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NaK Heat Transfer Study for a 19-Rod Bundle
(P/D = 1.05) Employing Helical-Fin Spacers

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ABSTRACT

An experimental heat transfer study is reported for the case of longitudinal flow of a liquid metal (NaK-78) through a closely spaced rod bundle. The rod bundle consisted of 19 electrically heated elements which were arranged on hexagonal arrays having a pitch-to-diameter (P/D) ratio of 1.05. Helical-fin spacers were attached to the cladding tubes to promote increased intra-channel turbulence and inter-channel mixing, or crossflow. In addition, the fins served to maintain symmetric and positive rod spacing. Rod azimuthal temperature distributions were determined from thermocouples which were welded to the inside cladding tubes. Instrumentation was also provided to measure the coolant temperature distribution at the inlet and outlet to the rod bundle, the power supplied to each rod, and the coolant flow rate. The above instrumentation provided the necessary measurements for determining the rod-average heat transfer coefficient.

Heat transfer results for the cladding circumferential temperature distributions and the rod-average film coefficients were obtained over a range of heating and flow conditions of interest to a compact ZrH reactor core. Because of the increased intra-channel turbulence created by the helical-fins, negligible rod azimuthal temperature variations and significantly improved rod-average film coefficients were observed. In the flow range investigated, the heat transfer results were found to be independent of the Peclet number. In addition, the effect of fin-induced inter-channel mixing, or crossflow, was to significantly reduce coolant channel-to-channel temperature differences. The increased mixing should do a great deal in reducing cross fuel element ΔT s and the resulting bending stresses in an actual ZrH reactor core.

* TITLE PAGE ONLY

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1. INTRODUCTION

This report presents the results of part of a continuing research program at Atomics International to determine the heat transfer characteristics of NaK flowing in-line through closely spaced rod bundles. The results are intended to provide information needed in the design and evaluation of various Zirconium Hydride (ZrH) compact nuclear reactor concepts. Previous analytical (1)* and experimental (2) studies have been reported.

As the pitch-to-diameter (P/D) ratio of fuel rods in a nuclear reactor is reduced, the rod-average heat transfer coefficient is decreased and the rod circumferential temperature gradient is increased. For closely packed ($P/D \leq 1.05$) rod bundles cooled by liquid metals, azimuthal temperature variations can be large enough to create severe thermal stress, corrosion, and hot spot problems. In addition, rod bundles which have no intermediate tube spacing devices along their length are subject to degrading asymmetry effects. The asymmetry created by rod bowing and dimensional tolerances can enhance rod circumferential temperature gradients above their symmetrical values. The reader is referred to the work of Dwyer (3, 4) and Hsu (5, 6) who studied the problem of geometrical asymmetry caused by dislocating a rod from its symmetrical position. They found that the asymmetry strongly affected the temperature field in the coolant flow area causing deterioration in heat transfer capability of the displaced rod.

*Numbers in parentheses designate references at end of report.

The above peripheral temperature variations could be minimized by designing for larger P/D ratios; however, from considerations of nuclear performance and space power applications, close rod spacings ($P/D \leq 1.05$) are desirable. For these low P/D rod bundles, rod spacing devices are required to guarantee positive tube spacing and minimize asymmetry effects. Since rod spacing devices cause added fluid turbulence and inter-channel mixing, it was expected that the rod bundle heat transfer performance would improve significantly. It was the primary objective of this investigation to determine the extent of this improvement.

For the present experimental study, a rod bundle, which has helical-fin spacers attached to the cladding tubes, was tested under turbulent longitudinal flow of NaK. The rod bundle consisted of 19 electrically heated elements which were arranged on symmetrical equilateral triangular arrays having a $P/D = 1.05$. To determine the rod azimuthal temperature variation, small-diameter thermocouples were attached to the cladding tube on all heaters. In addition, measurements were made of the test section inlet and outlet coolant temperature distributions, the power supplied to each heater, and the coolant flow rate. From these measurements, rod-average heat transfer coefficient and Nusselt number (Nu) variations with Peclet number (Pe) were determined.

2. EXPERIMENTAL EQUIPMENT

The experimental equipment, which includes the test section, instrumentation, and the NaK loop, is essentially the same as was used in the previous investigations (2). The reader is referred to Reference (2) for a detailed description. Only a brief description will be presented here. Certain modifications were added to the previous experimental hardware and will be discussed in this section.

The test section consisted of a bundle of 19 electrically heated elements, or rods, arranged on hexagonal arrays with a P/D ratio of 1.05. The rod bundle was held within a stainless-steel cylindrical shell which had half-round filler rods attached to the inner wall to maintain the proper coolant flow distribution. The same 19 rods which were used in the previous experimental studies (2) were used for the present investigation. Twelve rods were modified by the addition of helical-fin spacers which were brazed to the outer cladding surface. The test configuration is referred to as the right-left-neutral (R-L-N) test configuration which means that the fin helix is alternately right hand, left hand, and neutral (no fins) on successive rods throughout the bundle. Figure 2.1 shows views of the test section during assembly.

As reported in Reference (2), the 19 rods were special electric heaters which were designed to simulate the thermal performance of Zirconium Hydride (ZrH) fuel elements in a tightly packed bundle configuration. A design layout of a typical finned heater element is shown in Figure 2.2. The test rods consist basically of a Nichrome coil encased in magnesium oxide (MgO) electrical insulation which is swagged into a stainless steel tube.

Fig. 2.1 Assembly of 19-Rod, Finned Element Bundle.

- NOTES: UNLESS OTHERWISE SPECIFIED ON THIS DRAWING
1. LAY HEATER FLAT AND SCRIBE A LINE .001 INCHES FROM THE FLAT SURFACE ON THE SIDE OF THE HEATER OFFSET
 2. WATLOW ELECTRIC MFG CO. ST. LOUIS, MO. REF. N56820007
 3. THREE -16 FINS REED FOR EACH -01 THRU -12 ASSY.
 4. ATTACH THE 3 -16 FINS TO HEATER BY:
 - A. CLEAN THE HEATER & FINS BY WIPING WITH ACETONE, RINSE WITH ALCOHOL & DRYING WITH CLEAN AIR OR GAS. POLISH AS NECESSARY WITH ABRASIVE NYLON PAD PRIOR TO FINAL CLEANING
 - B. WELD FINS & RESISTANCE TACK WELD TO HEATER SHEATH AT APPROX 0.90 INCH INTERVALS TO RETAIN FINS PRIOR TO BRAZING
 - C. BRAZE IN HYDROGEN ATMOSPHERE AT 1025 ± 15°F FOR 75-90 MINUTES USING AWS BN1-7 (MICROBRAZE 50) ALLOY
 5. IDENTIFY BY TAGGING

SECTION A-A
 SCALE: 1/4

FIN LOCATION & ORIENTATION TABLE			
HEATER ASSY NO.	FIN NO. (2)	FIN DIRECTION	INDEX LINE LOCATION Θ
-01	24075	E.N.	19.5°
-02	24075	E.N.	19.5°
-03	24075	E.N.	19.5°
-04	24075	E.N.	79.5°
-05	24075	E.N.	79.5°
-06	24075	E.N.	79.5°
-07	24075	L.N.	40.5°
-08	24075	L.N.	40.5°
-09	24075	L.N.	40.5°
-10	24075	L.N.	100.5°
-11	24075	L.N.	100.5°
-12	24075	L.N.	100.5°

Fig. 2.2 Design layout of a finned heater element

EX-N759200015-12 FIN		S.S. STRIP	CONV. 30055 FINS
EX-N759200015-12 HEATER ASSY		MAKE FROM 3 24075 HEATER (2)	
-11			
-10			
-09			
-08			
-07			
-06			
-05			
-04			
-03			
-02			
EX-N759200015-01 HEATER ASSY		MAKE FROM 3 24075 HEATER (2)	
QTY REQD	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	ZONE MATERIAL DATA SPECIFICATIONS SIZES, NOTES, VENDORS
PARTS LIST			
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES. TOLERANCES ON: DECIMALS ANGLES FRACTIONS .005 ± .001 .010 ± .002 .015 ± .003 .020 ± .004 .030 ± .005 .040 ± .006 .050 ± .007 .060 ± .008 .070 ± .009 .080 ± .010 .090 ± .011 .100 ± .012 .125 ± .015 .150 ± .018 .175 ± .020 .200 ± .022 .250 ± .025 .300 ± .030 .375 ± .035 .450 ± .040 .500 ± .045 .600 ± .050 .750 ± .060 .900 ± .070 1.000 ± .080 1.250 ± .090 1.500 ± .100 2.000 ± .125 2.500 ± .150 3.000 ± .180 4.000 ± .200 5.000 ± .250 6.000 ± .300 8.000 ± .400 10.000 ± .500			
DO NOT SCALE PRINT			
HOLES NOTED "DRILL"			
213 THRU 240 ± .001 - .001			
241 THRU 130 ± .001 - .001			
132 THRU 229 ± .001 - .001			
230 THRU 300 ± .001 - .001			
201 THRU 790 ± .001 - .001			
791 THRU 1200 ± .001 - .001			
1201 THRU 2200 ± .001 - .001			
APPLICATION			
-12 EX-N759200015-12 TEST			
-01 EX-N759200015-01 TEST			
NEXT USING DWS MODEL			
DR BY: K. BILBUSH/SM		ATOMIC INTERNATIONAL	
CHK BY: [Signature]		HEATER ASSY- BRAZED FIN CONFIGURATION	
DATE: 10/1/74		SIZE: CODE IDENT NO. DRAWING NO.	
SCALE: 1/4" = 1"		E 09974 EX-N759200015	
SHEET		SHEET	

The finned elements, which have either a right-hand or left-hand fin helix, have 3 fins per rod spaced 120 degrees apart with an axial pitch of 5.5 in. The fins are 0.030-in high by 0.060-in. wide. Rod heat fluxes up to 139,000 Btu/hr-sq.ft. were maintained uniformly over the 10 in. heated length. The electrical resistances of all heaters agreed to within 1/2%. All rods were radiographed to check both concentricity and uniformity of the nichrome coil.

A complete summary of the test section statistics is shown in Table 1.

TABLE 1
SUMMARY OF TEST SECTION STATISTICS

Number of rods in bundle	19
Outer diameter of rods, in.	9/16
Geometrical Arrangement	Equilateral Triangular
Length of rods (9/16 in. O. D. region), in	16.5
Heated length, in	10.0
Overall length, in	39.0
Rod spacers	Helical-Fin
Fin configuration	R-L-N
Fin height, in	0.030
Number of fins per rod (except neutral rods)	3
Fin axial pitch, in	5.5
Rod pitch-to-diameter ratio	1.053
Hydraulic diameter, in.	0.1095
z_F/D_h (Cladding thermocouple location with respect to flow development)	96
z_H/D_h (Cladding thermocouple location with respect to thermal development)	73

At a single axial plane, the test rods had small diameter (0.010 in.) thermocouples which were welded to the inside cladding tube prior to filling with MgO and fabricating the heater element. The thermocouple system consisted of Chromel and Alumel wires, surrounded by MgO insulation, and sheathed in Inconel 600 tubing. Up to nine thermocouples were accurately located (± 1 degree) and spaced around the inside cladding periphery to measure the rod circumferential temperature variation.

A cross sectional view of the rod bundle showing the relative cladding thermocouple locations is illustrated in Figure 2. 3. The azimuthal locations ($\theta \leq 30$ degrees) are given with respect to the nearest line connecting the centers of adjacent rods. Two of the rods (H-1 and H-4) had nine cladding thermocouples; however, since each heater had one inoperable thermocouple, only eight thermocouples are shown. The other rods had either two or three cladding thermocouples. The cladding thermocouple locations on H-1 through H-7 were chosen to give an adequate mapping of the cladding circumferential temperature distribution, while the locations on H-8 through H-19 were used primarily for rod symmetry checks.

The outlet temperatures of selected individual tricus coolant channels were recorded by 1/16-in. O. D., Chromel-Alumel thermocouples. Eighteen coolant channels were monitored, and the locations in the rod bundle are shown in Figure 2. 3. The thermocouples were pointed into, and aligned parallel to, the flow stream. They were held in place by 0.030-in. thick bands which were attached to the heaters. The axial position of the thermocouples was 0.5 in. downstream from the end of the heated zone. In order to maintain flow symmetry, dummy wires, 1/16-in. O. D., were banded in the same manner at the same axial location, and were located in coolant channels where no thermocouples existed.

The average test section inlet and outlet temperatures were measured by 1/8-in. O. D., Chromel-Alumel thermocouples. Four thermocouples were inserted in the inlet plenum leading to the test section, and two thermocouples were in the main flow line exiting from the test section.

To keep heat losses to a minimum, the outer wall of the test section

TEST ASSEMBLY (FINNED) TOP VIEW-TEST SECTION 3

Fig. 2.3 Relative thermocouple locations in 19-rod bundle

was insulated with 2 in. of Fiberfrax insulation under 3 in. of high-temperature asbestos insulation.

A schematic flowsheet of the loop, in which the test bundle was placed, is shown in Figure 2.4. It was built of 1-1/2 in., Schedule 10, Type 316 SS pipe, with an all-welded construction. Before fabrication of the loop, the piping and components were carefully cleaned with an acetone solution, and all welding was done under an argon atmosphere. After fabrication and before filling with NaK, the loop was kept under a positive pressure of pure argon. The entire loop is insulated with at least 3 in. of high-temperature asbestos insulation.

Besides the test section the principle components of the loop were two expansion tanks, a drain tank, three parallel D. C. conduction pumps, an electromagnetic linear induction pump, a 150-kw. in-line heater assembly, a finned air-cooled heat exchanger, a flow-through cold trap, and a permanent magnet flowmeter.

The power to each test rod was controlled by 19 separate variable transformers, connected in series with the heaters. The power to each heater element was measured by a precision ammeter and voltmeter, which were calibrated. The accuracy of the power measurement was within 1%.

The NaK flow rate was measured by a D. C. permanent magnet flowmeter. The flowmeter was calibrated in a NaK flowmeter calibration loop, and was accurate to within 3%.

Fig. 2.4 Schematic flowsheet of the NaK heat transfer loop

3. EXPERIMENTAL PROCEDURE

To determine an accurate heat transfer coefficient for a rod bundle geometry, it is important to maintain a uniform coolant temperature distribution across the test section. This can be accomplished by creating the following conditions: (1) a uniform coolant velocity profile at the entrance to the test section, and (2) a proper test section coolant flow distribution. In the present study the first condition was achieved by the use of a plenum and bellmouth nozzle arrangement at the inlet to the test section. Because of the rapid coolant acceleration, in flowing from the plenum into the bellmouth nozzle, the fluid boundary layer remains attached to the wall and is relatively thin, causing the pressure loss to be small and the nozzle exit velocity to be uniform. The second condition was arrived at by proper sizing of the individual coolant channel flow areas. The peripheral coolant channels, which are adjacent to the half-round filler rods, receive heat from either one or two rods, while the interior channels receive heat from three rods. To keep the bulk coolant temperature rise for the outer edge channels the same as for the interior channels, the flow rate through the peripheral channels had to be reduced in direct proportion to the reduced heat input. This was accomplished by inserting small-diameter wires into the outer edge channels. The wires were sized such that the resulting coolant flow distribution would result in equal coolant temperature rise across the rod bundle.

Since it was the primary objective of the present study to produce dependable data obtained under carefully controlled conditions, steps were taken to insure that the quantity of dissolved oxides, impurities, and entrained gases were held to a minimum. During inoperative periods,

the loop was purged continuously with argon. Prior to filling with NaK, the loop was evacuated to an absolute pressure of 3 microns. With the NaK at room temperature, the loop was loaded by pressurizing the drain tank. In addition, the NaK was charged through a 5-micron micrometallic filter. The fill line in the drain tank was low enough, and the residual NaK level was kept high enough to minimize the intake of gas or any floating oxides.

While the NaK was circulating through the loop, approximately 10% of the flow was continuously diverted through the cold trap. The minimum temperature of the cold trap was held to 100°F. By means of the special sampling section (see Figure 2.4), NaK samples were taken periodically throughout the test. Chemical analysis verified that the oxygen concentration was held to 5 ppm.

All thermocouples, including test rod cladding, test section inlet and outlet, and individual coolant channels, were calibrated before the test and checked periodically during the test while the NaK was circulated isothermally at various temperatures. Maximum discrepancy between any two thermocouples was <2°F. AC noise pickup by the thermocouples was determined to be negligible. A digital data logging system, which was used to record the data, was equipped with special devices to filter out any AC noise pickup.

The resistances of the heater elements were checked periodically throughout the test. The calibrations of the precision ammeters and voltmeters, which were used for measuring the power input to all 19 test rods, were also checked from time to time during the investigation.

Prior to making a run, the flow rate was set, the test rods were adjusted to the same power level within 1%, and the test section inlet coolant temperature was allowed to come to a predetermined equilibrium value within 1°F. Before taking data, sufficient time was allowed to reach steady-state conditions. Although the time to reach equilibrium depended on flow rate and temperature, it was usually <30 min. To verify that the consistency of the data was good, several runs were made at any one particular set of conditions before going on to the next set. In addition, after proceeding through the complete range of conditions, many repeat runs were made.

The scope of the experimental study is presented in Table 2.

TABLE 2.
SCOPE OF THE EXPERIMENTAL
STUDY

Nak temperature range, °F	400 to 800
Heat flux range, Btu/hr-sq.ft.	27,800 to 111,300
Reynolds number range	5,000 to 29,000
Prandtl number range	0.0067 to 0.0115
Peclet number range	35 to 240
Flow direction	Vertically upward

The NaK was circulated continuously through the loop, even when no power was supplied to the heater elements or when testing was not taking place, such as nights and weekends. The NaK flow was stopped only when it came time to disassemble the test section. At that time, the NaK was dumped at 400 °F by pressurizing the surge tank. The NaK was stored in the sealed drain tank until it was time to load the loop for another test configuration.

The physical property values of NaK-78, which were used in the calculations and correlations to follow, were taken from the Sodium-Nak Supplement of the Liquid-Metals Handbook (7) .

4. EXPERIMENTAL RESULTS

In this section, raw data will be presented for the rod circumferential temperature distributions over a range of heating and flow conditions. These data represent the actual temperature measurements obtained from thermocouples which were welded to the inside cladding tubes. Since heater numbers one and four (H-1 and H-4, Figure 2.3) had eight operable cladding thermocouples, azimuthal temperature distributions will be presented separately for these rods. In addition, from cladding thermocouples on the inner seven heaters, combined plots of the rod temperatures will be presented.

For various heat fluxes examined in the study, Figures 4.1 through 4.5 present circumferential temperature variations on the center (neutral) test rod (H-1) and on an adjacent (finned) test rod (H-4). The temperature distributions are presented in terms of the local cladding temperature above the bulk coolant temperature $[T_{w_i}(\Theta) - T_b]$. The local inside wall temperatures, $T_{w_i}(\Theta)$, are determined by thermocouples (T/C) which are welded to the inside cladding tube at selective azimuthal locations. The bulk coolant temperature (T_b) which is subtracted from the local azimuthal temperature is the average NaK temperature at the heater thermocouple plane, $z_H/L_H = 0.80$. T_b is determined from the average inlet temperature, the average of the individual outlet coolant channel temperatures surrounding the center test rod (T/C numbers 77 through 85, Figure 2.3), and the measured power supplied to each heater. All 19 rods were operated at the same power level, and the heat flux is uniform in the axial direction. Heat balances made for various operating conditions indicated that test section heat losses were $\leq 1\%$.

Fig. 4.1 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 AND H-4

Fig. 4.2 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 AND H-4

P/D = 1.05
R-L-N FINNED

DP 401 B
1.7 KW
MAX. FLOW (32 gpm)
600°F
(RERUN)

FIG. 4.3 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 AND H-4

FIG. 4N CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 AND H-4

P/D = 1.05
R-L-N FINNED
DP. 403 B
3.0 KW
MAX. FLOW (32.9 PM)
600° F

$T_{wc}(\theta) - T_b$
°F

O-HEATER #4
(RN)

Δ-HEATER #1
(N)

θ - DEGREES

Fig. 4.5 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 AND H-4

The circumferential angle, θ , in Figures 4.1 through 4.5 and in subsequent plots lies in the range $0^\circ \leq \theta \leq 30^\circ$ and is measured from the cladding thermocouple to the nearest line connecting the centers of adjacent elements. Since the rods are arranged on hexagonal arrays, the circumferential temperature profiles repeat every 60 degrees, and are symmetrical with respect to each 30-degree interval. Although straight lines have been drawn through the mean of the data points shown in Figures 4.1 through 4.5, a temperature variation is evident, and a curved line would represent a better fit to the data. However, it will be shown later that the temperature variation is not the result of close rod packing, but rather the result of tricuspid coolant-to-coolant channel temperature variations and a temperature variation that has been "built into" the rod thermocouples due to repeated testing over a period of time.

Temperature distributions, as recorded by thermocouples on the inner seven test rods, are illustrated in Figures 4.6 through 4.10. The relative thermocouple locations can be found by reference to Figure 2.3. Comparing the data shown in Figures 4.6 through 4.10 to that shown in Figures 4.1 through 4.5 for single rods, it is evident that considerably more data scatter exists for temperatures recorded by thermocouples on the inner seven test rods. This can be attributed to fabrication non-uniformities of the heater-thermocouple assemblies and a "built in" T/C bias due to repeated testing of the heater. By applying corrective temperature factors determined from individual heater calibration tests, it will be shown later that most of the data scatter, evident in Figures 4.6 through 4.10, can be removed.

Fig. 4.6 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 THRU H-7

P/D = 1.05
R-L-N FINNED
DP 400
1.0 KW
32 GPM
600°F

Fig. 4.7 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 THRU H-7

P/D=1.05
R-L-N FINNED

DP 401 B
1.7 KW
MAX. FLOW (327 ft/min)
600 °F - NaK

Fig. 4.8 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 THRU H-7

$P/D = 1.05$
R-L-N FINNED

DP 402 A
2.4 KW
32. GPM
600° F

Fig. 4.9 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 THRU H-7

P/D = 1.05
R-L-N FINNED

DP 403 B
3.0 KW
MAX. FLOW (32477)
600°F

FIG. 4.10 CIRCUMFERENTIAL TEMPERATURE
DISTRIBUTIONS FOR H-1 THRU H-7
P/D=1.05
R-L-N FINNED.

DP 406 A
440 KW
32 GPM
400° F

HEATER NO. SYMBOL

H-1	△
H-2	□
H-3	▽
H-4	○
H-5	◇
H-6	○
H-7	×

Part of the rod temperature variations, exhibited in Figures 4.1 through 4.10, can be attributed to variations in the individual coolant channel temperatures. From the individual outlet coolant channel thermocouples (T/C numbers 77 - 117, Figure 2.3), channel-to-channel temperature differences were observed. For the previously tested ring spacer bundle and the present finned configuration, Table 3 compares the coolant temperature rise for the channels adjacent to the center test rod. For the finned element bundle, temperature differences ranging from 4 - 11°F are evident, while the bundle employing ring spacers had $< 2^{\circ}\text{F}$ temperature differences. The greater coolant temperature variations can be attributed to the larger dimensional tolerances on the fins which resulted in greater variations in the individual coolant channel flow areas and flow rates.

The cladding T/C arrangement for the center test rod, shown in Figure 2.3, is based on geometric symmetry occurring every 30 degrees. In order to adequately determine the azimuthal temperature variation, an adequate number of thermocouples had to be located in this 30° interval. This required using the full circumference of the center rod (twelve-30° intervals) and spacing the thermocouples at various positions within each 30° interval. The above arrangement assumed that coolant channel temperature symmetry would be maintained around the center heater. As is evident from Table 3, this was a good assumption for the ring spacer bundle, but this assumption was violated for the R-L-N finned test configuration.

To account for the above discrepancies, the cladding circumferential temperature distributions for the center test rod were corrected for in the following manner. As previously mentioned, the azimuthal cladding temperature variations are presented in terms of the local inside wall temperature

TABLE 3 INDIVIDUAL COOLANT CHANNEL TEMPERATURE RISE FOR THE RING SPACER AND
THE R-L-N FINNED ELEMENT BUNDLES

Power (kw)	1.7		2.4		3.0		4.0	
Test Configuration	(a) ¹	(b) ²	(a)	(b)	(a)	(b)	(a)	(b)
T/C (#)	COOLANT		CHANNEL		TEMPERATURE		RISE (°F)	
77	- ³	37.6	-	53.7	-	67.4	-	84.5
78	-	35.0	-	49.7	-	61.8	-	75.6
80	46.9	39.3	65.4	56.3	83.0	70.0	98.1	86.7
82	47.7	35.9	65.8	51.1	82.1	64.4	99.0	79.2
83	47.7	37.6	65.4	53.7	83.0	66.6	99.5	82.7
85	46.8	38.0	65.5	53.7	82.8	66.6	98.4	83.6

1. Test bundle employing ring spacers; P/D = 1.05.
2. Test bundle employing R-L-N finned elements; P/D = 1.05.
3. No T/C in these locations for test configuration (a).

above the average bulk coolant temperature $[T_{w_i}(\Theta) - T_b]$, where T_b is the average of the six coolant channel temperatures adjacent to the center test rod. To correct for the variations in channel temperatures, the individual coolant channel temperatures, T_{b_i} (T/C Nos. 77-85), were subtracted from the corresponding, adjacent wall temperatures. For example, T/C No. 77 at $z_H/L_H = 0.80$ was subtracted from T/C No. 2. For the center test rod, Figures 4.11 through 4.14 show the temperature distributions with and without this correction. These results show that ~50% of the circumferential temperature variation can be attributed to coolant-to-coolant channel temperature variations.

Fig. 4.11 CIRCUMFERENTIAL TEMPERATURE
DISTRIBUTIONS FOR H-1 - CORRECTED
FOR COOLANT CHANNEL TEMPERATURE
VARIATIONS

P/D = 1.05
R-L-N FINNED
DP = 401 B
1.7 KW
32.4 gpm
600 °F

UNCORRECTED

CORRECTED

θ (DEGREES)

Fig. 4.12 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-I-CORRECTED FOR COOLANT CHANNEL TEMPERATURE VARIATIONS

Fig. 4.13 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1-CORRECTED FOR COOLANT CHANNEL TEMPERATURE VARIATIONS

Fig. 4.14 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS FOR H-1 - CORRECTED FOR COOLANT CHANNEL TEMPERATURE VARIATIONS

5. POST-TEST CALIBRATION TESTS

Before continuing with a discussion of the rod bundle tests, individual heater post-test calibration results will be presented here. After the 19-rod finned element bundle tests were completed, single element calibration tests were performed. These tests consisted of operating individual heaters at power under well described, uniform heat transfer conditions of: 1) annular flow of liquid NaK, and 2) pool boiling of water. Reference (2) provides a detailed description of these tests. For the two previous test configurations described in Reference (2), calibration tests were performed only for the center rod (H-1) and were conducted before assembly of the rod bundles. For the present finned element configuration, calibration tests were conducted on the inner seven test rods (H-1 through H-7) and were performed after disassembly of the rod bundle.

The primary purpose of the individual rod calibration tests was to determine the degree of uniformity of cladding thermocouple measurements. Since the rods were tested under symmetrical geometric, flow, and heat transfer conditions, the extent of any "built-in" azimuthal temperature variation can be determined. Although calibration tests conducted on H-1, prior to the testing of the $P/D=1.00$ bundle, indicated a very uniform circumferential temperature distribution, it was believed that repeated assembly, testing, and disassembly over a period of time could have an effect. In addition, it was believed that most of the data scatter evident in Figures 4.6 through 4.10 is due to heater fabrication non-uniformities. Also, since the six rods (H-2 through H-7) surrounding the center rod had fins brazed on the outer cladding surfaces, it is conceivable that the thermocouples welded to the inner cladding surface could have been influenced.

It should be pointed out that the data scatter evident in Figures 4.6 through 4.10 could be due to different effective radial locations of cladding thermocouples. Although the cladding thermocouples are welded to the inner wall, the effective T/C diameter is 0.010 in., and with power supplied to the heater, there exists a large radial temperature gradient ($\sim 4^\circ\text{F}/\text{mil}$) through the MgO. Therefore, if the effective radial locations of the T/C junctions differ from thermocouple to thermocouple by only a few mils, the data scatter shown in Figures 4.6 through 4.10 could easily be accounted for. In addition, in order to determine the rod film coefficient, the radial temperature difference between the thermocouples and the inside cladding surface must be determined. These temperature differences were determined in Reference (2) for the center test rod; however, it was necessary to repeat these measurements to verify that they had not been changed.

5.1 NaK Calibration Tests

After disassembly of the 19-rod, finned element bundle, NaK annular flow calibration tests were conducted on the center rod (H-1). The test section, shown in Figure 5.1, consisted of a 2-in. stainless steel pipe into which the test rod was concentrically located. The test section was installed in a specially designed NaK loop and operated over the temperature range of 400-800°F with a maximum flow rate of ~ 10 gal/min. Power levels ranging from 1 to 4 kw were supplied to the test rod. These power and temperature ranges are characteristic of those used for the 19-rod bundle tests. Measurements of the rod power, NaK flow rate, test section inlet and outlet coolant temperatures, and heat cladding temperatures were provided. A cold trap, which was used to remove impurities from the loop, kept the oxide content below 10 ppm.

Fig. 5.1 Test section for NaK calibration test

For various power levels examined in the NaK calibration test, Figure 5.2 presents the results of the circumferential distributions of cladding thermocouple readings above the bulk coolant temperature. The lines drawn through the data points represent mean values. To make an easy comparison, the calibration data shown in Figure 5.2 and the following figures has been plotted on the same basis ($\Theta \leq 30$ deg.) as is done for the 19-rod bundle tests. Figure 5.3 shows similar results for the same test rod. These results were obtained from pre-test calibrations which were performed prior to testing the $P/D = 1.00$ rod bundle configuration. For the present results the average deviation from the mean is $\pm 3^\circ\text{F}$, while the results shown in Figure 5.3 exhibit an average deviation of $\pm 1.5^\circ\text{F}$. Later, corrections based on the difference between the thermocouple measurement and the mean value will be applied to the 19-rod, finned element data.

By comparing Figures 5.2 and 5.3 for the same power levels, it is seen that the repeatability of the mean of the cladding temperature data was excellent for the two tests. This indicates that the radial temperature correction factors, determined in Reference (2) and shown in Figure 5.4 for convenience, are still valid for determining the center rod-average heat transfer coefficient in the 19-rod, finned element bundle.

5.2 Water Calibration Tests

The inner seven heaters of the 19-rod, finned element bundle were tested individually in water under pool boiling conditions. Each test rod was installed vertically in a tank of distilled water which was maintained at saturation temperature. Power was supplied to the heater in the range of 1.0 to 4.0 kw. After steady state pool boiling conditions were attained, measurements were taken of the cladding temperatures, the bulk water

Fig. 5.2 POST-TEST N₂K CALIBRATION TEST RESULTS FOR H-1 FOR THE CIRCUMFERENTIAL TEMPERATURE

Fig. 5.3 PRE-TEST NAK CALIBRATION TEST
RESULTS FOR N-1 FOR THE CIRCUM-
FERENTIAL TEMPERATURE DISTRIBUTIONS

Fig. 5.4 Radial temperature correction factors for H-1 determined from the NaK calibration tests

temperature, and the rod power.

For the center rod (H-1), Figure 5.5 presents azimuthal distributions for the cladding temperature above the bulk water saturation temperature. For each power level, the lines drawn through the data points represent mean values. Similar results obtained for H-1 prior to the $P/D = 1.00$ rod bundle tests are shown in Figure 5.6. For the present results the average deviation from the mean is within $\pm 3.5^\circ\text{F}$, while the results shown in Figure 5.6 have an average deviation within $\pm 1.5^\circ\text{F}$.

Comparing the results shown in Figures 5.5 and 5.6 for the same power levels, it is found that the average values of $[T_{w_i}(\Theta) - T_b]$ for the present study are $\sim 23\%$ greater than the previous results. Because of the dependence of boiling on heat transfer surface characteristics, the increased ΔT is most likely due to a change in cladding surface roughness as a result of repeated testing in a NaK environment. This argument is supported by the fact that the results of the 600°F NaK annular flow tests showed no difference between the pre-test and post-test calibrations.

The next test rod which was calibrated in water was H-4, which is a finned element (see Figure 2.3) having eight cladding thermocouples. For various power levels, Figures 5.7 and 5.8 present the results for the cladding temperature distributions. Straight lines representing the average values of $[T_{w_i}(\Theta) - T_b]$ are drawn through the data points. The average deviation of the data points from the mean value is within $\pm 6.5^\circ\text{F}$. This is greater than the 3.5°F average deviation obtained with H-1. In addition, the mean values of $[T_{w_i}(\Theta) - T_b]$ for H-4 were approximately 5% greater than the corresponding values for H-1.

FIG. 5.5 POST-TEST WATER CALIBRATION TEST
RESULTS FOR H-1 FOR THE CIRCUM-
FERENTIAL TEMPERATURE DISTRIBUTIONS

Fig. 5.6 PRE-TEST WATER CALIBRATION TEST
RESULTS FOR H-1 FOR THE CIRCUM-
FERENTIAL TEMPERATURE DISTRIBUTIONS

Fig. 5.7 POST-TEST WATER CALIBRATION TEST
RESULTS FOR H-4 FOR THE CIRCUM-
FERENTIAL TEMPERATURE DISTRIBUTIONS

Fig. 5.8 POST-TEST WATER CALIBRATION TEST
RESULTS FOR H-4 FOR THE CIRCUM-
FERENTIAL TEMPERATURE DISTRIBUTIONS

Proceeding with the water calibration results, Figures 5.9 through 5.12 show the cladding temperature data obtained for H-2, H-3, H-5, H-6, and H-7. Each of these finned elements had two cladding thermocouples (see Figure 2.3). One of the thermocouples (T/C No. 12) on H-2 was inoperative. For each power level, a straight line is drawn through the mean of the data. As is evident, considerable data scatter exists with an average deviation from the mean of $\pm 13.8^{\circ}\text{F}$. This is appreciably greater than the average deviation of 3.5°F obtained for the center test rod (H-1). For these test rods, the mean values of the cladding thermocouple-to-bulk coolant temperature differences were about 9% greater than the corresponding values for H-1.

Figures 5.13 through 5.16 present composite plots of the cladding temperature data obtained for the inner seven heaters (H-1 through H-7) tested individually under conditions of water pool boiling. The lines drawn through the data at each power level represent the mean value of $\left[T_{w_i}(\Theta) - T_b \right]$ for the center test rod (H-1). Based on the difference between each thermocouple reading and the mean value for H-1, temperature correction factors were determined for all thermocouples on the inner seven rods. These corrective ΔT s will be applied successively to the corresponding thermocouple measurements obtained in the 19-rod, finned element tests.

The reason for using the mean value of $\left[T_{w_i}(\Theta) - T_b \right]$ for H-1 as a base point for the thermocouple corrections on the inner seven elements is as follows. The center heater was the only test rod calibrated both in water and in NaK. For both of these calibration tests, the degree of uniformity of the cladding thermocouples was good, having an average deviation from the mean of $< 3.5^{\circ}\text{F}$. The degree of uniformity of cladding thermocouple

Fig 5.9 POST-TEST WATER CALIBRATION TEST
RESULTS FOR H-2, H-3, H-5, H-6, AND H-7
FOR THE CIRCUMFERENTIAL TEMPERATURE
DISTRIBUTION

Fig. 5.10 POST-TEST WATER CALIBRATION TEST
RESULTS FOR H-2, H-3, H-5, H-6, AND H-7
FOR THE CIRCUMFERENTIAL TEMPERATURE
DISTRIBUTION

Fig. 5.11 POST-TEST WATER CALIBRATION TEST
RESULTS FOR H-2, H-3, H-5, H-6, AND H-7
FOR THE CIRCUMFERENTIAL TEMPERATURE
DISTRIBUTION

Fig. 5.12 POST-TEST WATER CALIBRATION TEST

RESULTS FOR H-2, H-3, H-5, H-6 AND H-7
FOR THE CIRCUMFERENTIAL TEMPERATURE
DISTRIBUTION

Fig. 5.13 WATER POOL BOILING CALIBRATION TEST
RESULTS PERFORMED INDIVIDUALLY ON
H-1 THRU H-7

FIG. 5.14 WATER POOL BOILING CALIBRATION
TEST RESULTS PERFORMED INDIVIDUALLY
ON H-1 THRU H-7

FIG. 5.15 WATER POOL BOILING CALIBRATION
TEST RESULTS PERFORMED INDIVIDUALLY
ON H-1 THRU H-7
3.0 KW

Fig. 5.16 WATER POOL BOILING CALIBRATION TEST
RESULTS PERFORMED INDIVIDUALLY
ON H-1 TAKU H-7

readings for H-1 was considerably better than any of the other inner seven test rods. In addition, since the average deviation of cladding temperature measurements from the mean value was approximately the same for H-1 for both the water and NaK calibration tests, the correction factors based on H-1 are considered to be more reliable with respect to temperature dependence between 212°F (H₂O saturation temperature) and 600°F (NaK inlet temperature).

6. CORRECTED EXPERIMENTAL RESULTS

6.1 Cladding Thermocouple Measurements

From the NaK calibration test results for H-1 shown in Figure 5.2, temperature corrections for the center-rod thermocouple readings were obtained. These corrections were based on the difference between the thermocouple reading and the mean value of the data points. These corrective ΔT s were applied to the corresponding thermocouple readings for H-1 obtained in the 19-rod, finned element tests (see Figures 4.11 through 4.14) and resulted in the corrected azimuthal temperature variations shown in Figures 6.1 through 6.4. By comparing these results to those shown in Figures 4.11 through 4.14, it is evident that most of the original azimuthal temperature variation can be attributed to coolant channel-to-channel temperature differences and a "built in" thermocouple bias. The remaining temperature variation, shown in Figures 6.1 through 6.4, is due to experimental data scatter. This will become more evident later, when the variation with rod power is examined.

For the center test rod, Figures 6.5 through 6.8 present results which have been corrected from the water calibration test results shown in Figure 5.5. Since the degree of uniformity of the cladding temperature distributions obtained in the NaK and water calibration tests was approximately the same, the corrected results

Fig. 6.1 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR H-1 CORRECTED FROM THE NaK
CALIBRATION TEST RESULTS (See Fig. 5.2).

$P/D = 1.05$
R-L-N FINNED

DR-40/B
1.7 KW
329 Pm
600 °F

TR. NO.

Fig. 6.2 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR H-1 CORRECTED FROM THE NGK
CALIBRATION TEST RESULTS (SEE FIG. 5-2).

P/D = 1.05
R-L-N FINNED

DP-402

2.4 KW

32.9 PM

600°F

TC. NO.

FIG. 6-3 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR H-1 CORRECTED FROM THE NaK
CALIBRATION TEST RESULT. (SEE FIG. 5-2).

$P/D = 1.05$
R-L-N FINNED

DP-403B
3.0 KN
32 rpm
600°F

TC. NO.

$T_{\text{th}} - T_{\text{air}}$
(°F)

Θ - DEGREES

Fig. 6-3 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR HY CORRECTED FROM THE NAK
CALIBRATION TEST RESULTS (See Fig. 5-2).

P/D = 1.05
R-L-N FINNED

FIG. 6.5 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR HT CORRECTED FROM THE WATER
CALIBRATION TEST RESULTS (see Fig. 5.5).

P/D = 1.05
R-LN FINNED

DN-401 B
1.7 KW
32.97m
600°F

FIG. 6.6 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR H-1 CORRELATED FROM THE WATER
CALIBRATION TEST RESULTS (see FIG. 5.5).

PID-1.05
R-L-N FINN. D.

DIP-402
2.4 KW
32 gpm
600°F

FIG. 6-7 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR FIN CORRELATED FROM THE WATER
CALIBRATION TEST RESULTS (SEE FIG. 5.5).

$R/D = 1.05$
R-LN FINNED

$T_{\text{fin}}(\theta) - T_{\text{bf}}$
(°F)

60

40

20

0

0

5

10

15

20

25

30

θ (DEGREES)

DP-403B
3.0 KW
32.97m
600°F

FIG. 68 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR H-1 CORRECTED FROM THE WATER
CALIBRATION TEST RESULTS (See FIG. 5.5).

$P/D = 1.05$
R-L-N FINNED

shown in Figures 6.5 through 6.8 are very similar to those shown in Figures 6.1 through 6.4. The fact, that the NaK and water calibration test results for the degree of uniformity of cladding thermocouple measurements are very similar, indicates that absolute temperature independence exists. Because of this, the remaining six elements (H-2 through H-7) were calibrated under conditions of water pool boiling. The water tests are much less costly and time-consuming than the NaK tests.

For H-4, which is a finned-element having eight cladding thermocouples, Figures 6.9 through 6.12 present results for the cladding temperature distributions before and after corrections have been made. The corrective ΔT s were determined from the water calibration results for H-4, shown in Figures 5.7 and 5.8. As is evident from Figures 6.9 through 6.12, most of the azimuthal temperature variation has been removed by applying the water calibration results, indicating that a "built-in" thermocouple bias existed for H-4 in the 19-rod, finned element test.

For the cladding thermocouple measurements on the inner seven test rods (H-1 through H-7), Figures 6.13 through 6.16 present corrected circumferential temperature distributions. These results have been obtained from the 19-rod bundle NaK data, shown in Figures 4.6 through 4.10, and temperature correction factors

Fig. 6.8 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS
FOR H-4 - CORRECTED FROM THE WATER
CALIBRATION TEST RESULTS (SEE FIG. 5.8)

$T_w(\theta) - T_b$ (°F)

$T_w(\theta) - T_b$ (°F)

60

40

20

0

60

40

20

0

0

5

10

15

20

25

30

θ - (DEGREES)

UNCORRECTED

P/D=1.05
R/L N FINNED
IP-401 B
1.7 KW
32 RPM
600°F

CORRECTED

FIG. 6.10 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTION
FOR H-4 - CORRECTED FROM THE WATER
CALIBRATION TEST RESULTS (SEE FIG. 5.8).

$T_c(\theta) - T_b$

$T_c(\theta) - T_b$

60

40

20

0

60

40

20

0

0

5

10

15

20

25

30

θ (DEGREES)

UNCORRECTED

P/D = 1.05
R-L-N FINNED

DD 502A

2.4 KW

32 gpm

600 °F

CORRECTED

Fig. 6.11 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS
FOR 11-4 - CORRECTED FROM THE WATER
CALIBRATION TEST RESULTS (SEE 5.7).

Fig. 6.12 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS
FOR H-4 - CORRECTED FROM THE WATER
CALIBRATION TEST RESULTS (SIC FIT-517)

Fig. 6.13 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS
FOR H-1 THRU H-7 CORRECTED FROM THE
WATER CALIBRATION TEST RESULTS

P/D = 1.05
1.7 KW
32.97 MM
600°F - ALK

HEATER NO.	SYMBOL
H-1	△
H-2	□
H-3	△
H-4	○
H-5	◇
H-6	○
H-7	X

Fig. 6.14 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS
FOR H-1 THRU H-7 CORRECTED FROM THE
WATER CALIBRATION TEST RESULTS

$P/D = 1.05$
R-L-N FINNED
2.4 KW
3270 RPM
600°F - No K

HEAT NO.	SYMBOL
H-1	Δ
H-2	$\square$
H-3	Δ
H-4	$\circ$
H-5	$\diamond$
H-6	$\circ$
H-7	X

$T_w (C) - T_b (F)$

80
60
40
20
0

0

5

10

15

20

25

30

θ (DEGREES)

Fig. 6-15 CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS
FOR H-1 THRU H-7 CORRECTED FROM THE
WATER CALIBRATION TEST RESULTS

P/D = 1.05
R-L-M FINNED
3.0 KW
32.71 mm
600°F - NaK

HEATER NO. SYMBOL

H-1 Δ
H-2 $\square$
H-3 Δ
H-4 $\circ$
H-5 $\circ$
H-6 $\circ$
H-7 X

$T_{\text{ref}}(G) - T_b$
(°F)

Θ (DEGREES)

Fig-6.14a CIRCUMFERENTIAL TEMPERATURE DISTRIBUTIONS
FOR H-1 THRU H-7 CORRECTED FROM THE
WATER CALIBRATION TEST RESULTS

P/D = 1.25
R-L-N FINNED
4.0 TW
32.9 THM
400°F - NaK

determined from the calibration test results, shown in Figures 5.13 through 5.16. From the calibration test results on H-1 through H-7, the corrective ΔT s were based on the difference between the actual thermocouple measurement for each rod and the mean value of $(T_w(\theta) - T_b)$ for H-1. Comparison of the raw data (Figures 4.6 through 4.10) to the corrected data clearly illustrates that most of the data scatter can be attributed to fabrication non-uniformities of heater-thermocouple assemblies from one rod to the next. The best fit to the data, shown in Figures 6.13 through 6.16, is a horizontal straight line with an average deviation from the mean of $\pm 4^\circ\text{F}$. This indicates that no circumferential temperature variation existed on any of the inner seven rods in the 19-rod, finned element test conducted in NaK. It should be noted that T/C No. 23, shown in Figures 6.13 through 6.16, is believed to be operating incorrectly. This is evidenced by the fact that a considerable temperature difference exists between this thermocouple and the mean value for each power level. None of the other thermocouples exhibit as great a discrepancy.

For the three test configurations examined to date (see Reference 2), Figure 6.17 presents the experimental results for the variation of the maximum azimuthal temperature difference with rod power for the center test rod (H-1). These results have

Fig. 6.17 VARIATION OF MAXIMUM CIRCUMFERENTIAL TEMPERATURE DIFFERENCE WITH ROD POWER ON THE CENTER TEST ROD (H-1)

been corrected from the water calibration tests conducted on H-1 (see Figures 5.5 and 5.6). A true circumferential temperature gradient, caused by tight rod packing, would have a linear dependence on heat flux, or rod power. As is evident from Figure 6.17, this is only true for the $P/D = 1.00$ test configuration. For the ring spacer and finned element test configurations, both at $P/D = 1.05$, the azimuthal temperature differences are independent of heat flux and can be attributed to experimental data scatter.

In addition to obtaining data over a range of heat flux conditions, cladding circumferential temperature distributions were measured for various Reynolds numbers (or Peclet numbers) of interest to a compact ZrH reactor core. For the center test rod (H-1), Table 4 presents data for the local cladding temperature above the local bulk coolant temperature ($T_{w_i}(\theta) - T_{b_i}$). These results have been corrected for the coolant channel temperature variations, such as those shown in Table 3, and the NaK calibration test results for H-1 shown in Figure 5.5. As is evident from Table 4, there is essentially no Re or Pe dependence over the range investigated ($35 \leq Pe \leq 220$).

The average values of the quantity, $(T_{w_i}(\theta) - T_{b_i})_{\text{corr.}}$, for various flow conditions, are also shown in Table 4. It should be

TABLE 4. LOCAL CLADDING TEMPERATURE ABOVE THE BULK COOLANT TEMPERATURE FOR VARIOUS REYNOLDS NOS., OR PECLET NOS.

$$\bar{q}'' = 46,700 \text{ Btu/hr-ft}^2$$

$$T_{w_i}(\theta) - T_{b_i}$$

(°F)

θ (degrees)	Re = 27,600 Pe = 220	Re = 22,600 Pe = 180	Re = 17,600 Pe = 140	Re = 13,200 Pe = 100	Re = 9100 Pe = 70
0	35.0	35.3	35.1	35.7	36.3
5	32.7	31.1	31.7	32.0	31.0
10	32.9 38.3	31.5 38.5	31.5 38.8	32.1 40.2	31.4 40.3
15	-	-	-	-	-
20	37.7 32.3	37.6 32.5	37.3 32.7	37.5 32.8	37.9 33.1
25	32.3 31.2	30.3 29.5	30.2 29.1	31.8 29.8	30.0 29.8
30	-	-	-	-	-
$T_{w_i}(\theta) - T_{b_i}$	34.1	33.3	33.3	34.0	33.7

pointed out that the average value of $(T_{w_i}(\theta) - T_b)$, before corrections were applied for the local coolant temperature variation and the NaK calibration tests, was equal to the average value of $(T_{w_i}(\theta) - T_{b_i})_{\text{corr.}}$, after the corrections were applied. As is evident from Table 4, there is essentially no dependence of $(T_{w_i}(\theta) - T_{b_i})_{\text{corr.}}$ on Reynolds number, or Peclet number.

6.2 Inner Cladding Wall Temperature Distributions

To determine the true inside cladding wall temperature distribution, the results shown in Figures 6.1 through 6.4 had to be corrected from the NaK calibration test results shown in Figure 5.4. The thermocouples, which are welded to the inner cladding tube, were not measuring the true inner wall temperature. As was found in Reference (2), the thermocouples were recording temperatures which correspond to ~5-mils into the MgO. Post-test NaK calibration tests on H-1 have confirmed that the correction factors, shown in Figure 5.4, are still valid. After the radial temperature correction factors shown in Figure 5.4 for NaK were applied to the above data at the corresponding power levels, the results shown in Figures 6.18 through 6.21 were arrived at. From Reference (2), the predicted results for the inner cladding azimuthal temperature variations are shown in Figure 6.22 for comparison. The poor agreement between theory and experiment can be attributed to the

Fig. 6.18 EXPERIMENTALLY CORRECTED RESULTS FOR
THE INSIDE CLADDING WALL CIRCUMFEREN-
TIAL TEMPERATURE DISTRIBUTION FOR H-1

$P/D = 1.05$
R-L-N FINNED
1.7 KN
32.9 mm
600°F-W/K

Fig. 6.17 EXPERIMENTALLY CORRECTED RESULTS FOR
THE INSIDE CLADDING WALL CIRCUMFER-
ENTIAL TEMPERATURE DISTRIBUTION FOR H-1

$T/L = 1.05$
R-L-N FINNED
2.11 KW
32.9 mm
600 °F - NGK

Fig. 6.20 EXPERIMENTALLY CORRECTED RESULTS FOR
TYPE INSIDE CLADDING WALL CIRCUMFER-
ENTIAL TEMPERATURE DISTRIBUTION FOR H-1

P/D = 1.05
R-L-N FINED
3.0 KW
32.75 in
600°F - NoK

Fig. 6-21 EXPERIMENTALLY CORRECTED RESULTS FOR
THE INSIDE CLADDING WALL CIRCUMFER-
ENTIAL TEMPERATURE DISTRIBUTION FOR H-1

$P/D = 1.05$
R-L-N FINNED
440 KW
32 gpm
400°F - NGK

FIG. 6.22 PREDICTED AZIMUTHAL VARIATION OF
INSIDE CLADDING WALL TEMPERATURE

fact that the predicted results were obtained from a smooth tube analytical model, which does not account for the turbulent mixing effect of fin spacers. However, the comparison between the actual and predicted results does give an insight into the extent of reduction of the azimuthal temperature variation caused by the spiral fin spacers.

6.3 Rod-Average Heat Transfer Coefficient

Experimental values for the rod average heat transfer coefficient ($\bar{h}$) were determined for the center test rod. From results such as those shown in Figures 6.18 through 6.21, which have been corrected for the radial temperature factors of Figure 5.4, average values of the quantity $(T_{w_i}(\theta) - T_b)$ were determined for various flow and heating conditions. The outer cladding temperature can then be found from

$$T_{w_o} = T_{w_i} - \frac{3413 W_r \ln \left(\frac{r_o}{r_i} \right)}{2\pi L_H k_w}$$

From measurements of the power supplied to the center test rod and the bulk coolant temperature at $z_H/L_H = 0.80$, the rod-average film coefficient is determined by

$$\bar{h} = \frac{3413 W_r}{\pi D L_H (T_{w_o} - T_b)}$$

The experimental values of $\bar{h}$ are shown in Figure 6.23 in dimensionless form of Nusselt number vs Peclet number. In the flow range investigated, the Nu values are seen to be independent of Pe. The mean value of the data points, $Nu = 4.20$, corresponds to a heat transfer coefficient of $\bar{h} = 6900 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$. The average deviation of the data points from the mean value is $\pm 2\%$. In addition, Figure 6.23 shows the predicted Nusselt number based on the smooth tube theoretical model described in Reference (2). From a comparison of the predicted and experimental results, it can be concluded that the spiral fins caused a 53% increase in the rod-average Nu.

6.4 Transition Flow Test

For the present study, an attempt was made to determine the transition Reynolds number, that is, the Re value at which transition from turbulent to laminar flow takes place. Tests were conducted at low coolant flow rates corresponding to a Re range of 2000-5000. To determine the transition Re, temperature vs time recordings were obtained from selective cladding and coolant channel thermocouples. At the transition Re, relatively large temperature fluctuations would be observed. It was found, however, that no temperature oscillations were recorded for Re values as low as 2000. The presence of the rod helical fins have apparently shifted the

transition Re to a value below 2000. Operating at Reynolds numbers below 2000 was not possible with the present loop configuration.

6.5 Comparison of Results for Three Test Configurations

Three 19-rod bundle test configurations have been examined to date. For these configurations, Figures 6.24 and 6.25 show comparisons for the center rod azimuthal temperature variation and the average Nusselt number, or film coefficient. In addition, these figures show the predicted rod temperature variation and Nusselt number based on a smooth tube (no spacers) analytical model described in References (1,2). Figure 6.24 shows that the effect of the ring and finned spacers was to eliminate the rod azimuthal temperature variation. With respect to the rod-average film coefficient, Figure 6.25 shows considerably greater values for the $P/D = 1.05$ bundles than for the $P/D = 1.00$ bundle. In addition, comparing the results shown in Figures 6.24 and 6.25 for the two rod bundles at $P/D = 1.05$, it is evident that the finned spacers resulted in a lower average value of the wall temperature difference ($T_{w_i}(\theta) - T_b$) and a greater rod-average film coefficient, as compared to the ring spacer results. Since the effects of the spacers is not included in the analytical model, good agreement between theory and experiment is evident only for the smooth tube, $P/D = 1.00$ rod bundle.

Fig. 6.24 Center-rod azimuthal temperature variation for the three test configurations examined to date

Fig. 6.25 Nusselt number variation with Peclet number for the three test configurations examined to date

7. ASYMMETRIC HEATING TESTS

Asymmetric heating tests were performed to determine the extent of coolant channel temperature change due to fin-induced mixing. The asymmetric heating conditions were produced by turning off selective heaters in the 19-rod bundle. This, in effect, produced coolant-to-coolant channel temperature differences. Experimental results were determined for the individual outlet coolant channel temperatures under various asymmetric heating conditions. By comparing these results to predicted values assuming no inter-channel mixing, the effect of the fins in changing the coolant channel ΔT s can be determined.

For the illustrations that follow, results will be presented for the axial temperature rise for selective individual coolant channels in the 19-rod bundle. With all 19 heaters operating at the same power level, Figure 7.1 presents coolant temperature results for interior channels of the 19-rod bundle. These results, which were obtained under symmetric heating conditions, will be compared to results obtained under asymmetric heating conditions. As previously mentioned, the coolant channel temperature variations, evident in Figure 7.1, can be attributed to rod and fin dimensional tolerances which result in flow area variations.

Fig. 7.1 COOLANT CHANNEL TEMPERATURE RISE
WITH ALL RODS AT 1.7 KW AND 26 gpm
P/D = 1.05
R-L-N FINNED

Coolant channel temperature results are presented in Figure 7.2 for conditions where power is supplied only to the center test rod (H-1). The arrows shown on the diagram indicate the direction of the spiral fin wrap. Referring to the six tricuspid coolant channels adjacent to H-1, it is evident that inter-channel mixing is taking place due to the alternating hot and cold channels. Relatively hot and cold channels result where the fins are sweeping out from and into the center rod, respectively. With power supplied only to the center heater and assuming no inter-channel mixing, the coolant temperature rise for those channels adjacent to H-1 can be computed by multiplying the values shown in Figure 7.1 by $1/3$. These results are shown in Figure 7.2. By averaging the six channel temperatures adjacent to H-1, for the results shown in Figures 7.2, with and without mixing, it is found that the presence of the fins resulted in an overall 43% reduction in temperature rise for the fluid adjacent to H-1.

With power supplied to the inner seven test rods (H-1 through H-7) and the outer twelve rods (H-8 through H-19) at zero power, Figure 7.3 shows the temperature rise for the twelve interior channels. Again, with the relatively hot and cold channels where the fins are sweeping out and into H-1, respectively, the existence of inter-channel mixing is evident. With power supplied to the inner

Fig. 7.2 COOLANT CHANNEL TEMPERATURE RISE
WITH H-1 ON ONLY AT 1.7KW AND 269pm.

P/D = 1.05

R-L-N FINNED

FIG. 7.3 COOLANT CHANNEL TEMPERATURE RISE
WITH H-1 THRU H-7 ON ONLY AT 1.7KW; 269PM
P/D=1.05
R-L-N FINNED

seven rods only and assuming no inter-channel mixing, the coolant temperature rise for those channels adjacent to H-1 would be identical to the values shown in Figure 7.1. It is found by averaging the six coolant temperatures adjacent to H-1, for the results shown in Figures 7.1 and 7.3, that a 26% reduction in the overall temperature rise can be attributed to inter-channel mixing.

Figure 7.4 presents results for the coolant channel temperatures with power supplied to all rods, except H-2. By referring to the "no mixing" results shown in Figure 7.4, the extent of influence on the rod bundle interior channel temperatures is evident. The "no mixing" results were determined from Figure 7.1 by assuming no inter-channel mixing and a $2/3$ heat input to channels adjacent to H-2. Figure 7.4 shows that inter-channel mixing resulted in a 23% average increase in the coolant temperature rise for the two channels adjacent to H-2. With respect to the cross-coolant temperature difference, the results shown in Figure 7.4 indicate that a 44% reduction was obtained due to fin-induced inter-channel mixing.

For the three rod bundle configurations examined to date (see Reference 2), Figure 7.5 presents coolant temperature results for the case of power supplied to the center rod (H-1) only. By comparing the results of the three test configurations, the influence of the fins on the coolant channel temperature rise is clearly

Fig. 7.4 COOLANT CHANNEL TEMPERATURE RISE
WITH POWER (1.7KW) SUPPLIED TO ALL
RODS, EXCEPT H-2 WHICH IS AT ZERO POWER

$P/D = 1.05$
R-L-N FINNED

□ - EXPT. MEAS.
○ - THED. - NO MIXING

Fig. 7.5 COOLANT CHANNEL TEMPERATURE RISE
WITH H-1 ON ONLY AT 1.7 KW AND 269 PM
FOR THE THREE TEST CONFIGURATIONS
EXAMINED TO DATE

- ▲ — P/D = 1.00
 □ — P/D = 1.05 (RING SPACERS)
 ○ — P/D = 1.05 (R-L-N FINNED)

illustrated. For the results shown in Figure 7.5, the average value of the coolant temperature rise adjacent to H-1 was computed for each test configuration and compared to the corresponding value assuming no inter-channel mixing. It was found that inter-channel mixing resulted in 4%, 19%, and 43% reduction in coolant temperature rise for the smooth tube ($P/D = 1.00$), ring spacer ($P/D = 1.05$), and R-L-N finned element ($P/D = 1.05$) bundles, respectively.

With respect to cross-coolant ΔT reduction due to inter-channel mixing, Table 5 shows a comparison of results for the three rod bundle configurations. These results were determined with no power supplied to H-2 in order to create a cross coolant ΔT from channels "A" to "B". The predicted results, shown in Table 5, were determined by assuming no inter-channel mixing and 2/3 heat input to channels "B-B". As is evident, there is considerably greater inter-channel mixing taking place in the finned element bundle as compared to the ring spacer bundle, both of which are at $P/D = 1.05$. As expected, due to zero spacing between elements, the smooth tube rod bundle ($P/D = 1.00$) shows no reduction in the cross-coolant ΔT .

In addition to the results shown in Figures 7.1 through 7.5 and Table 5, asymmetric heating tests were performed at other power levels and flow rates. It was found that the conclusions, in terms of percentage changes, were independent of power and flow rate over the range (see Table 2) investigated.

TABLE 5 Comparison of Results for the Cross-Coolant Channel Temperature Differences for the Three Rod Bundles Examined to Date

$\Delta T = \bar{T}_A - \bar{T}_B$	CROSS COOLANT ΔT /WITH ONE HEATER OFF*		
	SMOOTH WALL P/D = 1.0	RING SPACERS P/D = 1.05	FINS P/D = 1.05
PREDICTED (W/O MIXING)	17	21	16
MEASURED	17	17	9
% REDUCTION	0	19	44

* 1.7 KW, 26 GPM, HEATER NO. 2 OFF

8. CONCLUSIONS AND DISCUSSION OF RESULTS

A closely spaced ($P/D = 1.05$) rod bundle has been tested under the conditions of turbulent longitudinal flow of liquid NaK. Helical-fin spacers were employed to maintain uniform spacing between rods and to promote both intra-channel turbulence and inter-channel mixing. Testing was performed in the low Pe regime (35 to 240) and under heating conditions (28,000 to 110,000 Btu/hr-sq.ft) that are considered typical for a compact ZrH reactor core. Based upon the experimental results, the following important conclusions can be made:

1) Due to a significant increase in the intra-channel turbulence caused by the helical-fin spacers, negligible circumferential temperature variations were observed.

2) The increased turbulence created by the fins resulted in a 55% increase in the rod-average Nu value over the smooth tube value.

3) In the flow range investigated, the cladding temperature distribution and the rod-average film coefficient (or Nu) are independent of Re, or Pe.

4) The R-L-N, helical-fin spacer configuration produced appreciable inter-channel mixing, or crossflow. This was observed for the asymmetric heating tests in which a 44% reduction in the cross coolant-to-coolant channel ΔT was found. This reduction was

more than twice that observed for the rod bundle employing ring spacers.

To the present author's knowledge, the study presented here represents the first time that experimental liquid metal heat transfer data have been obtained for a closely spaced rod bundle employing helical-fin spacers. The data confirmed earlier expectations that improved heat transfer performance would result from the use of this type of rod spacer. The increased intra-channel turbulence created by the fins made negligible any rod azimuthal temperature variation and significantly improved the rod-average film coefficient. The fin induced inter-channel mixing, or crossflow was observed to be significant. For the actual ZrH reactor core, the added crossflow should do a great deal in reducing cross fuel element ΔT s and the resulting bending stresses which occur during clustered rod and asymmetric fuel slug conditions.

As previously indicated, great care was taken in the experimental loop and test section design and in insuring a clean liquid metal system. These precautions resulted in obtaining reliable data which can be applied with confidence in the design and analysis of compact reactor cores. It should be noted, however, that the results presented earlier are strictly true only for the conditions of the experimental study. Care must be exercised in applying the present test results to conditions other than those examined.

9. NOTATION

D = rod diameter, ft.

D_h = $D \left[\frac{2\sqrt{3}}{\pi} (P/D)^2 - 1 \right]$ = hydraulic diameter of rod bundle, ft.

g_o = gravitational constant, $\text{lb}_m\text{-ft./lb}_f\text{-sq.hr.}$

h = heat transfer coefficient, $\text{B.t.u./hr.-sq.ft.-}^\circ\text{F.}$

k = thermal conductivity, $\text{B.t.u./hr.-ft.-}^\circ\text{F.}$

L_H = heated length, ft.

Nu = $\bar{h} D_h / k_f$ = Nusselt number, dimensionless

P = pitch, or distance between rod centers, ft.

Pe = $(Re)(Pr)$ = Peclet number, dimensionless

Pr = $\mu C_p / k_f$ = Prandtl number, dimensionless

q'' = heat flux, B.t.u./hr.-sq.ft.

Re = $\rho \bar{u} D_h / \mu$ = Reynolds number, dimensionless

r = radial coordinate, ft.

T = temperature, $^\circ\text{F.}$

W_r = electrical power per rod, kw.

z = axial coordinate, ft.

Greek Letters

θ = azimuthal coordinate, radians

μ = viscosity of coolant, $\text{lb}_m/\text{ft.-hr.}$

ρ = density of coolant, $\text{lb}_m/\text{cu.ft.}$

Subscripts

b = bulk coolant
F = flow development; fuel or MgO region of test rod
f = coolant
H = heated region of test rod; thermal profile development
i = inside; local
o = outside
w = cladding wall

Other

$$\overline{(\quad)} = \frac{6}{\pi} \int_0^{\pi/6} (\quad) d\theta = \text{average value}$$

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