$\left(\frac{T_b}{T_s} \right)^{0.575} = Y_2$ versus N_{Re} on Figures 1 to 81 in Appendix A.

The first sixteen are composite curves of all six tubes and the remaining are maximum or minimum correlations for each individual tube. The Reynolds Number exponent for each correlation may be obtained from the slope of the applicable plot. The coefficients A and B for each correlation may be obtained, once the Reynolds Number exponent is known, by substituting the proper ordinate and abscissa values from the plots. The equation for each plot has been calculated by the method of least mean square and is shown on each of the plots.

Tables I and II at the end of this section contain a tabulation of the heat-transfer correlations for each test set-up. The tables also contain a list of normalized equations, which may be compared to the equations obtained by least-mean-square analysis. The normalized equations were obtained by assuming an 8/10 exponent on the Reynolds Number at a Reynolds Number of 50,000. The normalizing procedure is outlined in the Discussion

section of this report. Some generalizations can be made, based upon the tabulated data for the normalized equations:

1. With a 3.000-in.-ID carbon-steel sleeve, 2.100-in.-BC spacing of the outer fuel tubes, and helical spacers omitted at the fuel-element mid-point, results at TC Station No. 3 indicate that for an average for all six tubes:
 - (a) The variation of temperature around the circumference of the outer six tubes has a single hot spot on the tube surface, which occurs near the point on the tube surface closest to the sleeve wall. This point is defined as the zero-degree circumferential location.
 - (b) The average heat-transfer coefficient is about 14% lower than would be predicted by the conventional Dittus-Boelter equation, $N_u = 0.023 (N_{Re})^{0.8} (N_{Pr})^{0.4}$
 - (c) The minimum heat-transfer coefficient is about 28% lower than would be predicted by the Dittus-Boelter equation.
 - (d) The ratio of the average maximum-to-minimum heat-transfer coefficient is approximately 1.35.
2. With a 3.000-in.-ID carbon-steel sleeve, 2.000-in.-BC spacing of the outer fuel tubes, and helical spacers omitted at the fuel-element mid-point, results at TC Station No. 3 indicate that for the average of all six tubes:
 - (a) The plot of temperature around the circumference of the outer tubes contains two lobes with the hot spots near the zero-degree and 180-degree locations.
 - (b) The average heat-transfer coefficient is about 8% lower than would be predicted by the Dittus-Boelter equation. Thus the 2.000-in. BC spacing of the outer fuel tubes gives roughly 7% better heat transfer than the 2.100-in. BC spacing.
 - (c) The minimum heat-transfer coefficient is approximately 6% lower than the average coefficient and, when compared to the coefficient for the 2.100-in. BC configuration, reflects an improvement of about 15%.
 - (d) The ratio of the average maximum-to-minimum heat-transfer coefficient is approximately 1.13 and represents a 70% reduction in temperature variation around the circumference of the tubes compared to the 2.100-in. BC configuration.

3. For the 3.000-in.-ID carbon-steel sleeve, a 2.000-in.-BC spacing of the outer fuel tubes with helical spacers (6 fins each) added at the mid-point of each fuel element resulted in a gross change in the axial temperature profile of the outer tubes. The spacers essentially created a second entrance effect at the spacer location, so that the surface temperature dropped sharply in the immediate vicinity of the spacers. The recovery of temperature downstream of the spacers was slightly steeper than occurred upstream, and the film drop at TC Station No. 3 indicated that the effect of the entrance condition still existed. Results at this station indicated that:
- (a) The plot of temperature around the circumference of the outer rods has a single lobe with the hot spot near the 180-degree location, which is the point closest to the central tube.
 - (b) The average heat-transfer coefficient for this case is approximately 1% above that which would be predicted by the Dittus-Boelter equation, indicating that the addition of spacers increases the average heat-transfer coefficient 15% over that obtained with the 2.100-in. BC and no mid-length spacers.
 - (c) The minimum heat-transfer coefficient for this case is approximately 14% below the Dittus-Boelter coefficient, which is close to that of Case 2 above.
 - (d) The ratio of the average maximum-to-minimum heat-transfer coefficient is approximately 1.35.

It should be further borne in mind that the discussion of Table I and II is for the average results of all six outer tubes. A portion of the variation from one tube to the next is due to the variation of individual-tube electrical resistance and accounts for approximately $\pm 1.5\%$. The additional variation of approximately another $\pm 7\%$ noted at a Reynolds Number of 50,000 is considered inherent in the design, influenced by the non-symmetry of entrance and flow patterns, and likely to occur in the actual design to some extent.

TABLE I
HEAT TRANSFER EQUATIONS

$$Y_1 = N_{Nu} / (N_{Pr})^{0.4}$$

Test Condi- tion	Max. and Min. h	Range	Tube No.	Least Mean Square Equation	Normalized Equation	Average Normalized Equation	$\frac{Y_1 - Y_1}{Y_1} 100\%$		Standard Deviation of Y_1 (Least Mean Square)
							Re=20,000	Re=60,000	
1	Max. h	Upper Limit	2&3	$Y_1 = 0.0307 \text{ Re}^{0.777}$	$Y_1' = 0.0237 \text{ Re}^{0.80}$	$Y_1 = 0.0198 \text{ Re}^{0.80}$	-2.71	+0.3	5.6016
		Lower Limit	1	$Y_1 = 0.0323 \text{ Re}^{0.763}$	$Y_1' = 0.0218 \text{ Re}^{0.80}$		-3.37	+0.3	5.0922
	Min. h	Upper Limit	4	$Y_1 = 0.0106 \text{ Re}^{0.851}$	$Y_1' = 0.0183 \text{ Re}^{0.80}$		+3.96	-0.5	4.7684
		Lower Limit	6	$Y_1 = 0.0085 \text{ Re}^{0.855}$	$Y_1' = 0.0153 \text{ Re}^{0.80}$		+5.62	-0.5	3.7701
2	Max. h	Upper Limit	4	$Y_1 = 0.0310 \text{ Re}^{0.775}$	$Y_1' = 0.0237 \text{ Re}^{0.80}$	$Y_1 = 0.0213 \text{ Re}^{0.80}$	-2.29	+0.2	6.6333
		Lower Limit	1	$Y_1 = 0.0200 \text{ Re}^{0.805}$	$Y_1' = 0.0212 \text{ Re}^{0.80}$		+0.71	-0.06	4.9901
	Min. h	Upper Limit	5	$Y_1 = 0.0150 \text{ Re}^{0.833}$	$Y_1' = 0.0206 \text{ Re}^{0.80}$		+4.15	-0.4	6.5651
		Lower Limit	1	$Y_1 = 0.0134 \text{ Re}^{0.831}$	$Y_1' = 0.0188 \text{ Re}^{0.80}$		+3.18	-0.24	4.1614
3	Max. h	Upper Limit	4	$Y_1 = 0.0155 \text{ Re}^{0.857}$	$Y_1' = 0.0287 \text{ Re}^{0.80}$	$Y_1 = 0.0232 \text{ Re}^{0.80}$	+5.54	-0.6	5.6648
		Lower Limit	3	$Y_1 = 0.0347 \text{ Re}^{0.768}$	$Y_1' = 0.0246 \text{ Re}^{0.80}$		-3.103	+0.3	13.195
	Min. h	Upper Limit	2	$Y_1 = 0.0088 \text{ Re}^{0.880}$	$Y_1' = 0.0209 \text{ Re}^{0.80}$		+7.78	-0.8	7.2084
		Lower Limit	1&5	$Y_1 = 0.0145 \text{ Re}^{0.824}$	$Y_1' = 0.0188 \text{ Re}^{0.80}$		+1.83	-0.2	2.6392
4	Max. h	Upper Limit	1	$Y_1 = 0.0142 \text{ Re}^{0.869}$	$Y_1' = 0.0299 \text{ Re}^{0.80}$	$Y_1 = 0.0236 \text{ Re}^{0.80}$	+6.81	-0.7	10.514
		Lower Limit	3	$Y_1 = 0.0142 \text{ Re}^{0.855}$	$Y_1' = 0.0257 \text{ Re}^{0.80}$		+4.72	-0.5	10.134
	Min. h	Upper Limit	6	$Y_1 = 0.0087 \text{ Re}^{0.878}$	$Y_1' = 0.0202 \text{ Re}^{0.80}$		+7.75	-1.1	9.1906
		Lower Limit	5	$Y_1 = 0.0136 \text{ Re}^{0.827}$	$Y_1' = 0.0183 \text{ Re}^{0.80}$		+2.96	-0.3	5.0073

TABLE II

HEAT TRANSFER EQUATIONS

$$Y_2 = N_{Nu} / (N_{Pr})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}$$

Test Condi- tion	Max. and Min. h	Range	Tube No.	Least Mean Square Equation	Normalized Equation	Average Normalized Equation	$\frac{Y_2 - Y_2'}{Y_2}$ 100%		Standard Deviation of Y_2 (Least Mean Square)
							Re= 20,000	Re= 60,000	
1	Max. h	Upper Limit	3	$Y_2 = 0.0545 \text{ Re}^{0.734}$	$Y_2' = 0.0266 \text{ Re}^{0.80}$	$Y_2 = 0.0224 \text{ Re}^{0.80}$	-5.7	+0.014	6.4179
		Lower Limit	5	$Y_2 = 0.0606 \text{ Re}^{0.716}$	$Y_2' = 0.0244 \text{ Re}^{0.80}$		-7.4	+0.8	3.5946
	Min. h	Upper Limit	4	$Y_2 = 0.0154 \text{ Re}^{0.829}$	$Y_2' = 0.0211 \text{ Re}^{0.80}$		+2.9	-0.3	10.503
		Lower Limit	6	$Y_2 = 0.0156 \text{ Re}^{0.810}$	$Y_2' = 0.0173 \text{ Re}^{0.80}$		+1.1	-0.1	6.2686
2	Max. h	Upper Limit	6	$Y_2 = 0.0415 \text{ Re}^{0.760}$	$Y_2' = 0.0270 \text{ Re}^{0.80}$	$Y_2 = 0.0245 \text{ Re}^{0.80}$	-3.7	+0.4	7.1543
		Lower Limit	1	$Y_2 = 0.0279 \text{ Re}^{0.788}$	$Y_2' = 0.0242 \text{ Re}^{0.80}$		-1.3	+0.1	5.3633
	Min. h	Upper Limit	4	$Y_2 = 0.0206 \text{ Re}^{0.817}$	$Y_2' = 0.0251 \text{ Re}^{0.80}$		+1.8	-0.2	6.9641
		Lower Limit	1	$Y_2 = 0.0184 \text{ Re}^{0.815}$	$Y_2' = 0.0216 \text{ Re}^{0.80}$		+1.6	-0.2	3.9348
3	Max. h	Upper Limit	4	$Y_2 = 0.0262 \text{ Re}^{0.817}$	$Y_2' = 0.0317 \text{ Re}^{0.80}$	$Y_2 = 0.0259 \text{ Re}^{0.80}$	+1.79	-0.13	5.9604
		Lower Limit	3	$Y_2 = 0.0637 \text{ Re}^{0.722}$	$Y_2' = 0.0273 \text{ Re}^{0.80}$		-6.6	+0.7	13.677
	Min. h	Upper Limit	2	$Y_2 = 0.0163 \text{ Re}^{0.834}$	$Y_2' = 0.0235 \text{ Re}^{0.80}$		+3.4	-0.4	5.0697
		Lower Limit	1	$Y_2 = 0.0279 \text{ Re}^{0.776}$	$Y_2' = 0.0214 \text{ Re}^{0.80}$		-2.45	+0.19	2.9049
4	Max. h	Upper Limit	1	$Y_2 = 0.0206 \text{ Re}^{0.843}$	$Y_2' = 0.0329 \text{ Re}^{0.80}$	$Y_2 = 0.0264 \text{ Re}^{0.80}$	+4.41	-0.39	13.003
		Lower Limit	3	$Y_2 = 0.0224 \text{ Re}^{0.824}$	$Y_2' = 0.0291 \text{ Re}^{0.80}$		+2.34	-0.31	11.443
	Min. h	Upper Limit	6	$Y_2 = 0.0116 \text{ Re}^{0.863}$	$Y_2' = 0.0230 \text{ Re}^{0.80}$		+6.29	-0.77	11.587
		Lower Limit	5	$Y_2 = 0.0199 \text{ Re}^{0.804}$	$Y_2' = 0.0207 \text{ Re}^{0.80}$		+0.5	-0.05	6.4216

V. CONCLUSIONS

The first two tests involving a seven-rod cluster with no spacer or air-flow restrictions for its full length clearly indicated the improvement of heat transfer as the diametrical location of the outer six tubes was reduced to a 2.000-in. circle compared to a 2.100-in. circle. The average coefficient improved 7% and the minimum coefficient increased 15%.

The 2.000-in. BC location appears to be near optimum; however, this cannot be a firm conclusion, since the over-all test program was revised in favor of the 2.000-in. BC with spacers at the mid-length of each tube rather than to include additional confirming BC locations.

The addition of the spacer with 6 helical fins at the mid-length of each tube offers improved heat transfer for the reactor application for two reasons. It improves the over-all heat transfer of the outer six tubes at the extreme downstream end of the rig about 8% and causes the hot spot to be located at the 180-degree circumferential point, which is toward the center of the assembly, in contrast to the 0-degree circumferential location for the 2.000-in. BC without spacers. In the reactor the reduction of flux and hence heating in the fuel assembly from outside to center will therefore tend to be compensated by a similar reduction of the heat-transfer coefficient from outside to inside.

The test-result heat-transfer correlation suggested for the extreme downstream position of the fuel element with spacers at the mid-length is:

- (1) $Nu = 0.0232 N_{Re}^{0.80} N_{Pr}^{0.4}$ average for entire circumference
- (2) Maximum = 115% of average at 0 degrees
- (3) Minimum = 85% of average at 180 degrees

VI. TEST RIG

The heat-transfer experiments duplicated the flow geometry of a full-size fuel assembly positioned vertically and secured to a test stand. Plenum chambers were placed at the upstream and downstream ends of the test section. A centrifugal compressor delivered air at approximately 170 F to the test section. Air flow through the test section was in the downward direction. The compressor inlet and the test section exit were open to the atmosphere. An orifice meter was installed between the compressor discharge and the test-section inlet to measure the flow rate. (See Drawing E-110-R&D, Heat Transfer Test Assembly, and associated drawings.)

Air-temperature measurements in the test rig were made at the orifice, at the inlet of the test section, at three axial positions within the test specimen, and at the outlet of the test section. The air-temperature measurements were taken with both thermocouples and mercury-in-glass thermometers, except for the measurements within the test specimen, which were obtained with thermocouples only. Thermocouple temperature readings were read on a direct-reading Brown indicator.

Flow measurements through the test rig were made by means of a concentric orifice plate mounted within standard orifice flanges. Both the differential pressure and the static pressure downstream of the orifice were measured by means of manometers. Flow control was achieved by means of two butterfly valves. One valve was located immediately downstream of the compressor discharge and vented to atmosphere; the other valve was located immediately upstream of the heat-transfer test section and functioned as a throttling valve.

Heat flux in the thin tube walls was established by passing electric current through the seven tubes connected in series. The power was supplied to the test section by an a-c motor-generator set. Electrical output from the generator unit to the test section was variable over the range from 15 to 70 volts at 60 cycles (nominal) with a maximum power not exceeding 15 kw.

Two protective measures to prevent damage to the heat-transfer test section were incorporated in the design of the test rig. The first protective measure consisted of a temperature-alarm system. A thermocouple sensing element was imbedded in the wall of the central tube of the assembly, and a second thermocouple monitored the gas outlet temperature. If either of the two temperatures exceeded a predetermined temperature level, a temperature-control switch was actuated to trip the motor-generator set. The other protective device consisted of a pressure-differential element installed across the orifice-flow measuring device. If the flow through the orifice resulted in a pressure differential across the orifice below a predetermined level, a pressure switch was actuated to trip the motor-generator set.

A more detailed description of the heat-transfer test loop and equipment is contained in Appendix C and Drawing SK-D-143, Schematic - Heat Transfer Flow Sheet.

VII. TEST SPECIMEN

The full-size heat-transfer test specimen duplicated the length of constant-cross-section flow area of the actual fuel assembly, Reference Drawing SK-MS-15 of A-C Study No.100*, by spacing seven full-size tubes within a 3-in. bore of a 28-in.-long sleeve. The tubular fuel elements were spaced on a triangular pitch with one tube on the axial centerline of the carbon-steel sleeve and the remaining six tubes evenly spaced on a nominal bolt circle. Spacers were provided between the tubes at each end of the sleeve length. Entrance and exit geometry were not duplicated; however, an attempt was made to produce the effects of the actual inlet conditions on the downstream heat transfer by creating a similar over-all fluid-velocity change at the test-specimen inlet to the heated section. The general arrangement of the test specimen is shown on Drawing E-110-R&D. Details of the carbon steel sleeve are shown on Drawing D-121-R&D.

Ordinarily, duplicating exact entrance conditions would be considered essential; however, major interest is centered on the heat transfer at the discharge end of the assembly, where the benefits of the turbulence of the entrance condition have essentially vanished. Also, in certain tests, the addition of helical-finned spacers at the mid-point of each tube length created a new entrance condition for the second half of the tube which further minimized the effect of the original entrance condition on heat transfer near the exit end or critical section of the tube length.

The heated portions of the test fuel elements were hollow stainless-steel tubes with a 0.71-in. ID, a 0.75-in. OD, and a 30-in. length. For reactor operation, the stainless-steel tubes will contain UO_2 pellets. Tubular copper busses were silver-soldered to the ends of each fuel-element tube as shown on Drawing D-112-R&D. Heat within the stainless tubes was created by passing electric current through the tubes. The bore of the copper busses matched that of the stainless-steel tubes, and since the copper busses passed through the inlet and exit plenums to the outside of the rig, access to the inner surface of the stainless-steel tube was possible from either end. Temperature readings of four of the simulated fuel elements were taken with a glass thermocouple probe inserted inside each tube. The probes were capable of being moved the entire axial length of the fuel elements. Details of the glass thermocouple probe are shown on Drawing SK-D-151.

The remaining three tubes, two outer and one central, were provided with 12 fixed thermocouples at 30-degree intervals around the periphery of each tube at each of three axial positions along the tube length, as shown by the placement of the locating holes on Drawing D-120-R&D.

* A-C EGCR Title 1 Study No. 100, Fuel Assembly for the Experimental Gas Cooled Reactor, August 12, 1959.

A special technique was used to fasten the fixed thermocouple, which provided a precisely-located junction with no disturbance to the flow of fluid. This was done by threading each of the 36 thermocouples through the ID of one end of a given tube, with its two wires drawn into precisely-located 0.020-in.-diameter holes (drilled) in the tube wall. With the thermocouple wires held in place, silver solder was used to anchor the wires and to form the thermocouple junction. Care was taken to avoid excess solder, and the outer surface was lightly buffed to restore the original smooth contour of the tube.

Gas-temperature readings from three axial locations in the test specimen were provided by thermocouples extending radially through the carbon-steel sleeve wall into the gas stream. Space limitations within the carbon-steel sleeve precluded attaching thermal radiation shields to the thermocouples. The thermocouples were movable so as to make a radial traverse from the sleeve ID to the center tube.

Voltage measurements across each tubular fuel element, current flow in the series circuit, and power input into the test specimen were recorded for all test runs. The instruments used to obtain these measurements are described in Appendix C.

Heat-transfer tests were also made by substituting a glass sleeve in place of the previously-described carbon-steel sleeve. The glass sleeve conformed in all essential respects to the carbon-steel sleeve. However, there were minor differences between the two sleeves:

- (1) the glass sleeve did not permit the insertion of thermocouples into the gas stream;
- (2) bow measuring probes were not included;
- (3) the spacers between tubes at each end of the sleeve length were of a different design.
(For the carbon-steel sleeve the end spacers were tubular, as shown on Drawing D-114-R&D, Item E. For the glass sleeve the spacers were flat strips, as shown on Drawing SK-D-159.)

By merely changing the micarta locating plates, the spacing of the tubes could be altered to place the outer six tubes on a 2.000, 2.100, 2.170, 2.200, or a 2.300-in. bolt circle. The glass sleeve was made with a 3.000-in. inside diameter, whereas carbon steel sleeves were provided for each of three bore sizes, 3.000; 3.125, and 3.250-in. diameters. The design was firmed using a 3.000-in. sleeve ID, and tests of the 3.125 and 3.250-in. bores were omitted in favor of re-running tests with spacers added at the mid-point of the tube length.

The added spacers are shown on Drawing SK-FF-136, Item 2,
and the location of the spacers on the tube is shown on SK-D-150.

VIII. DISCUSSION

The open-rig construction of the seven tubes used in the heat-transfer rig offered a very flexible arrangement, since any point along the entire surface could be explored with a temperature probe. By use of such probes in four of the outer six tubes, axial data was obtained along the full length of the tubes for a limited number of runs. The fixed thermocouples embedded in the other three tube walls at 30-deg circumferential increments at three axial locations along the tube length limited data to these points. During all runs, tube-temperature data was recorded from the 12 circumferentially-located thermocouples at each of three stations for two outer tubes and the center tube. The probes, one in each of the four remaining tubes, were generally located opposite the fixed thermocouple near the exit end of the test rig, called TC Station No. 3, 26-inches downstream of the upper or entrance ends of the 30-inch stainless steel tubes. While all of the data recorded has been used in analysis, the majority of effort was concentrated on the data obtained on all seven tubes at TC Station No. 3, which corresponds to the high-temperature regions of the fuel element.

In general, the electric current flowing in the tubes, connected in series, was regulated at each air-flow setting so that the film drop between the average gas temperature and the average tube surface at TC Station No. 3 was 250 F. With an average bulk gas temperature of 250 F and tube-surface temperature of 600 F, the ratio of absolute temperatures of tube surface to gas temperature closely matched that expected in the reactor and will tend to minimize the effect of power and film drops in applying the data. A few tests were also run with the electric current and air flow regulated to provide film drops as low as 50 F.

The heat-transfer correlations plotted on Figures 1 to 81 in Appendix A were prepared from data obtained near the exit end of the fuel-assembly test specimen, the exact axial location being identified as Fixed Thermocouple Station No. 3 on Drawing SK-D-150.

Correlations for local heat transfer are presented for two circumferential positions for the given axial location of each of the seven tubular fuel elements of the test fuel assembly. The two positions were selected on the basis of maximum and minimum tube-surface temperature. The heat-transfer data were correlated by means of three conventional equations:

$$N_{Nu} = C (N_{Re})^x (N_{Pr})^{0.4} \text{ --- --- --- --- --- (1)}$$

$$N_{Nu} = C (N_{Re})^x (N_{Pr})^{0.33} \frac{\mu_b}{\mu_s}^{0.14} \text{ --- --- --- (2)}$$

$$N_{Nu} = C (N_{Re})^x (N_{Pr})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575} \text{ --- --- --- (3)}$$

The plots contained in Appendix A are for the first and third correlations listed above. Results based on the second correlation are not presented because they do not differ from the results obtained for the first correlation.

The local heat-transfer coefficients around the periphery of the fuel elements were computed from the following equation:

$$h = \frac{q''' \Delta y}{t_s - t_b} + \frac{k \Delta y}{\Delta x^2 (t_s - t_b)} (t_{(s-1)} + t_{(s+1)} - 2t_s) \quad (4)$$

where:

- h = local heat-transfer coefficient, Btu/hr-ft²-°F
- q''' = volumetric heat generation, Btu/hr-ft³
- Δy = fuel-tube wall thickness, ft
- Δx = $\frac{\text{Total Clad Circumferential Length}}{\text{Number of Circumferential Segments}}$
- k = thermal conductivity of fuel-tube materials $\frac{\text{Btu}}{\text{hr-ft-°F}}$
- t_b = bulk-coolant temperature, °F
- t_s = tube-surface temperature, °F, at a given circumferential position
- $t_{(s+1)}$ and $t_{(s-1)}$ = tube-surface temperature, °F, at circumferential positions neighboring t_s

Physical properties of the coolant, used in evaluating the dimension parameters of Equations 1, 2, 3, and 4, were evaluated at bulk conditions. All physical properties of the coolant were taken from Reference 8.

The second term on the right-hand side of Equation (4) takes into account the effect of circumferential conduction of heat in the fuel-tube cladding. Circumferential conduction of heat in the fuel-tube clad may or may not be significant, depending upon the magnitude of the fuel-tube circumferential temperature variation, the conductivity of the metal, and the film coefficient. The fuel-tube circumferential temperature variations encountered in the heat-transfer air tests were such that the effect of circumferential conduction of heat must be accounted for in calculating the local heat-transfer coefficients. The air test is made with a uniform heat flux and a film drop of 250 F. When, under these conditions, the temperature variation around the tube wall measures 60 F, it may be shown by calculation that without the effect of thermal conduction through the circumference of the tube wall this variation would amount to 100 F. However, in the reactor with helium as the coolant, heat conducted through the metal will be insignificant, because the ratio of conductivity of the metal to that of the helium film is so small. Very little if any reduction of temperature variation will occur.

The conventional definition of equivalent diameter for flow — four times the free-flow area divided by the total wetted perimeter — was used to evaluate the Reynolds Number and the Nusselts Number. The method of analysis is covered more fully in Appendix B.

The heat-transfer coefficients calculated by means of Equation (4) were based on the average fuel-tube electrical power. The total power input into the test specimen was recorded by means of a wattmeter, and the total power was divided by the number of fuel elements in order to obtain the average power per fuel tube. During the earlier phases of testing, a difference of about 25% was noted between three of the tube voltmeter readings and the voltmeter readings of the other four tubes when a carbon-steel sleeve was used. The difference was only 8% when the glass sleeve was used. By reconnecting leads and physically switching tubes, it was proved that the readings were erroneous and did not reflect difference in power levels of the tubes but were caused by induced voltages in the lead wires. It was not until the latter phase of the test program that a method of measurement of tube voltages was perfected to cancel out the induced voltages by bringing both voltmeter leads to the bottom of the rig with one attached directly to the lower end of the tube to be measured. The second lead was brought up through the inside of one of the tubes and then connected to the upper end of the tube to be measured. With this technique the induced voltages were eliminated. The individual voltage-reading variation was then less than 3% and closely matched the variation of individual-tube electrical-resistance measurements.

This same induced-voltage error was present in the wattmeter to a lesser degree, although the wattmeter also included the small electrical-jumper losses. By comparing the product of the sum of the correct individual tube-voltage readings times the ampere readings with the wattmeter readings, it was found that wattmeter readings were high by 4% and 5% for the carbon-steel and glass-sleeve cases, respectively.

Using the refinement noted above and including a 0.25 kw addition to the sensible heat measurement established as heat losses from the rig, the heat balance of electrical power vs sensible heat checked within 4%.

A radial traverse of the bulk-gas temperature was made with thermocouple probes located one inch downstream of the fixed Thermocouple Stations 1, 2, and 3. The probes passed between two adjacent outer tubes and measured the bulk-gas temperature from the center tube out to the sleeve bore. Figures 94, 95, and 96 indicate that the temperature variation was materially increased at Station 3 as the bolt-circle location of the outer tubes was decreased to 2.000 inches from 2.100 inches. The addition of the mid-plane spacers had little effect on the bulk-gas temperature distribution along the measured radial path.

Plots of the outer fuel-element circumferential temperature at axial Station TC 3 are presented on Figures 82 to 84 for one run of each test set-up. The circumferential temperature plots are for average film drops of 250 F at Reynolds Numbers of

about 20,000 to 60,000 in increments of 10,000. For those cases where the Reynolds Number was approximately 50,000, the circumferential-temperature plots are presented for all seven fuel elements of the fuel assembly.

Figure 82 is a circumferential-temperature plot for Test Set-Up No. 1 (3.000-in.-ID carbon-steel sleeve, 2.100-in.-BC spacing, with central spacers omitted). It clearly indicates that the fuel-element surface temperature has a single lobe with the maximum at zero degrees and the minimum temperature at about 180 degrees. Zero is the point closest to the sleeve wall, and conversely 180 degrees is the point closest to the center tube. The variation in tube circumferential temperature for this case is about 60 F. At constant heat flux around the periphery of the tube, if the effect of radial conduction in the tube wall were considered, the variation in tube circumferential temperature would increase to about 100 F, assuming that the heat-transfer coefficient is independent of power and remains constant in both cases.

The circumferential-temperature plot for the second test set-up (3.000-in.-ID carbon-steel sleeve, 2.000-in.-BC spacing, and spacers omitted) is contained in Figure 83. The fuel-element circumferential temperature variation for this case has two lobes; the two hot spots occur at about 0 and 180 degrees and the minimum tube temperatures occur at about 60 and 270 degrees. A distinct temperature grouping of tubes is apparent. The temperature distribution curves for Tubes 4 and 5 are similar and indicate lower surface temperatures than those found on Tubes 1, 3, and 6. Differences in tube electrical resistivity partially account for this behavior. For Tubes 4 and 5, the magnitude of the circumferential temperature variation is about 15 F; the variation would increase to about 34 F at constant heat flux if tube-wall conductivity were negligible in the testing.

Figure 84 contains the circumferential-temperature plot for the third test set-up (3.000-in.-ID carbon-steel sleeve, 2.000-in.-BC spacing, and helical spacers (6 fins) at the fuel-element mid-point, as shown on Drawing SK-FF-136, Item 2). The circumferential temperature variation has only one lobe, and the maximum and minimum temperatures occur at about 180 and 330 degrees on the tube surface -- directly opposed to the locations found in the first set-up. The magnitude of the measured temperature variation is about 50 F. This would increase to about 90 F at constant heat flux around the periphery of the tube.

By comparing the axial temperature-profile plot of Figure 88 with that of Figure 87, it is clear that the addition of the spacers at the mid-point of the length of each tube has, in essence, created a second entrance effect at the spacer location. The tube-surface temperatures dip appreciably at the immediate location of the spacers. The temperature downstream recovers more rapidly than in the first half of the tube length, although the film drop at TC Station No. 3 has not developed fully.

For the EGCR fuel-assembly design conditions, represented by the third test condition -- 3.000-in.-ID fuel-assembly sleeve and 2.000-in.-BC location, with helical-finned (6 fins) spacers

at the fuel tube mid-point — the average heat-transfer coefficient at TC No. 3, determined from test data, using the normalized equations, is identical to that which would be predicted by the Dittus-Boelter equation. The maximum and minimum heat-transfer coefficients vary from the average by about 15%.

In summary, the introduction of the short spacers at the mid-point of the tube lengths has resulted in a second entrance effect at the mid-length, improved the average heat transfer at Station TC 3, produced (instead of two lobes) a single-lobe profile on tube circumference with its hot spot at the point nearest the center tube, and increased the circumferential variation by a factor of about 3 to 1.

The fourth test condition contains data for runs made with a glass sleeve substituted for the carbon-steel sleeve. The use of a glass sleeve stems originally from the designer's request that data be obtained on test assemblies having brazed helical spacers at the mid-point of each alternate fuel tube of the outer six fuel tubes. This requirement would have necessitated a fuel sleeve of non-conducting material. In the actual tests, however, the helical spacers were cemented on the fuel tubes with Saurisen cement, which is also an effective electrical insulator. The glass sleeve was still desirable, since it afforded an opportunity for visual inspection of the cemented spacers. The data obtained with a glass sleeve placed in the test set-up is in agreement with the data obtained using a carbon-steel sleeve. Equations tabulated in Table I substantiate this conclusion.

Attempts were made to correlate the heat-transfer data along the length of the fuel tubes. For the test conditions without helical spacers at the fuel tube mid-point, a factor of $(L/De)^{0.1}$ will accurately correlate the heat-transfer data downstream of the fuel-tube mid-point and can be injected into the correlation if desired. Figure 91 contains a plot of h versus length for the second test set-up without helical spacers. The introduction of helical-finned spacers at the fuel-element mid-point, however, upset establishment of the heat-transfer film, requiring treatment of two separate entrance locations, so that satisfactory correlations of axial fuel-tube temperature by means of the L/De approach were not obtained. As previously mentioned, Figure 88 of Appendix A for a typical case with helical-finned spacers at the fuel-element mid-point illustrates that the film drop and, hence, the heat-transfer coefficient has not fully established its asymptotic value upstream of the helical spacers. Over the downstream portion of the fuel tube, also, the second heat-transfer film has not established its asymptotic value.

Equations at TC Station 3 generated on the basis of least-mean-square analysis for each of the plotted heat-transfer correlation curves in Figures 1 and 81 are shown on each figure. Selected equations for the maximum and minimum heat-transfer coefficient are also tabulated in Table I and II of results. The standard deviation of each equation obtained by the method of

least squares, assuming a power-function relationship of the data, is also shown in Tables I and II. With respect to the standard deviations calculated for each equation, it is significant to note that the average standard deviation of all these equations is about 4, which indicates a tight grouping of the data around the least-mean-square equation. The program used in the Bendix calculator in the course of the least-square analysis included linear, quadratic, exponential, and logarithmic functions, as well as the power function. Of the four types of functions, it was interesting to note that a quadratic actually fits the data best. This is considered to be attributable to a slight change in slope of the plotted data noted at the lower Reynolds Number and may actually indicate that a separate curve or power function could be justified for the lower range. However, the usual conventional power function is presented for the heat-transfer data. The trends noted above are not of sufficient magnitude to justify deviation from the standard presentation of heat-transfer data.

The equations obtained for the heat-transfer correlations of individual tubes have varying, though closely uniform, coefficients and exponents. The slope of these equations, which is a measure of the exponent of the Reynolds Number, was normalized to $8/10$ at a Reynolds Number of 50,000. Results calculated by means of the normalized equations were checked for accuracy by comparing with the actual experimental results. The deviations of the normalized equation from the experimental results, as reflected by the least-mean-square equations, are tabulated in Tables I and II for the extreme values of Reynolds Number covered in the experiments. At a Reynolds Number of 10,000, the deviation of the normalized equation is acceptable and usually does not exceed 5%. However, excessive values (about 14%) have been observed in isolated cases. At Reynolds Numbers of 20,000, the average deviation is about 4%, while, by definition, a Reynolds Number of 50,000 yields a deviation of zero.

The equations tabulated in Results, Tables I and II, cover the range of both the maximum and minimum heat-transfer coefficient for each test set-up investigated. A composite plot of the least-mean-square equation for each fuel tube, at both the maximum and minimum heat-transfer coefficient, was prepared for each test condition. The fuel tubes having the highest and the lowest heat-transfer coefficients at a Reynolds Number of 50,000, were selected from the composite plot. The normalized equations for each of the fuel tubes selected were calculated in the manner previously described. The normalized equations afford an easier means of comparing and contrasting the heat transfer for the test conditions investigated.

The following discussion with respect to the heat-transfer correlations for the various test conditions investigated will be made with reference to the Dittus-Boelter equation. Although the Dittus-Boelter equation is applicable for average heat-transfer coefficients, it also provides a base to compare the correlations for local coefficients.

For the first test condition (3.000-in.-ID carbon-steel fuel-assembly sleeve, 2.100-in.-BC spacing, and helical spacers omitted) the average heat-transfer coefficient was about 14% lower than would be predicted by using the Dittus-Boelter equation. Also, of the four test conditions investigated, the first test condition gave the minimum heat-transfer coefficient for one of the tubes. This was about 35% lower than would be predicted by the Dittus-Boelter equation. The average minimum heat-transfer coefficient for all of the outer tubes is about 28% lower than the over-all average Dittus-Boelter coefficient.

A change of bolt-circle diameter to 2.000 in., the second test condition, improved the average heat-transfer coefficient approximately 7%. This is about 7.4% lower than would be predicted by the Dittus-Boelter equation. The maximum and minimum coefficient varied from the average by about 6%.

The EGCR Title I fuel-assembly design condition required a 3.000-in. sleeve ID, 2.000-in.-BC location of the outer six (0.750-in.-OD) fuel tubes surrounding the central fuel tube, with each of the seven fuel tubes containing the short 45-deg helical-finned spacers at the mid-point. This is shown on Drawing SK-FF-136, Item 2. The average heat-transfer coefficient determined from test data, using normalized equations, is identical within 1% with that predicted by the Dittus-Boelter equation. The maximum and minimum heat-transfer coefficients at Thermocouple Station No. 3 vary from the average by about 15%.

The average heat-transfer coefficient for each test condition may be calculated by using the average of the maximum and minimum heat-transfer equations contained in Tables I and II in the Results section of this report. The average circumferential temperature of the fuel tubes was compared to the mean based on the maximum and minimum temperature. In all cases, with negligible exceptions, the average temperature based on the maximum and minimum tube temperature truly represented the average tube temperature.

The heat-transfer correlation involving the ratio of bulk-coolant temperature to fuel-tube surface temperature is summarized in Table II of Results. A 0.575 exponent improved the correlation of those test runs performed at varying tube-surface temperatures. The ratio of bulk-coolant temperature to fuel-tube surface temperature was not varied over a wide range during the tests. Over the limited range covered, analysis of the data indicated that an exponent of 0.66 on the ratio would make a slight, almost insignificant improvement. It should be recognized that the ratio of absolute bulk to surface temperature in the air-loop test closely corresponds to that expected in the reactor helium case. As noted from the standard deviations listed in Table II (Results section), the temperature-ratio correlation did not improve the over-all heat-transfer correlation when compared to the simpler Dittus-Boelter approach (Table I). Since the equations contained in Table I do not involve a trial-and-error calculation (as they would if the temperature ratio correlation were used), it would

appear that the equations presented in Table I would be preferred when calculating the average and minimum fuel-tube temperature at EGCR operating conditions.

The mechanical accuracy of any given test point has been predicted, based upon measurements and instrument tolerances used in the experiments. The individual tolerances are listed as:

D_s	= sleeve diameter = 3.016 in. $\pm$ 0.001 in.
d_t	= tube diameter = 0.752 in. $\pm$ 0.001 in.
T	= film drop = as measured $\pm$ 5 deg.
T	= gas temp. reading as measured $\pm$ 3 deg.
P	= gas pressure reading = reading $\pm$ 0.1 in. Hg
d_o	= orifice diameter = 2.0128 in. $\pm$ 0.0002 in.
d_p	= flange bore = 4.026 in. $\pm$ 0.004 in.
C_o	= coefficient of discharge = $\pm$ 0.55%
Y	= orifice expansion factor = $\pm$ 0.0045%
F	= velocity of approach = $\pm$ 0.09%
V_i	= individual tube voltage instrument = $\pm$ 1.9% at low reading = $\pm$ 0.84% at high reading
A	= amperage reading = $\pm$ 1.7% at low reading = $\pm$ 0.77% at high reading

When the tolerance factors are applied directly to the correlations, an over-all mechanical inaccuracy of $\pm$ 6% at the higher readings and 7.7% at the lower range is expected, predicated on the occurrence of all factors simultaneously at their peak value, resulting in a maximum error. Through use of the square-root-of-the-sum-of-the-square law, the expected over-all inaccuracy would be 3 to 4% for any given test point.

The scatter or deviation of test points from the curve selected by the method of least squares must also be evaluated. If two standard deviations, or approximately 10 units (see chart in Results), is used as the scatter criterion, the uncertainty due to scatter is approximately 10% at a Reynolds Number of 50,000 and approximately 20% at a Reynolds Number of 20,000.

Allowing the factors described in the two preceding paragraphs results in an over-all accuracy prediction of approximately 25% at the lower Reynolds Numbers and 14% at Reynolds Numbers at or above 50,000.

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X. NOMENCLATURE

A	=	coolant flow area, ft ²
C _v	=	specific heat at constant volume, BTU/lb-°F
C _p	=	specific heat at constant pressure, BTU/lb°F
De	=	equivalent diameter for flow, ft
g _c	=	conversion factor for gravity, ft- $\frac{\text{lbm}}{\text{lb-sec}^2}$
G	=	mass flow, lb/ft ²
h	=	heat-transfer coefficient, BTU/hr-ft ² -°F
k	=	conductivity of coolant, BTU/°F-ft
K	=	ratio of specific heats, = C _p /C _v
N _{Nu}	=	Nusselt number = $\frac{h De}{K}$, dimensionless
N _{Pr}	=	Prandl number = $\frac{C_{pu}}{K}$, dimensionless
N _{Re}	=	Reynolds number, $\frac{G De}{\mu}$, dimensionless
q'''	=	volumetric heat generation, BTU/ft ³ -hr
q''	=	surface-area heat generation, BTU/ft ² -hr
q	=	heat input, BTU/hr
t _b	=	coolant bulk temperature, °F
t _s	=	tube-surface temperature, °F
TC Station No.1	=	defines axial location of fixed thermocouples in tube surfaces near entrance (See Dwg. SK-D-150)
TC Station No.2	=	defines axial location of fixed thermocouples in tube surfaces near center of tube length
TC Station No.3	=	defines axial location of fixed thermocouples in tube surfaces near exit end
μ	=	viscosity, lb/hr-ft

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Appendix A

Heat-Transfer Data Curves

DESCRIPTIVE INDEX OF FIGURES

Fig. No.	Tube No.	Type Curve	Test No.	Run No.'s	Set Up Description							Sleeve Mat'l	End Spacers
					Sleeve I.D.	Tube O.D.	Tube B.C.	Spacers at Midlength					
								Present	Vaness		Dwg. No.		
									No.	Type			
1 & 2	1 - 6	Y ₁ Correlation	1	22-50	3.000	0.752	2.10	No				Carbon	Tubular
3 & 4	1 - 6	Y ₂ Correlation	1	22-50	3.000	0.752	2.10	No				Steel	↓ Flat
5 & 6	1 - 6	Y ₁ Correlation	2	51-84	3.000	0.752	2.00	No				Carbon	
7 & 8	1 - 6	Y ₂ Correlation	2	51-84	3.000	0.752	2.00	No				Steel	
9 & 10	1 - 6	Y ₁ Correlation	3	88-121	3.000	0.752	2.00	Yes	6	45°Hel.	SK-FF-136	Carbon	
11 & 12	1 - 6	Y ₂ Correlation	3	88-121	3.000	0.752	2.00	Yes	6	45°Hel.	SK-FF-136	Steel	↓ Flat
13 & 14	1 - 6	Y ₁ Correlation	4	122-172	3.000	0.752	2.00	Yes	6	45°Hel.	SK-FF-136	Glass	
15 & 16	1 - 6	Y ₂ Correlation	4	122-172	3.000	0.752	2.00	Yes	6	45°Hel.	SK-FF-136	↓	
Individual Tube Curves													
17	1	Y ₁ Correlation	1	22-50	3.000	0.752	2.10	No				Carbon	Flat
18	2	Y ₁ Correlation	1	↓	↓	↓	↓	↓				Steel	↓
19	3	Y ₁ Correlation	1	↓	↓	↓	↓	↓				↓	↓
20	4	Y ₁ Correlation	1	↓	↓	↓	↓	↓				↓	↓
21	5	Y ₁ Correlation	1	↓	↓	↓	↓	↓				↓	↓
22	6	Y ₁ Correlation	1	↓	↓	↓	↓	↓				↓	↓
23, 24	7	Y ₁ Correlation	1	↓	↓	↓	↓	↓				↓	↓
25	1	Y ₂ Correlation	1	22-50	3.000	0.752	2.10	No				Carbon	Flat
26	2	Y ₂ Correlation	1	↓	↓	↓	↓	↓				Steel	↓
27	3	Y ₂ Correlation	1	↓	↓	↓	↓	↓				↓	↓
28	4	Y ₂ Correlation	1	↓	↓	↓	↓	↓				↓	↓
29	5	Y ₂ Correlation	1	↓	↓	↓	↓	↓				↓	↓
30	6	Y ₂ Correlation	1	↓	↓	↓	↓	↓				↓	↓
31, 32	7	Y ₂ Correlation	1	↓	↓	↓	↓	↓				↓	↓
33	1	Y ₁ Correlation	2	51-84	3.000	0.752	2.00	No				Carbon	Tubular
34	2	Y ₁ Correlation	↓	↓	↓	↓	↓	No				Steel	↓
35	3	Y ₁ Correlation	↓	↓	↓	↓	↓	No				↓	↓
36	4	Y ₁ Correlation	↓	↓	↓	↓	↓	No				↓	↓
37	5	Y ₁ Correlation	↓	↓	↓	↓	↓	No				↓	↓
38	6	Y ₁ Correlation	↓	↓	↓	↓	↓	No				↓	↓
39, 40	7	Y ₁ Correlation	↓	↓	↓	↓	↓	No				↓	↓
41	1	Y ₂ Correlation	2	51-84	3.000	0.752	2.00	No				Carbon	Tubular
42	2	Y ₂ Correlation	↓	↓	↓	↓	↓	No				Steel	↓
43	3	Y ₂ Correlation	↓	↓	↓	↓	↓	No				↓	↓
44	4	Y ₂ Correlation	↓	↓	↓	↓	↓	No				↓	↓
45, 46	5	Y ₂ Correlation	↓	↓	↓	↓	↓	No				↓	↓
47	6	Y ₂ Correlation	↓	↓	↓	↓	↓	No				↓	↓
48, 49	7	Y ₂ Correlation	↓	↓	↓	↓	↓	No				↓	↓

Fig. No.	Tube No.	Type Curve	Test No.	Run No.'s	Set Up Description							Sleeve Mat'l	End Spacers
					Sleeve I.D.	Tube O.D.	Tube B.C.	Spacers at Midlength					
								Vanes					
								Present	No.	Type	Dwg. No.		
50 51 52 53 54 55 56, 57	1 2 3 4 5 6 7	Y ₁ Correlation ↓	3 ↓ ↓ ↓ ↓ ↓ ↓	88-121 ↓ ↓ ↓ ↓ ↓ ↓	3.000 ↓ ↓ ↓ ↓ ↓ ↓	0.752 ↓ ↓ ↓ ↓ ↓ ↓	2.00 ↓ ↓ ↓ ↓ ↓ ↓	Yes ↓ ↓ ↓ ↓ ↓ ↓	6 ↓ ↓ ↓ ↓ ↓ ↓	45°Hel. ↓ ↓ ↓ ↓ ↓ ↓	SK-FF-136 ↓ ↓ ↓ ↓ ↓ ↓	Carbon Steel ↓ ↓ ↓ ↓ ↓ ↓	Tubular ↓ ↓ ↓ ↓ ↓ ↓
58 59 60 61 62 63 64, 65	1 2 3 4 5 6 7	Y ₂ Correlation ↓	3 ↓ ↓ ↓ ↓ ↓ ↓	88-121 ↓ ↓ ↓ ↓ ↓ ↓	3.000 ↓ ↓ ↓ ↓ ↓ ↓	0.752 ↓ ↓ ↓ ↓ ↓ ↓	2.00 ↓ ↓ ↓ ↓ ↓ ↓	Yes ↓ ↓ ↓ ↓ ↓ ↓	6 ↓ ↓ ↓ ↓ ↓ ↓	45°Hel. ↓ ↓ ↓ ↓ ↓ ↓	SK-FF-136 ↓ ↓ ↓ ↓ ↓ ↓	Carbon Steel ↓ ↓ ↓ ↓ ↓ ↓	Tubular ↓ ↓ ↓ ↓ ↓ ↓
66 67 68 69 70 71 72, 73	1 2 3 4 5 6 7	Y ₁ Correlation ↓	4 ↓ ↓ ↓ ↓ ↓ ↓	121-177 ↓ ↓ ↓ ↓ ↓ ↓	3.000 ↓ ↓ ↓ ↓ ↓ ↓	0.752 ↓ ↓ ↓ ↓ ↓ ↓	2.00 ↓ ↓ ↓ ↓ ↓ ↓	Yes ↓ ↓ ↓ ↓ ↓ ↓	6 ↓ ↓ ↓ ↓ ↓ ↓	45°Hel. ↓ ↓ ↓ ↓ ↓ ↓	SK-FF-136 (Part II) ↓ ↓ ↓ ↓ ↓ ↓	Glass ↓ ↓ ↓ ↓ ↓ ↓	Flat ↓ ↓ ↓ ↓ ↓ ↓
74 75 76 77 78 79 80, 81	1 2 3 4 5 6 7	Y ₂ Correlation ↓	4 ↓ ↓ ↓ ↓ ↓ ↓	121-177 ↓ ↓ ↓ ↓ ↓ ↓	3.000 ↓ ↓ ↓ ↓ ↓ ↓	0.752 ↓ ↓ ↓ ↓ ↓ ↓	2.00 ↓ ↓ ↓ ↓ ↓ ↓	Yes ↓ ↓ ↓ ↓ ↓ ↓	6 ↓ ↓ ↓ ↓ ↓ ↓	45°Hel. ↓ ↓ ↓ ↓ ↓ ↓	SK-FF-136 (Part II) ↓ ↓ ↓ ↓ ↓ ↓	Glass ↓ ↓ ↓ ↓ ↓ ↓	Flat ↓ ↓ ↓ ↓ ↓ ↓
82 83 84 85	1 - 7 1 - 7 1 - 7 1 - 7	Circum. Temp at T.C. No. 3 (Raw Data)	1 2 3 4	40 61 103 131	3.000 ↓ ↓ ↓	0.752 ↓ ↓ ↓	2.000 ↓ ↓ ↓	No No Yes Yes	 6 6	 45°Hel. 45°Hel.	 SK-FF-136 (Part II)	Carbon Steel C.S. Glass	
86 87 88 89	 	Temp vs Circum. Temp vs Axial	1 2 3 4	32 72 106 131	3.000 ↓ ↓ ↓	0.752 ↓ ↓ ↓	2.000 ↓ ↓ ↓	No No Yes Yes	 6 6	 45°Hel. 45°Hel.	 SK-FF-136 (Part II)	Carbon Steel C.S. Glass	

Fig. No.	Tube No.	Type Curve	Test No.	Run No.'s	Set Up Description								Sleeve Mat'l	End Spacers
					Sleeve I.D.	Tube O.D.	Tube B.C.	Spacers at Midlength						
								Vaness						
								Present	No.	Type	Dwg. No.			
90	4	h vs θ	1	40	3.000	0.752	2.000	No				Carbon		
91	5		1	40				No				Steel		
92	4		2	61				No						
93	5		2	61				No						
94	4		3	103				Yes	6	45°Hel.	SK-FF-136		Glass	Flat
95	5		3	103				Yes	6	45°Hel.	(Part II)			
96	4		4	131				Yes	6	45°Hel.	SK-FF-136			
97	5		4	131				Yes	6	45°Hel.	(Part II)			
98		Bulk Gas Temp vs Radial Position	1	46			2.100	No			Carbon	Tubular		
99			2	61			2.000	No			Steel
100			3	105			2.000	Yes	6	45°Hel.	SK-FF-136 (Part II)			
101		h vs length	1	32	3.000	0.752	2.100	No			Carbon	Tubular		
102			2	72			2.000	No			Steel
103			3	106				Yes	6	45°Hel.	SK-FF-136		C.S	
104			4	131				Yes	6	45°Hel.	(Part II)		Glass	Flat

1000

FIGURE 2
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER
TUBES NO. 1-6 RUNS NO. 22-50

Test Assembly No.-----1
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.100
 (No Spacers at Mid-length)

300

2.5

200

1.5

100

 N_{NU} $(N_{PR})^{0.4}$

9

8

7

6

5

4

3

TUBE #4
 TUBE #2
 TUBE #3.5
 TUBE #5
 TUBE #6
 TUBE #1.2

Minimum h

ALLIS CHALMERS MFG. CO.
 NUCLEAR POWER DEPT.
 ATOMIC ENERGY DIV.
 WASH. 11, D.C.

1.5

A-2

10

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

1000

FIGURE 3
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NOS. 1-6 RUNS NO. 22-50

Test Assembly No. ----- 1
Sleeve Material ----- Carbon Steel
Sleeve I.D., in. ----- 3.000
Tube O.D., in. ----- 0.752
Tube Spacing, B.C., in. ----- 2.10
(No Spacers at Mid-length)

300

TUBES #2#3

2.5

TUBE #6

200

TUBE #1

1.5

Maximum h

100

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

TUBE #5

TUBE #4

3

2.5

2

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11 D.C.

1.5

10

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

FIGURE 4
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBES NO. 1-5 RUNS NO. 22-50

Test Assembly No.----- 1
 Sleeve Material----- Carbon Steel
 Sleeve I.D., in.----- 3.000
 Tube O.D., in.----- 0.752
 Tube Spacing, E.C., in.----- 2.100
 (No Spacers at Mid-length)

$$\frac{N_{NU}}{(N_{PR})^{0.33} (T_b)^{0.575} \frac{T_s}{T_b}}$$

1000

FIGURE 6
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBES NO. 1-6 RUNS NO. 51-84

Test Assembly No.-----2
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B. C., in.-----2.000
(No Spacers at Mid-length)

300

2.5

200

1.5

Minimum h

100

TUBE #5
TUBE #4
TUBE #2
TUBE #3
TUBE #6
TUBE #1

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

9

8

7

6

5

4

3

2.5

2

1.5

1

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

1.5

1

1

1

1

Reynolds Number $\times 10^{-4}$

A-6

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

1000

9
8
7
6
5
4
300
2.5
200
1.5
100
9
8
7
6
5
4
3
2.5
2
1.5
10

FIGURE 7
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBES NO. 1-6 RUNS NO. 51-84

Test Assembly No. ----- 2
Sleeve Material ----- Carbon Steel
Sleeve I.D., in. ----- 3.000
Tube O.D., in. ----- 0.752
Tube Spacing, B.C., in. ----- 2.000
(No Spacers at Mid-length)

TUBE #4
TUBE #5
TUBE #6
TUBE #3
TUBE #2
TUBE #1

Maximum h

ALLIS-CHALMERS MFG. CO.
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ATOMIC ENERGY DIV.
WASH. 11 D.C.

Reynolds Number x 10⁻⁴

1000

FIGURE 8
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBES NO. 1-6 RUNS NO. 51-84

Test Assembly No.----- 2
Sleeve Material----- Carbon Steel
Sleeve I.D., in.----- 3.000
Tube O.D., in.----- 0.752
Tube Spacing, B.C., in.----- 2.000
(No Spacers at Mid-length)

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.125

0.0625

0.03125

0.015625

0.0078125

0.00390625

0.001953125

0.0009765625

0.00048828125

0.000244140625

TUBE #6

TUBE #5
TUBE #4
TUBE #3
TUBE #2
TUBE #1

Minimum h

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

$$\frac{N_{NU}}{(N_{PR})^{0.33} (T_b)^{0.575} / T_s}$$

1000

FIGURE 9
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBES 1-6 RUNS NO. 88-121

Test Assembly No. 3
Sleeve Material Carbon Steel
Sleeve I.D., in. 3.000
Tube O.D., in. 0.752
Tube Spacing, B.C., in. 2.000
Spacer Design 6 Vanes, 45° Helical

300

2.5

200

1.5

Maximum h

100

9

8

7

6

5

4

3

2.5

2

1.5

1.0

0.5

0.4

0.3

0.2

0.1

0.05

0.02

0.01

TUBE #4
TUBE #5
TUBE #6
TUBE #1
TUBE #2
TUBE #3

$$\frac{N_{NU}}{(NPR)^{0.4}}$$

ALLIS-CHALMERS MFG. CO.
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ATOMIC ENERGY DIV.
WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

1000

FIGURE 10
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBES NO. 1-6 RUNS NO. 88-121

Test Assembly No.----- 3
 Sleeve Material----- Carbon Steel
 Sleeve I.D., in.----- 3.000
 Tube O.D., in.----- 0.752
 Tube Spacing, B.C., in.----- 2.000
 Spacer Design----- 6 Vanes, 45° Helical

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.125

0.0625

0.03125

0.015625

0.0078125

0.00390625

0.001953125

0.0009765625

0.00048828125

0.000244140625

0.0001220703125

TUBE #2
 TUBE #6
 TUBE #3
 TUBE #4
 TUBE #1
 TUBE #5

Minimum h

ALLIS-CHALMERS MFG. CO.
 NUCLEAR POWER DEPT.
 ATOMIC ENERGY DIV.
 WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

A-10

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

FIGURE 12
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER
TUBE NO. 1-6 RUNS NO. 122-172

Test Assembly No.-----	3
Sleeve Material-----	Glass
Sleeve I.D., in.-----	3.000
Tube O.D., in.-----	0.752
Tube Spacing, B.C., in.-----	2.000
Spacer Design-----	6 Vanes, 45° Helical

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_g} \right)^{0.575}}$$

FIGURE 16
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER
TUBES NO. 1-6 RONS NO. 122-172

Test Assembly NO.-----4
Sleeve Material-----Glass
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design-----6 Vanes, 45° Helical

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

10000

FIGURE 19
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 3

RUNS NO. 22-50

Test Assembly No. ----- 1
 Sleeve Material ----- Carbon Steel
 Sleeve I.D., in. ----- 3.000
 Tube O.D., in. ----- 0.752
 Tube Spacing, B.C., in. ----- 2.10
 (No Spacers at Midlength)

3000

2.5

200

1.5

100

Max.

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

9

8

7

6

5

4

3

2.5

2

1.5

1.0

0.5

0.25

0.1

0.05

0.025

0.01

0.005

0.0025

ALLIS-CHALMERS MFG. CO.
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 WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

1000

FIGURE 20
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 4 RUNS NO. 22-50

Test Assembly No.-----1
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.100
(No Spacers at Midlength)

300

25

200

150

100

90

80

70

60

50

40

30

25

20

15

10

8

6

4

3

2.5

2

1.5

1

0.5

0.25

0.1

0.05

0.025

Max. (at $\theta = 180^\circ$)Min. (at $\theta = 0^\circ$)

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WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

A-20

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

1000

FIGURE 22
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 6 **RUNS NO. 22-50**

Test Assembly No.----- 1
 Sleeve Material----- Carbon Steel
 Sleeve I.D., in.----- 3.000
 Tube O.D., in.----- 0.752
 Tube Spacing, B.C., in.----- 2.100
 (No Spacers at Midlength)

300

2.5

200

1.5

100

Max.

 N_{NU} $(N_{PR})^{0.4}$

9

8

7

6

5

4

3

2.5

2

1.5

1.5

1.5

1.5

1.5

1.5

1.5

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 WASH. 11. D.C.

Reynolds Number $\times 10^{-4}$

1000

FIGURE 23
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 7 RUNS NO. 22-50

Test Assembly No.-----1
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.100
(No Spacers at Mid-length)

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.4

0.3

0.25

0.2

0.15

0.1

0.05

0.025

0.01

0.005

0.0025

0.001

0.0005

0.00025

0.0001

0.00005

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

Min. (at $\theta = 0^\circ$)

ALLIS CHAMBERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

Reynolds Number 10

$$\text{Max. (at } \theta = 180^\circ)$$

TUBE NO. 7 HONS NO. 22-50

72 3301219

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

1000

FIGURE 26
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 2 RUNS NO. 22-50

Test Assembly No.-----1
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.10
(No Spacers at Mid-length)

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1.0

Max.

Min.

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

A-20

1 1.5 2 2.5 3 4 5 6 7 8 9 10

10000

FIGURE 28
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE No. 4 **RUNS NO. 22-50**

Test Assembly No. ----- 1
 Sleeve Material ----- Carbon Steel
 Sleeve I.D., in. ----- 3.000
 Tube O.D., in. ----- 0.752
 Tube Spacing, B.C., in. ----- 2.100
 (No Spacers at Mid-length)

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

3000

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

10

Max.

Min.

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

100010

FIGURE 30
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 6 **RUNS NO. 22-50**

Test Assembly No.-----1
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.100
 (No Spacers at Mid-length)

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.125

0.0625

0.03125

0.015625

0.0078125

0.00390625

Max.

Min.

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 NUCLEAR POWER DEPT.
 ATOMIC ENERGY DIV.
 WASH 11, D.C.

REYNOLDS NUMBER $\times 10^{-4}$

A-30

101

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

1000

FIGURE 33
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 1 RUNS NO. 51-84

Test Assembly No.----- 2
Sleeve Material----- Carbon Steel
Sleeve I.D., in.----- 3.000
Tube O.D., in.----- 0.752
Tube Spacing, B.C., in.----- 2.000
(No Spacers at Mid-length)

300

2.5

200

1.5

100 Max. (at $\theta = 270^\circ$)

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.125

0.0625

0.03125

0.015625

0.0078125

0.00390625

0.001953125

0.0009765625

0.00048828125

0.000244140625

0.0001220703125

0.00006103515625

0.000030517578125

0.0000152587890625

0.00000762939453125

0.000003814697265625

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

Min. (at $\theta = 30^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

100

1

1.5

2

2.5

3

4

5

6

7

8

9

10

100Q0

FIGURE 34
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 2 **RUNS NO. 51-84**

Test Assembly No. ----- 2
 Sleeve Material ----- Carbon Steel
 Sleeve I.D., in. ----- 3.000
 Tube O.D., in. ----- 0.752
 Tube Spacing, B.C., in. ----- 2.000
 (No Spacers at Midlength)

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

10

Max. (at $\theta = 270^\circ$)Min. (at $\theta = 30^\circ$)Reynolds Number $\times 10^{-4}$

A-34

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

1000

FIGURE 37
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 5 RUNS NO. 51-84

Test Assembly No.----- 2
Sleeve Material----- Carbon Steel
Sleeve I.D., in.----- 3.000
Tube O.D., in.----- 0.752
Tube Spacing, B.C., in.----- 2.000
(No Spacers at Mid-length)

300

2.5

200

1.5

100

Max. (at $\theta = 60^\circ$)

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

$$(N_{PR})^{0.4}$$

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.125

0.0625

0.03125

0.015625

0.0078125

0.00390625

0.001953125

0.0009765625

0.00048828125

0.000244140625

0.0001220703125

0.00006103515625

Min. (at $\theta = 180^\circ$)

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NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 25, D.C.

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

100010

FIGURE 58
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 6 **RUNS NO. 51-64**

Test Assembly No.----- 2
 Sleeve Material----- Carbon Steel
 Sleeve I.D., in.----- 3.000
 Tube O.D., in.----- 0.752
 Tube Spacing, B.C., in.----- 2.000
 (No Spacers at Mid-length)

300

2.5

200

1.5

100

Max. (at $\theta = 270^\circ$) N_{NU}

0.4

 (N_{PR})

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.125

0.0625

0.03125

0.015625

0.0078125

0.00390625

0.001953125

0.0009765625

0.00048828125

0.000244140625

0.0001220703125

0.00006103515625

Min. (at $\theta = 30^\circ$)

A-38

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

100010

FIGURE 39
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 7 RUNS NO. 51-84

Test Assembly No. ----- 2
Sleeve Material----- Carbon Steel
Sleeve I.D., in.----- 3.000
Tube O.D., in.----- 0.752
Tube Spacing, B.C., in.----- 2.000
(No Spacers at Mid-length)

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.1

0.05

0.025

0.01

0.005

0.0025

0.001

0.0005

0.00025

0.0001

Max. (at $\theta = 90^\circ$)Min. (at $\theta = 0^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

1000

FIGURE 42
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 2 RIMS NO. 51-84

Test Assembly No. ----- 2
Sleeve Material ----- Carbon Steel
Sleeve I.D., in. ----- 3.000
Tube O.D., in. ----- 0.752
Tube Spacing, B.C., in. ----- 2.000
(No Spacers at Mid-length)

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

300

200

150

100

90

80

70

60

50

40

30

25

20

18

16

15

14

13

12

11

10

9

8

7

6

5

4

3

2

1

Max. (at $\theta = 270^\circ$)Min. (at $\theta = 30^\circ$)

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ATOMIC ENERGY DIV.
WASH. 11, D.C.

A-42 10

Reynolds Number $\times 10^{-4}$

1 1.5 2 2.5 3 4 5 6 7 8 9 10

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_g} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_g} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_p}{T_s} \right)^{0.575}}$$

1000

FIGURE 48
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 7 RUNS NO. 51-84

Test Assembly No.----- 2
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
(No Spacers at Mid-length)

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.1

0.05

0.025

0.01

0.005

0.0025

0.001

Min. (at $\theta = 0^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

1000

FIGURE 54
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 5 RUNS NO. 88-121

Test Assembly No. ----- 3
Sleeve Material----- Carbon Steel
Sleeve I.D., in.----- 3.000
Tube O.D., in.----- 0.752
Tube Spacing, B.C., in.----- 2.000
Spacer Design----- 6 Vanes, 45° Helical

300

2.5

200

1.5

100

Max. (at $\theta = 330^\circ$)

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.125

0.0625

0.03125

0.015625

0.0078125

0.00390625

0.001953125

0.0009765625

0.00048828125

0.000244140625

0.0001220703125

0.00006103515625

0.000030517578125

0.0000152587890625

0.00000762939453125

0.000003814697265625

0.0000019073486328125

0.00000095367431640625

Min. (at $\theta = 180^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

A-54

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

1000

FIGURE 55
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 6 RUNS NO. 88-121

Test Assembly No.-----3
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.000
 Spacer Design-----6 Vanes, 45° Helical

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

10

1

1.5

2

2.5

3

3.5

4

4.5

5

5.5

6

6.5

7

7.5

8

8.5

9

9.5

10

Max. (at $\theta = 330^\circ$)Min. (at $\theta = 180^\circ$)

ALLIS-CHALMERS MFG. CO.
 NUCLEAR POWER DEPT.
 ATOMIC ENERGY DIV.
 WASH. 11, D.C.

Reynolds Number $\times 10^{-4}$

1000

FIGURE 56
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 7 **RUNS NO. 88-121**

Test Assembly No. ----- 3
 Sleeve Material ----- Carbon Steel
 Sleeve I.D., in. ----- 3.000
 Tube O.D., in. ----- 0.752
 Tube Spacing, B.C., in. ----- 2.000
 Spacer Design ----- 6 Vanes, 45° Helical

300

2.5

200

1.5

100

Max. (at $\theta = 180^\circ$)

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.2

0.1

0.05

0.02

0.01

0.005

0.002

0.001

0.0005

0.0002

0.0001

0.00005

0.00002

0.00001

0.000005

0.000002

0.000001

0.0000005

0.0000002

0.0000001

0.00000005

0.00000002

0.00000001

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

A-56

Reynolds Number x 10⁻⁴

1

1.5

2

2.5

3

4

5

6

7

8

9

10

FIGURE 58
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 1 RUNS NO. 88-121
Test Assembly No. 3
Sleeve Material Carbon Steel
Sleeve I.D., in. 3.000
Tube O.D., in. 0.752
Tube Spacing, B.C., in. 2.000
Spacer Design 6 Vanes, 45° Helical

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_g} \right)^{0.575}}$$

10000

FIGURE 60
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 3 RUNS NO. 88-121

Test Assembly No.-----3
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C. in.-----2.000
Spacer Design-----6 Vanes, 45° Helical

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

300

200

150

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.1

0.05

0.025

0.01

0.005

0.0025

0.001

0.0005

0.00025

0.0001

0.00005

Max. (at $\theta = 330^\circ$)

Min. (at $\theta = 180^\circ$)

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NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

A-60

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

10000

FIGURE 62
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER
TUBE NO. 3 RUNS NO. 88-121

Test Assembly No.----- 3
Sleeve Material----- Carbon Steel
Sleeve I.D., in.----- 3.000
Tube O.D., in.----- 0.752
Tube Spacing, B.C. in.----- 2.000
Spacer Design---6 Vanes, 45° Helical

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

3000

2.5

2000

1.5

1000

Max. (at $\theta = 330^\circ$)

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.2

0.1

0.05

0.02

0.01

0.005

0.002

0.001

0.0005

0.0002

0.0001

0.00005

0.00002

0.00001

0.000005

0.000002

0.000001

0.0000005

0.0000002

0.0000001

0.00000005

0.00000002

 

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

1000

FIGURE 68
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 3 RUNS NO. 122-172

Test Assembly No.-----4
Sleeve Material-----Glass
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design---6 Vanes, 45° Helical

300

200

1.5

100

Max. (at $\theta = 330^\circ$)

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.1

0.05

0.025

0.01

0.005

0.0025

0.001

0.0005

0.00025

0.0001

0.00005

Min. (at $\theta = 180^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 25, D.C.

Reynolds Number $\times 10^{-4}$

A-58

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

FIGURE 70
 HEAT TRANSFER CORRELATION
 VERSUS
 REYNOLDS NUMBER

TUBE NO. 5 RUNS NO. 122-172

Test Assembly No.-----4
 Sleeve Material-----Glass
 Sleeve I.D., in.-----3.000
 Tube O.D. in.-----0.752
 Tube Spacing, B.C., in.-----2.000
 Spacer Design-----6 Vanes, 45° Helical

1000

FIGURE 72
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 7 RUNS NO. 122-172

Test Assembly No.-----4
Sleeve Material-----Glass
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design-----6 Vanes, 45° Helical

300

2.5

200

1.5

100

Max. (at $\theta = 180^\circ$)

9

8

7

6

5

4

3

2.5

2

1.5

1

$$\frac{N_{NU}}{(N_{PR})^{0.4}}$$

$$(N_{PR})^{0.4}$$

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NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 25, D.C.

1.5

A-72

10

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

1000

FIGURE 73
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 7 RUNS NO. 122-172

Test Assembly No.-----4
Sleeve Material-----Glass
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design-----6 Vanes, 45° Helical

300

2.5

200

1.5

100

 N_{NU} $(N_{PR})^{0.4}$

9

8

7

6

5

4

3

2.5

2

1.5

10

Min. (at $\theta = 330^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. H. D.C.

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

1000

FIGURE 78
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 5 RUNS NO. 122-172

Test Assembly No.-----4
Sleeve Material-----Glass
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design-----6 Vanes, 45° Helical

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

300

25

200

15

100

9

8

7

6

5

4

3

2.5

2

1.5

1

10

Max. (at $\theta = 330^\circ$)

Min. (at $\theta = 180^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11. D.C.

Reynolds Number $\times 10^{-4}$

A-7C

1

15

2

25

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575}}$$

1000

FIGURE 80
HEAT TRANSFER CORRELATION
VERSUS
REYNOLDS NUMBER

TUBE NO. 7 RUNS NO. 122-172

Test Assembly No. ----- 4
Sleeve Material ----- Glass
Sleeve I.D., in. ----- 3.000
Tube O.D., in. ----- 0.752
Tube Spacing, B.C., in. ----- 2.000
Spacer Design ----- 6 Vanes, 45° Helical

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_s}\right)^{0.575}}$$

300

2.5

200

1.5

100

9

8

7

6

5

4

3

2.5

2

1.5

1

0.5

0.25

0.1

0.05

0.025

0.01

Max. (at $\theta = 180^\circ$)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

A-80

10

Reynolds Number $\times 10^{-4}$

1

1.5

2

2.5

3

4

5

6

7

8

9

10

$$\frac{N_{NU}}{(N_{PR})^{0.33} \left(\frac{T_b}{T_g} \right)^{0.575}}$$

FIGURE 82
TUBE SURFACE TEMPERATURE
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

FIGURE 83
TUBE SURFACE TEMPERATURE
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. D. C.

Run No.-----61
Test Assembly No.-----2
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
(No Spacers at Mid-length)
Flow Approx. 1375 #/hr.
Ave. Film Drop-----250°

Temperature, °F

570

560

550

540

530

520

510

Tube Number	1	3	4	5	7
Curve Identity	△	+	x	□	○

Circumferential Location, Degrees

60

120

180

240

300

360

60

120

FIGURE 84
TUBE SURFACE TEMPERATURE
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

Run No.-----103
Test Assembly No.-----3

FIGURE 85
TUBE SURFACE TEMPERATURE
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

ALLIS-CHALMERS MFG. CO.
NUCLEAR POWER DEPT.
ATOMIC ENERGY DIV.
WASH. 11, D.C.

Temperature, °F

570
560
550
540
530
520
510
500
490
480
470
460
450

Circumferential Location, Degrees

Run No.-----131
Test Assembly No.-----4
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design--6 Vanes, 45° Helical
Flow Approx. 1345 #/hr
Ave. Film Drop-----250°

Tube Number 1 2 3 4 5 6 7
Curve Identity - o + x @

A-85

FIGURE 86
SURFACE TEMPERATURE
VERSUS
AXIAL LENGTH

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ATOMIC ENERGY DIV.
WASH. 11, D.C.

FIGURE 89
 SURFACE TEMPERATURE VERSUS
 CIRCUMFERENTIAL POSITION
 (At Various Axial Locations)
 TUBE NO. 2 RUN NO. 131

Test Assembly No. --- 4
 Spacer Design --- 6 Vanes,
 45° Helical
 Flow 1380 #/hr
 Coolant In-181 °F
 Coolant Out-268 °F

Inches Refer to Axial Location
 Zero - Upstream Junction of
 Copper Bus to S.S. Tube

TUBE # 2 SURFACE TEMP.
 VS
 AXIAL LENGTH

Note: O = Upstream
 Junction of Copper
 Bus to S. S. Tube

ALLIIS-CHALMERS MFG. CO.
 NUCLEAR POWER DEPT.
 ATOMIC ENERGY DIV.
 WASH. 11, D.C.

FIGURE 90
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(At Station T.C. 3)

Tube No.-----4
Run No.-----40
Test Assembly No.-----1
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, P.C., in.-----2.100
(No Spacers at Mid-length)
Flow Approx. 1340 #/hr
Ave. Film Drop-----250°

FIGURE 91
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

Tube No.-----5
 Run No.-----40
 Test Assembly No.-----1
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.060
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.100
 (No Spacers at Mid-length)
 Flow Approx. 1340 #/hr
 Ave. Film Drop-----250°

. = h uncorrected
 (k of tube metal not considered)

x = h corrected
 (k of tube metal included)

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 NUCLEAR POWER DEPT.
 ATOMIC ENERGY DIV.
 WASH. 11, D.C.

FIGURE 92
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

Tube No.-----4
 Run No.-----61
 Test Assembly No.-----2
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.000
 (No Spacers at Mid-length)
 Flow Approx. 1375 #/hr
 Ave. Film Drop----250°

FIGURE 93
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

Tube No.-----5
 Run No.-----61
 Test Assembly No.-----2
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.000
 (No Spacers at Mid-length)
 Flow Approx. 1375 #/hr
 Ave. Film Drop-----250°

FIGURE 94
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

Tube No.-----4
Run No.-----103
Test Assembly No.-----3
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design--6 Vanes, 45° Helical
Flow Approx. 1350 #/hr
Ave. Film Drop----250°

FIGURE 95
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(AT T.C. Station 3)

Tube No.	-----	5
Run No.	-----	103
Test Assembly No.	-----	3
Sleeve Material	-----	Carbon Steel
Sleeve I.D., in.	-----	3.000
Tube O.D., in.	-----	0.752
Tube Spacing, B.C., in.	-----	2.000
Spacer Design	-----	6 Vanes, 45° Helical
Flow Approx.	-----	1350 #/hr
Ave. Film Drop	-----	250°

FIGURE 96
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

Tube No.-----4
Run No.-----131
Test Assembly No.-----4
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design---6 Vanes, 45° Helical
Flow Approx. 1345 #/hr
Ave. Film Drop---250°

FIGURE 97
HEAT TRANSFER COEFFICIENT
VERSUS
CIRCUMFERENTIAL LOCATION
(At T.C. Station 3)

Tube No.-----5
 Run No.-----131
 Test Assembly No.-----4
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.000
 Spacer Design---6 Vanes, 45° Helical
 Flow Approx. 1345 #/hr
 Ave. Film Drop---250°

FIGURE 98
TRAVERSE OF BULK
COOLANT TEMPERATURE

Run Number-----	46
Test Assembly Number-----	1
Sleeve Material-----	Carbon Steel
Sleeve I.D., in.-----	3.000
Tube O.D., in.-----	0.752
Tube Spacing, B.C., in.-----	2.100
(No Spacers at Mid-length)	
Flow Approximately	1340 #/hr
Average Film Drop -----	250°

Probe Path
 (See Dwg. SK-D-150
 for Axial Location)

FIGURE 99
TRAVERSE OF BULK
COOLANT TEMPERATURE

Run No.----- 61
Test Assembly No.----- 2
Sleeve Material----- Carbon Steel
Sleeve I.D., in.----- 3.000
Tube O.D., in.----- 0.752
Tube Spacing, B.C., in.----- 2.000
Spacer Design- 6 Vanes, 45° Helical
Flow Approximately 1375 #/hr
Average Film Drop----- 250°

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WASH. D. C.

FIGURE 100
TRAVERSE OF BULK
COOLANT TEMPERATURE

Run Number-----105
Test Assembly No.-----3
Sleeve Material-----Carbon Steel
Sleeve I.D., in.-----3.000
Tube O.D., in.-----0.752
Tube Spacing, B.C., in.-----2.000
Spacer Design--6 Vanes, 45° Helical
Flow Approximately 1350 #/hr
Average Film Drop-----250°

FIGURE 101
HEAT TRANSFER COEFFICIENT
VERSUS
AXIAL POSITION

Tube No.-----6
 Run No.-----32
 Test Assembly No.-----1
 Sleeve Material-----Carbon Steel
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.100
 (No Spacers at Mid-length)
 Flow Approximately 1340 #/hr
 Ave. Film Drop 235° @ 26"

Note: Inches are measured downstream of upper copper bus to S.S. tube junction.

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FIGURE 102
HEAT TRANSFER COEFFICIENT
VERSUS
AXIAL POSITION

Tube No.-----	2
Run No.-----	72
Test Assembly No.-----	2
Sleeve Material-----	Carbon Steel
Sleeve I.D., in.-----	3.000
Tube O.D., in.-----	0.752
Tube Spacing, B.C., in.-----	2.000
(No Spacers at Mid-length).	
Flow Approx. 1375 #/hr	
Ave. Film Drop----	250° @ 26'

$h = \text{BTU/hr-ft}^2\text{-}^\circ\text{F}$

80

70

60

50

40

NOTE: Inches are measured
downstream from upper
copper bus to S.S.
tube junction.

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0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30

Axial Position, Inches

FIGURE 103
HEAT TRANSFER COEFFICIENT
VERSUS
AXIAL POSITION

Tube No.	-----	1
Run No.	-----	106
Test Assembly No.	-----	3
Sleeve Material	-----	Carbon Steel
Sleeve I.D., in.	-----	3.000
Tube O.D., in	-----	0.752
Tube Spacing B.C., in.	-----	2.000
Spacer	-----	6 Vane 45° Helical
Flow Approximately	-----	1340 #/hr
Ave. Film Drop	-----	260° @ 26"

FIGURE 104
HEAT TRANSFER COEFFICIENT
VERSUS
AXIAL POSITION

Tube No.-----1
 Run No.-----131
 Test Assembly No.-----4
 Sleeve Material-----Glass
 Sleeve I.D., in.-----3.000
 Tube O.D., in.-----0.752
 Tube Spacing, B.C., in.-----2.000
 Spacer Design-----6 Vane, 45° Helical
 Flow Approximately 1345 #/hr
 Average Film Drop---265° @ 26"

$h = \text{BTU/hr-ft}^2\text{-}^\circ\text{F}$

NOTE: Inches are measured
 downstream of upper
 copper bus to S.S.
 Tube junction.

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WASH. D. C.

Report No. R&D 0008

Appendix B

Heat-Transfer Analysis

A. Heat-Transfer Assumption

The following assumptions were made with respect to the heat-transfer analysis:

(1) The volumetric heat-generation rate in the fuel tubes is constant at any given axial position.

(2) Axial conduction of heat in the fuel tubes is not considered.

(3) Heat flow into the inside area of the fuel tube is not considered.

(4) The thermocouple imbedded in the 20-mil wall of the fuel tube measures the tube-surface temperature; tube-wall resistance to heat flow is negligible.

(5) Net accumulation of heat at steady-state conditions is zero.

(6) The fuel tube is assumed to be a flat plate for analytical purposes.

B. Diagram of Fuel Tube - Treated as a Flat Plate

Δt_u = fuel-tube wall thickness, ft

ΔX = $\frac{\text{Total Clad Circumferential Length}}{\text{Number of Circumferential Segments}}$

From assumptions (4) and (5) above, and based on unit-fuel tube length, a heat balance at any point, n , on the fuel-tube surface results in the following expressions:

$$Q_{\text{convection}} = Q_{\text{conduction}} + Q_{\text{heat generation}}$$

$$Q_{conv} = q'''(\Delta x)(\Delta y) - (t_s - t_{s+1})k \frac{\Delta y}{\Delta x} - (t_s - t_{s-1})k \frac{\Delta y}{\Delta x} \quad (1)$$

$$\text{Solving for } h = \frac{Q_{conv.}}{t_n(\Delta x)} \quad \text{---} \quad (2)$$

$$h_s = \frac{q'''(\Delta x)(\Delta y) - (2t_s - t_{s+1} - t_{s-1})k \frac{\Delta y}{\Delta x}}{(t_s - t_b) \Delta x} \quad \text{---} \quad (3)$$

Thus, h at any point, s , on the tube surface may be expressed in the following general form:

$$h_s = \frac{q''' \Delta y}{t_s - t_b} - \frac{(2t_s - t_{s+1} - t_{s-1})k \frac{\Delta y}{\Delta x}}{(t_s - t_b) (\Delta x)^2} \quad \text{---} \quad (4)$$

The first term in the bracket represents the apparent heat-transfer coefficient and the following portion represents the corrections for conduction. If circumferential conduction in the fuel-tube wall were neglected, Equation (4) would reduce to the familiar form:

$$h_s = \frac{q'''(\Delta y)}{t_s - t_b} \quad \text{---} \quad (5)$$

Local heat-transfer coefficients on the surface of each tube of the 7-tube fuel element were calculated by using Equation (4) for all test runs performed. For calculation purposes, the fuel-tube wall was divided into 12 equal parts to correspond with the fixed thermocouples imbedded in the fuel-tube wall at 30-deg increments. Calculations were also performed by dividing the fuel-tube wall into 24 and 36 divisions. For these latter cases, plots of film drop versus circumferential tube position produced a widely oscillating pattern, the average of which agreed quite closely with the 12-division case. The results suggest that selecting too fine an unit division results in too great a temperature gradient in the tube wall, tending to produce over- or under-corrected results, though selecting a small unit division results in small temperature differences between the points of interest. Yet, Equation (4) indicates that the conduction-correction term is inversely proportional to the square of the unit division. This latter factor assumes an altogether too great significance and becomes the controlling term from a mathematical standpoint; the 12-division approach was therefore accepted and has proved to be reliable.

The following heat-transfer correlations were used in an attempt to find the correlation best applicable to the data:

$$N_{Nu} = C (N_{Re})^x (N_{Pr})^{0.4} \text{ — — — — — } (6)$$

$$N_{Nu} = C (N_{Re})^x (N_{Pr})^{0.33} \left(\frac{\mu_b}{\mu_s} \right)^{0.14} \text{ — — — — — } (7)$$

$$N_{Nu} = C (N_{Re})^x (N_{Pr})^{0.33} \left(\frac{T_b}{T_s} \right)^{0.575} \text{ — — — — — } (8)$$

Equation (6) above is the conventional Dittus-Boelter equation (Reference 1); Equation (7) is normally referred to as the Seider-Tate equation (Reference 2); and, Equation (8) was that developed by Humble and Associates (Reference 5). In Equation (8), the Reynolds Number was based on bulk conditions rather than the modified basis suggested in Reference 5.

The equivalent diameter for each correlation was based on the conventional definition of four times the free-flow area divided by the total wetted perimeter. Also, physical properties of the coolant were evaluated at the bulk temperature in all cases.

REPORT NO. RD 0008

APPENDIX C

I PHOTOGRAPHS, II DRAWINGS, AND
III DESCRIPTION OF TEST EQUIPMENT

CONTENTS

1. PHOTOGRAPHS

1. View Toward Compressor of Orifice Section, Inlet and Outlet Hose, and Pressure Drop Specimens.
2. View Away from Compressor of Orifice Section, Heat-Transfer Rig and Immediate Hose Connections, Throttle Valve, and Pressure-Drop Specimens.
3. Motor Generator and Control Panel.
4. Electrical Instruments.
5. Heat-Transfer Fuel-Element Specimens, With 6-Tooth Helical-Vaned Spacers.
6. Close-Up of 12- and 6-Tooth 45-deg Helical-Vaned Spacers.
7. Close-Up of Seven-Tube Cluster with 45-deg Helical-Vaned Spacers Installed in Heat-Transfer Rig Glass Sleeve.

11. DRAWINGS

E-110-RD	Heat-Transfer Test Assembly
D-112-RD	Fuel-Element Tube
D-113-RD	Housing Weldment, Heat Transfer Test
D-114-RD	Item Details, I, Heat Transfer Test
D-115-RD	Item Details, II, Heat Transfer Test
D-116-RD	Jumper Details Heat Transfer Test
D-118-RD	Item Details, III, Heat Transfer Test
D-119-RD	Item Details, IV, Heat Transfer Test
D-120-RD	Orientation of Holes in Fuel-Element Tube Ass'y
D-121-RD	Detail of Fuel-Element Sleeve
SK-D-151	Thermocouple Probe
SK-D-143	Schematic - Heat Transfer Flow Sheet
SK-MS-15	Fuel-Assembly General Arrangement
SK-FF-136	Central Helical Spacers, Design IV
SK-D-150	Relationship of Thermocouples, Probes, Spacers
SK-D-159	Bow Restrainers and Spacers

111. DESCRIPTION OF TEST EQUIPMENT

FIGURE 1: View Toward Compressor of Orifice Section, Inlet and Outlet Hose, and Pressure Drop Specimens.

FIGURE 2: View Away from Compressor of Orifice Section, Heat Transfer Rig and Immediate Hose Connections, Throttle Valve, and Pressure Drop Specimens.

FIGURE 3: Motor Generator and Control Panel.

FIGURE 4: Electrical Instruments.

FIGURE 5: Heat-Transfer Fuel Element Specimens with 6-Tooth Helical-Vaned Spacers.

FIGURE 6: Close-up of 12- and 6-Tooth 45-deg Helical-Vaned Spacers.

GLASS (PYREX) SLEEVE
3.000 ID

FIGURE 7: Close-Up of Seven-Tube Cluster with 45-deg Helical-Vaned Spacers
Installed in Heat-Transfer Rig Glass Sleeve.

② TIN ENDS OF TUBE WITH SOLDER
OR COMPOSITION - 50% TIN, 50% LEAD

REV B — * AMOUNT INCLUDES SPARES
ONE ASSEMBLY REQUIRES 5 OF ITEM 1,
1 OF ITEM 2 AND 1 OF ITEM 3

[illegible]

TEST ARENT	DIM A
1	205
2	.170
3	120
5	220
8	.270

[illegible]

ITEM A
MATERIAL - CARBON STEEL
NO REQ'D - 3

E 110-R & D		NOTED
<p>ALLIS-CHALMERS MANUFACTURING COMPANY ATOMIC ENERGY DIVISION NUCLEAR POWER DEPARTMENT WASHINGTON, D. C.</p>		
<p>TITLE DETAILS IV HEAT TRANSFER TEST</p>		
<p>DATE 10/1/54</p>		<p>DATE</p>
<p>BY J. H. HARRIS</p>		<p>BY</p>
<p>APP. J. H. HARRIS</p>		<p>APP.</p>
<p>SCALE 1/2" = 1"</p>		<p>SCALE</p>
<p>DWG. NO. D-119-R & D</p>		<p>REV. NO. 1</p>

REV.	DESCRIPTION	DATE	BY	CL.
1	ORIGINAL ISSUE	10/1/54	J. H. HARRIS	

REVISIONS	
1	ORIGINAL ISSUE

MATERIAL	
AS NOTED	
SEE D/M	
E 110-R & D	

TOLERANCES	
FRACTIONAL	1/32
DECIMAL	.005
ANGLE	30° 30'

THERMOCOUPLE WIRES SHALL BE TAGGED TO IDENTIFY POSITION OF WIRE ON TUBE. THE ANGULAR POSITION WILL BE DESIGNATED WITH A LETTER AS SHOWN IN SECTION A-A. THIS LETTER WILL BE PRECEDED BY A NUMBER 1, 2, AND 3 TO INDICATE THE LONGITUDINAL POSITION OF THE WIRE FROM THE TOP OF THE TUBE

HOLE SCHEDULE								
TUBE ASSY NO.	D-112-R8D ITEM NO.	DIM D	DIM E	DIM F	ANGLE X	ANGLE Z	AMOUNT REQD	
1-5	-1	.937	43.812	--	30°	330°	4	
1-5T	-1	.937	43.812	--	30°	330°	2	△
2	-1	.937	43.812	--	0°	330°	5	
3	-3	2.875	43.812	2.688	0°	330°	3	
4-6	-1	.937	43.812	--	330°	30°	4	
4-6T	-1	.937	43.812	--	330°	30°	2	△
7	-2	2.875	46	--	210°	240°	2	
7T	-2	2.875	46	--	210°	240°	2	

NOTE -

1. TUBES DESIGNATED WITH SYMBOL "T" SHALL HAVE HOLES FOR ATTACHING THERMOCOUPLE WIRES AS LOCATED IN SECTION A-A.
2. REMOVE BURRS AND SHARP EDGES
3. SEE DWG D-112-R8D FOR DETAILS OF PURE ELEMENT TUBES
4. CAUTION TUBES HAVE BEEN CAREFULLY SELECTED FOR STRAIGHTNESS, CONCENTRICITY AND STAINLESS STEEL WALL THICKNESS, AND MUST BE HANDLED WITH EXTREME CARE, CHECK BOWING IN ACCORDANCE WITH NOTE #1 DWG D-112-R8D AFTER COMPLETION (INCLUDING THERMOCOUPLE INSTALLATION IN TUBES)

E-110-R & D AS NOTED

MATERIAL SEE DWG D-112-R8D		APPROVALS DATE 3/28/53 3/28/53	NEXT ASSEMBLY ALLIS-CHALMERS MANUFACTURING COMPANY ATOMIC ENERGY DIVISION NUCLEAR POWER DEPARTMENT WASHINGTON, D. C.
UNLESS OTHERWISE SPECIFIED ALL DIMENSIONS IN INCHES HORIZONTAL DIMENSIONS HOLE SHARP EDGES TOLERANCES FRACTIONAL DECIMAL ANGLES		CUSTOMERS APP DO NOT SCALE DWG SCALE AS NOTED	TITLE ORIENTATION OF HOLES FOR RHEE ELEMENT TUBE ASSEMBLY HEAT TRANSFER TEST
REV 15 NOTED A INITIAL ISSUE BY DATE		REV 15 NOTED A INITIAL ISSUE BY DATE	REV 15 NOTED A INITIAL ISSUE BY DATE

TEST	MAT'L	3.350 DIA	3.500 DIA	3.350 DIA	3.500 DIA
1,2,3	SCHED 40	3.000	4.33	1	
4	SCHED 40	3.125	4.70	1	
5	SCHED 40	3.250	4.97	1

NOTES

1. ALL WELDING TO BE COMPLETED BEFORE MACHINING DIAMETER "A"
2. INSIDE DIA "A" TO BE CONCENTRIC WITH 3.400 OUTSIDE DIA WITHIN .005 TIE
3. SLOPE DIA "A" TO BE STRAIGHT WHEN ROTATED ABOUT THE AXIAL W WITHIN .005 TIE
4. SLEEVE TO BE MARKED FOR IDENTIFICATION WITH TEST ARRANGEMENT NUMBER AT TOP END OF SLEEVE AS INDICATED (EXAMPLE - "3 TOP")
5. ALL BURS TO BE REMOVED FROM INTERNAL SURFACE OF SLEEVE
6. SURFACE ROUGHNESS SYMBOL PERTAINS TO MACHINED SURFACES ONLY

E 110 R & D NOTED

MATERIAL				APPROVALS		DATE
CARBON STEEL				DR	APP	3.25.50
SEE DIM				CK	APP	3.25.50
DWS E 110 R & D				APP		
UNLESS OTHERWISE SPECIFIED				APP		
ALL DIMENSIONS IN INCHES				APP		
SURFACE ROUGHNESS - .125				APP		
WELD MARK SYMBOL - SEE				APP		
F LUTY, SEE - 8 MAX				APP		
TOLERANCES				APP		
FRACTIONAL - .005				APP		
DECIMAL - .005				APP		
ANGLE - .005				APP		
DO NOT SCALE DWS				APP		
SCALE - 3/16" = 1"				APP		
SHEET 1 OF 1				APP		

ALLIS - CHALMERS
MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
NUCLEAR POWER DEPARTMENT
MADISON, WIS.

TITLE
DETAIL OF FUEL
ELEMENT SLEEVE
HEAT TRANSFER TEST

DWS NO D-121-R & D
SCALE 3/16" = 1"

REV
B

THERMOCOUPLE PROBE
 SK-D-151 8-5-59 R.E.M.

NOTED-
 F.S.

NOTES

- 1 ALL DIAMETERS TO BE CONCENTRIC WITHIN 0.01 TIR EXCEPT 0.825 DIAMETERS WHICH CAN BE WITHIN 0.05 TIR
- 2 ITEM 1 AS SHOWN
ITEM 2
(1) REMOVE EVERY OTHER FIN 6 FINS REQUIRED
(2) CHAMFER FIN EDGES AS SHOWN IN DETAIL A

2

DETAIL A
ITEM 2

NEXT ASSEMBLY		NO. REQD	
ALLIS - CHALMERS MANUFACTURING COMPANY ATOMIC ENERGY DIVISION NUCLEAR POWER DEPARTMENT WASHINGTON, D. C.			
CENTRAL HELICAL SPACER DESIGN 12 2 1/2" BC, 2 1/2" RATIO, 3 1/25" BORE FOR HEAT TRANSFER TEST ONLY			
DATE	APPROVED	BY	REV
6-18-59	QW10	W. J. W.	1
6-18-59	QW10	W. J. W.	1
DON'T SCALE DWG		REV	
SK-E-136		A

RELATION OF FIXED THERMOCOUPLES, PRESS. TAPS AND GAS TEMP. PROBES IN TEST SECTION - HEAT TRANSFER TEST.

SK-D-150
W.T.W. 5-25-59

SECTION X-X
FLAT SPACER ARRANGMENT
TOP

SECTION Y-Y
FLAT SPACER ARRANGMENT
BOTTOM

DIM A = 2.860	8 (REQ) 4 UPPER & 4 LOWER
DIM A = 3.000	4 (REQ) 2 UPPER & 2 LOWER

FUEL ELEMENT TUBE

BOW RESTRAINERS & SPACERS	REM	2-4 GC	(SK-D-159)
---------------------------	-----	--------	------------

SK-D-159

III. DESCRIPTION OF TEST EQUIPMENT

A. General Arrangement

1. Lab Layout

The general arrangement of the laboratory and of the pressure-drop and heat-transfer sections is shown on Photographs 1 and 2. The general locations of the instrument boards and tables are shown on the photographs.

2. Heat-Transfer Tests

The principal instruments used in the heat-transfer tests were thermocouples. Thermocouples were provided at three axial positions on three of the seven fuel tubes of the fuel-assembly test specimen, at the inlet and exit plenum chambers of the test section, and in the gas stream at three axial positions along the fuel-assembly test specimen. The Test-Specimen Section describes this feature more fully.

B. Compressor Starter

Photograph No. 3 shows the compressor, motor, and motor-starter installation. The starter box was mounted on a channel support attached to the front corner of the motor-mounting base. The auxiliary contact in the compressor starter was wired in series with the M-G set starter (see Wiring Diagram SK-D-134) to prevent starting the M-G set before the compressor was operating. The compressor starter was also wired to a circuit breaker located on the front wall of the laboratory.

C. Flow Control

The discharge pressure of the compressor and the flow to the test section were controlled by a pair of Continental Type 3045 butterfly valves (Items Q-1 and Q-2). The operating lever for these valves was mounted on a quadrant having 9 holes drilled over a 90-deg arc. A keeper pin locked the lever to the quadrant to maintain the valve setting. This feature permitted adjustment of the butterfly in 10-deg increments. Additional adjustments could be made by use of a C-clamp. The two butterfly valves are shown in Photograph No. 1; the valves are at the extreme ends of the lower horizontal cast-iron pipe.

D. Flow Measurement

Air flow to the test sections was measured through a concentric Foxboro orifice (2.015 in. ID) plate mounted between 4-in. IPS orifice flanges. The flange taps of the upstream and downstream flanges were connected to several U-tube manometers on the manometer board of various capacity ranges. A graph for approximating the weight rate of flow of air from the orifice differential-pressure measurement was prepared as a guide for

the operators. The orifice flanges are at about the mid-point of the lower horizontal cast-iron pipe as shown in Photograph No.1.

E. Static Pressure at Orifice

The static-pressure measurement at the orifice was taken from the downstream-flange tap. The downstream-flange tap was connected to a manometer of appropriate range on the manometer board.

F. Temperature at Orifice

The air temperature at the orifice was measured with a thermometer. The thermometer (Item T1-14) was a Taylor Mercury thermometer with a 100-300 F scale. The 3/4-in. NPT male connector on the thermometer was screwed into a 3/4-in. NPT half-coupling welded into the line.

G. Barometric Pressure

The barometric pressure was obtained from a mercury-column barometer attached to the manometer board. The barometer appears at the center of the manometer board on Photograph No. 2 .

H. Humidity

The moisture content of the air in the test section was obtained by measuring the humidity of the inlet air to the compressor by the wet-and-dry bulb method (a sling psychrometer).

J. Compressor Power

The power consumption of the compressor was measured with a General Electric Hook-On Volt-ammeter, Type AK-5 (Item A-3). The approximate full-load current for a 25-hp motor (220-v 3-phase) is 64 amp. The volt-ammeter is shown atop the motor-starter box on Photograph No. 3; the instrument is reading the current in one leg of a 3-phase hook-up.

K. Temperature Alarms

Two Assembly Products Safety No. 4500 Simplytrol Pyrometer Limit Controls are provided to protect the heat-transfer section from damage due to overheating. Iron-constantan thermocouples are used as the sensing elements. The instruments have single high-limit adjustable contacts. When the trip point is reached, the meter contacts lock up and remain locked until the manual reset is actuated. The leads of the sensing iron-constantan thermocouples are connected to the appropriate signal-input terminals of the Simplytrol. One instrument (Item T-5), Model 4535-MR, has a 0-1000 F range and serves to protect the tubes from overheating. The alarm contact is set at about 800 F. An iron-constantan thermocouple fixed to the internal wall of the center tube near the bottom end is used as the sensing element.

The other instrument (Item Tr) has a 0-300 F range and monitors the gas outlet temperature. An iron-constantan pencil thermocouple mounted in a 1/8-in. coupling on the outlet housing is used as the sensing element. Both Simplytrols are connected to the 110-volt output of the Sola transformer to isolate them from ground. Both instrument relays are connected with the pressure switch, PS-1, to the auxiliary contact of the compressor motor starter and the M-G set starter. When either T⁴, T⁵, or PS-1 contacts, the M-G set will be shut down.

L. Flow Pressure Switch

A Barksdale Meletron Pressure-Difference Switch is installed across the orifice flange taps to sense the orifice differential pressure and shut down the M-G set on low flow. This protects the heat-transfer section from burn-out in case of air-flow failure or obstruction. The switch is wired to the M-G starter as shown on the Wiring Diagram SK-D-13⁴.

M. Temperature Indicator

A Brown 0-800 F Potentiometer, calibrated for iron-constantan thermocouples, is provided for temperature measurement. The instrument is connected to the 110-volt output of the Sola Transformer (to isolate it from ground) to permit reading the energized thermocouples of the heat-transfer test. A porcelain fuse block with a 15-amp cartridge fuse is installed between the transformer and the indicator. Input terminals are provided on the front of the instrument to allow calibration with a reference standard (calibrated thermocouple) or independent measurement of the input millivolts from the permanent rear input.

N. Thermocouple Selector Switch

A Leeds and Northrup 24-point push-button thermocouple-selector switch is provided to connect any one of 24 thermocouples to the temperature indicator. A single pair of thermocouple wires is used to join the common output of the switch to the input of the temperature indicator (Paragraph 12). Thermocouple points can be connected in parallel to both the temperature indicator and temperature recorder by jumping the lead wire from the selector switch terminals to one set of the recorder terminals.

Each bank of twelve double leads of the selector switch was wired to the male half of an appropriate bayonet plug. Each of the three banks of twelve thermocouple leads (including as many as four outer tubes under test plug two sets of twelve miscellaneous thermocoupled regions) was wired to mating female plugs. The female plugs were mounted on a vertical board attached to the back of the instrument panel. With such an arrangement, any two sets of twelve readings were immediately available for scanning by the operator.

O. Motor Generator

A Bogue Model 4727 motor-generator set was supplied, with a control panel containing a starter, control rheostat, voltmeter, ammeter, and frequency meter. The motor-generator set was provided with appropriate connections to interconnect the temperature-alarm and flow-pressure switches described in Paragraphs 10 and 11. The connection leads to the heat-transfer test section were No. 000 welding cable.

P. Voltmeter, Ammeter, Wattmeter, and Current Transformer

The electrical instruments -- voltmeter, ammeter, and wattmeter -- were General Electric Type AP-11 portable indicating instruments, with 1/2% accuracy. All instruments were supplied with calibrated lead wires with clips at one end for connection to the lead and pins at the other end for insertion into the instrument. The instruments were calibrated for operation in a horizontal position (scale facing up). The ammeter and voltmeter were used with a current transformer with a permanent primary tap for 200 amps and 400 amps on a secondary of 5 amps.

Q. Instrument Table Arrangement

The arrangement of the temperature and electrical instruments on the table is shown in Photograph No. 4.