Investigation of Combined Free and Forced Convection in a 2 x 6 Rod Bundle During Controlled Flow Transients

J. M. Bates
E. U. Khan

October 1980

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IN A 2 x 6 ROD BUNDLE DURING CONTROLLED FLOW TRANSIENTS

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E. U. Khan

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Pacific Northwest Laboratory
Richland, Washington 99352

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SUMMARY

An experimental study was performed to obtain local fluid velocity and temperature measurements in the mixed (combined free and forced) convection regime for specific flow coastdown transients. A brief investigation of steady-state flows for the purely free-convection regime was also completed. The study was performed using an electrically heated 2 x 6 rod bundle contained in a flow housing. In addition a transient data base was obtained for evaluating the COBRA-WC thermal-hydraulic computer program (a modified version of the COBRA-IV code).

The objective of the study was to develop an understanding of the thermal-hydraulic phenomena at low flows in a rod bundle subjected to lateral power skews. Test conditions included 500-, 300-, 150- and 45-second flow coastdown transients, a Reynolds number range of ~90 to ~1300, and power skews of 1:0, 2:1, 3:1, and 4:1. The dimensionless group Gr^*/Re^2 , which represents the ratio of buoyancy to inertial forces, was varied in the range 0.0 to 2.4 at selected lateral power skews. Flow recirculation zones were detected in the bundle during transient conditions at large ratios of buoyancy to inertial forces as indicated by the measurements of downward flow in the colder subchannels and upward flow in the hotter subchannels. No flow recirculation was detected in the bundle at steady-state conditions except at extremely low Reynolds numbers where heat loss and/or hydraulic effects of the discharge geometry become important. The length of the recirculation zone in the axial direction was observed to be dependent on rod power level, the lateral power skew, and the total flow rate.

The data were compared to predictions obtained with the COBRA-WC computer code. COBRA-WC satisfactorily predicted the measured bundle subchannel velocity and temperature histories. At Reynolds numbers below 450 an improvement in the turbulent mixing model in COBRA-WC was required to satisfactorily predict experimental results. This improvement was necessary because as the magnitude of the buoyancy forces increased, thermal plumes grew laterally as they moved axially upward. When adjacent thermal plumes interacted, turbulence was

generated which appeared to promote lateral mixing between subchannels. A model incorporating the enhanced turbulent mixing due to the thermal plume interactions was used to improve the COBRA-WC predictions at large ratios of Gr^*/Re^2 . The enhanced turbulent mixing parameter was correlated as a function of Grashof and Reynolds numbers (Gr/Re^2) and the ratio of local heat generating rate to the bundle average heat generation rate.

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1.0 INTRODUCTION

Different types of transients must be considered in the design of Liquid Metal Fast Breeder Reactor (LMFBR) fuel and blanket assemblies. A postulated transient which can have a direct impact on fuel performance and on core design is the "Three-Loop Natural Circulation" transient. It is initiated by loss of all on-site and off-site power, resulting in reactor/turbine trip due to primary pump undervoltage relays. The auxiliary (pony) motors, which are supposed to provide forced cooling at a reduced flow rate, are assumed to be inoperative due to loss of their dc power supply. Consequently, sodium pumps coast down and stop, and natural circulation is established in all sodium loops. During this transient the core assemblies are subjected to a wide range of flow conditions, extending from laminar to turbulent flows and encompassing forced-, mixed-, and natural-convection flow regimes. A detailed discussion of the various thermal-hydraulic phenomena within the core during the natural circulation transient has been given by Markley, Coffield, and Khan (1979). The thermal-hydraulic phenomena which become important during a natural-circulation transient include interassembly heat transfer, interassembly flow redistribution due to buoyancy forces, and intra-assembly heat transfer and flow redistribution due to buoyancy.

Interassembly thermal-hydraulic phenomena were not considered in this study. The present study focused on understanding the two aforementioned intra-assembly thermal-hydraulic phenomena in the buoyancy-dominated flow regime during a controlled-flow transient. For mixed-convection flow transients, the flow was linearly decreased from an initial to a final flow condition which was then maintained constant for the remainder of the transient. This type of a flow transient represents the case where the pony motors are operational and forced cooling is available at the end of the transient for long times. The case of complete loss of forced cooling is reported for steady-state conditions only.

Another purpose of the present studies was to further evaluate the transient thermal-hydraulic models in existing subchannel analysis codes, such as COBRA-WC (George, Basehore, Wheeler, Prather and Masterson 1980) which are used for reactor design and safety analysis.

Reactor fuel and blanket assemblies can be subjected to severe radial heat flux gradients. At low-flow conditions, with power-to-flow ratios of nearly the same magnitude as safety analysis design conditions, flow redistributes to the side of a bundle with the higher heat generation rate. Buoyancy forces cause flow redistribution within the bundle. There is a significant mitigation of transverse temperature gradients within the bundle due to flow redistribution from the cooler to the hotter regions of the bundle. Quigley, McMonagle, and Bates (1977) found that at steady-state low-flow conditions the presence of a lateral power skew across a 2 x 6 rod bundle caused significant flow redistribution due to buoyancy forces with a consequent reduction in transverse temperature gradients. The geometry of the 2 x 6 rod bundle was chosen by Quigley et al. in order to facilitate direct velocity measurement by laser doppler anemometry. The present study extends Quigley's work to include mixed-convection flow transients and steady-state, free-convection flows.

Existing analytical studies (Tsai, Bishop, and Markley 1973; Khan et al. 1975) and experimental studies (Quigley et al. 1977; Singer, Kerian, and Parkinson 1972) have shown that at buoyancy-dominated low-flow conditions the important parameters include the radial power skew across the bundle, the bundle Reynolds number (Re), and the Grashof number (Gr). The lateral temperature difference has been related to the product of the axial mixed mean temperature rise within the bundle and the radial power skew by Khan et al. It was found that buoyancy effects become increasingly important as Gr^*/Re^2 increases. Gr^* is the product of Gr , the bundle Grashof number based on bundle mixed mean temperature rise, and $(\hat{Q}_p - 1)$, where $\hat{Q}_p$ is the ratio of the subchannel local heat generation rate to the bundle average heat generation rate. Other important parameters during a transient include the flow ramp rate and the initial and final Reynolds numbers. These parameters were varied in the present experiments in order to understand their importance in the low-flow, buoyancy-dominated regime.

2.0 CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

The results of this study permitted the following conclusions for the prescribed test conditions:

- An improvement in the turbulent crossflow mixing model in COBRA-WC resulted in acceptable predictions of velocity and temperature histories when the Reynolds number (Re) during the transient fell below ~450. The turbulent mixing is due to the interaction of thermal plumes developed in the vicinity of the heated pins.
- Recirculation was detected during a transient induced by the flow coastdown. No recirculation zones were formed during steady-state flow conditions with $Re \geq 300$. A hypothesis was formulated which adequately describes this behavior.
- A preliminary criterion for the inception of recirculation in the mixed-convection transient flow regime was found to be $Gr/Re^2 (\hat{Q}_p - 1) \geq \sim 0.2$. This criterion was obtained for the 2 x 6 rod bundle geometry investigated.
- Transient velocity and temperature predictions obtained with the COBRA-WC computer program using default input parameters were in satisfactory agreement with experimental data as long as the Reynolds number was above ~450 at all times during the transient.
- Natural-convection (purely buoyancy-driven) flow regime steady-state velocity profiles were indistinguishable from those measured in the mixed-convection regime for the limited range investigated.

2.2 RECOMMENDATIONS

After considering the results of this study, it is recommended that the following investigations be undertaken.

- Transient tests should be performed to study the detailed effects of a flow coastdown encompassing a transition from forced convection to purely natural convection. Such tests would more closely model the postulated "Three-Loop Natural Circulation Transient."
- Tests similar to those described in this report should be performed in geometries more characteristic of prototypic LMFBR assemblies.
- The relationship between subchannel centerpoint and subchannel average velocities and temperatures needs to be quantified (by more detailed measurements) in order to more directly correlate code predictions and experimental measurements.
- The effect of upper plenum geometry and thermal stratification on flow redistribution in the active heated length needs to be investigated.
- A generalized criterion for inception of recirculation within prototypic LMFBR assemblies is needed.

3.0 EQUIPMENT AND EXPERIMENTAL PROCEDURE FOR MIXED-CONVECTION FLOW STUDIES

This experiment was conducted in the test facility diagrammed in Figure 3.1. A detailed description of the facility, instrumentation, and experimental procedure is presented in the following sections.

3.1 TEST FACILITY

The basic equipment consisted of the electrically heated 2 x 6 rod bundle enclosed in a rectangular flow housing connected to an open flow loop with transient flow control capability.

3.1.1 Flow Loop

The once-through transient flow loop is shown in the schematic of Figure 3.1. During normal, daily operation the 3000-gallon water supply tank was filled at least 24 hours prior to loop operation. This procedure allowed the water supply to reach a near-ambient isothermal temperature that would remain essentially constant through each test period. Also any large particles that might be contained in the building process water were allowed to settle. Allowing the water to reach nearly ambient conditions helped to deaerate the water, reducing any tendency for bubble formation in the heated test section.

Water was drawn from the supply tank by the loop supply pump and pumped through a filter manifold and coiled rubber hose to the loop pressure control valve. The flexible hose helped to damp out vibrations and high-frequency, pump-induced flow oscillations.

A differential pressure relief valve was installed to allow the test-section pressure to remain nearly constant during transient flow conditions. As the total flow to the test section was ramped down, the relief valve diverted a proportionately larger fraction of the pump discharge total flow to drain. The test section pressure could therefore be maintained near the set-point pressure of ~20 psi.

Transient flow control was by means of an electro-pneumatic control valve downstream of the test section. Valve position and thus test section

FIGURE 3.1. Transient Flow Facility

total flow were proportional to a variable 4- to 20-mA input control signal. The valve positioner control signal was derived from the 0-5 V (converted to 4- to 20-mA) output of an X-Y curve follower with variable time sweep. The curve follower-signal converter-control valve system was programmed to ensure repeatable transient flow control capability.

3.1.2 Rod Bundle

The 2 x 6 rod bundle geometry for this study was exactly the same as that used by Quigley, McMonagle, and Bates (1977). A cross section of the 2 x 6 rod bundle test section is shown in Figure 3.2. Subchannels were sized such

SUBCHANNEL DIMENSIONS			
TYPE	AREA (in. ²)	WETTED PERIMETER (in.)	HEATED PERIMETER (in.)
CORNER	0.0782	1.073	0.3731
SIDE	0.1127	1.321	0.7461
CENTRAL	0.1534	1.492	1.492

FIGURE 3.2. Bundle Cross-Section with Subchannel Numbering Scheme and Bundle Dimensions (in.)

that an equal enthalpy rise would be obtained in the side (numbers 9-13 and 16-20) and adjacent central (numbers 2-6) subchannels. This design served to maintain major gradients in the long dimension of the bundle (X direction) and minimize flow housing wall effects.

Rod bundle dimensions and orientation with respect to the reference coordinate system are shown in Figure 3.2. The $X = 0.0$ reference point corresponds to the interior surface of the left side window, while the $Y = 0.0$ reference was taken as the centerline between the two rows of six heater rods.

3.1.3 Heater Rods and Rod Assembly

A typical instrumented, nickel-chrome wire internal-resistance-type heater rod used in the experiment is shown in Figure 3.3. The 0.475-in. diameter rods had a 4-ft heated length rated at 1 kW/ft at 270 V (ac). The assembled 2 x 6 rod bundle was held in position by support spacers (Figure 3.4) provided at three axial locations along the heated length as well as by two flow distribution plates at the inlet end of the flow housing. The individual heater rods were fixed at one end of the housing and held in spring-loaded tension at the other to allow for thermal expansion. The 2 x 6 bundle assembly is shown in Figure 3.5.

The support spacers were formed by stacking several 0.020-in.-thick photochemically machined Inconel units to the desired thickness. The design, with its small total area was intended to induce a minimum level of turbulence to the laminar flow profiles typical of this experiment. Spacers No. 1 and No. 2 were 0.300 in. thick, while spacer No. 3 was 0.100 in. thick.

The 2 x 6 rod bundle was contained within a rectangular stainless steel flow housing constructed of face plates, sides, and top and bottom end plates. Nine windows located in the face plates at 6-in. intervals over the 4-ft test section heated length permitted optical access for the laser Doppler anemometer (LDA) measurements. In addition the windows provided insertion and mounting locations for the thermocouple hardware. The top and bottom plates of the flow housing contained twelve 0.377-in.-dia holes for the penetration of the heater rod extensions. All joining surfaces of the assembly were sealed with O-rings to accommodate internal pressures to 60 psia.

FIGURE 3.3. Heater Rod

FIGURE 3.4. Support Spacer

3.2 INSTRUMENTATION

For each of the various test conditions of this study, fluid axial velocity and temperature (both local and bulk average inlet and outlet) were measured within the heated length of the rod bundle. Rod temperatures were monitored using the embedded thermocouples in each rod. Bundle total flow rate was monitored continuously. Rod power was monitored by means of ac wattmeters (six units total – one for each rod pair); voltage and current were measured to give an analog output of rod power. The complete instrumentation diagram for this study is shown in Figure 3.6.

3.2.1 Velocity Measurements

A laser Doppler anemometer (LDA) was used to measure local fluid velocities. For this experiment, the two most important advantages of the LDA method were that the probe volume did not disturb the flow and that the LDA approach is inherently accurate because of its easy calibration.

Figure 3.7 is a schematic of the LDA apparatus used in this study. A 400-mW argon-ion laser was the light source. A modular-design beam splitter split the incoming beam into two parallel beams which were unequally frequency shifted by acousto-optic modulation and focused to a probe volume approximately

FIGURE 3.5. Rod Bundle Assembly and Flow Housing

FIGURE 3.6. Instrumentation Diagram

FIGURE 3.7. Laser Doppler Anemometer System

0.012 in. in diameter and 0.092 in. long. This Bragg cell frequency shifting provided a reference frequency (51.1 kHz) offset to the LDA signal such that it was possible to measure zero or negative velocities without ambiguity. Natural contaminant, light-scattering particles within the water encountered the intersection probe volume interference fringe pattern. The resulting scattered light was Doppler-frequency shifted with respect to the incident laser light frequency. The collecting optics gathered and focused this scattered light onto the photomultiplier tube. The signal was processed with a TSI Model 1090 Tracker/signal processor and recorded by the data acquisition system (see Figure 3.6). A more complete description of the LDA measurement technique and the approach used in previous experiments in this loop is provided by Creer et al. (1976).

The signal processor analog output was equipped with resistance-capacitance (RC) damping circuit with a time constant (τ) of ~5 seconds. This damping circuitry served to damp out the large velocity oscillations induced by thermal plumes and convective mixing and give a time-averaged local velocity reading. For steady-state flow conditions this circuitry should give a reliable average frequency (thus velocity) reading.

However, during the course of the flow transient runs where the bundle average velocity was ramped linearly downward over a specified time period, the RC circuitry induced some lag in the velocity measurements. Detailed analysis (see Appendix B) has shown this damping-induced lag to be approximately 2.2% for the 150-sec flow transient period and 7.5% for the 45-sec flow transient period based on bundle average flow velocities.

The LDA optics were mounted on a traversing table that allowed positioning of the measurement probe volume in the X-Y horizontal plane within ± 0.001 in. Horizontal positioning was achieved with variable-speed servomotors and encoder readouts. A hydraulic lift system was used to position the table vertically to within ± 0.050 in.

3.2.2 Temperature Measurements

Local fluid temperature measurements were made with iron-Constantan thermocouples. A rake of seven thermocouples was mounted on a stainless steel plate as shown in Figure 3.8. Measurements were made by replacing one of the nine flow housing windows with the rake assembly such that the seven

FIGURE 3.8. Thermocouple Rake

thermocouples located along the $Y = 0.0$ axis (see Figure 3.2) measured the temperatures at the centers of subchannels 1 through 7. During data runs, the rake assembly was positioned at least two windows above the elevation at which LDA velocity measurements were being made. Previous velocity measurements by Quigley, McMonagle, and Bates (1977) had shown that the rake did not influence the velocity data for this spacing. Additional iron-Constantan thermocouples were used to measure test section bulk inlet and outlet temperatures. A calibrated commercial reference junction was used for all thermocouple measurements.

Individual heater rods were also instrumented with chromel-Alumel thermocouples at selected axial and radial locations as shown in Figure 3.3. Radial positions of the wall thermocouples could be adjusted by rotating the entire rod within the bundle assembly. Rod temperature data for all run conditions, both steady-state and transient, were collected but are not presented in this report.

3.2.3 Rod Power Measurements

Two 25-kVA, three-phase variacs provided power for the heater rods. Each pair of heater rods, e.g., rods 1 and 2, 3 and 4, 5 and 6, etc., were connected in parallel to one phase of each of the two three-phase supplies as shown in Figure 3.9. A two-step power gradient could thus be established in the X direction by individual adjustment of the two variacs' power levels.

Heater rod powers were continuously monitored by means of solid-state, Hall-effect type AC watt transducers. Each single-phase transducer was connected to one phase of each variac; thus six transducers were required to monitor power to the six rod pairs.

FIGURE 3.9. Power Supply Connections for a Two-Step Power Gradient

3.3 EXPERIMENTAL PROCEDURE

The LDA and data acquisition system were checked out and adjusted in isothermal flow prior to data collection for any given axial level and/or test condition. The optical table was first moved to the desired vertical position, and then the laser beams were checked for alignment with the rod rows. If necessary, the LDA optics were adjusted to optimize the Doppler signal. The centerline of the central subchannels between the two rod rows, $Y = 0.0$, was located by traversing the LDA probe volume in both the plus and minus Y directions until the Doppler signal completely disappeared as observed on an oscilloscope. The loss of signal indicated the position of the row of heater rods and was repeatable to ± 0.002 in., approximately 2 per cent of the rod gap.

The $Y = 0.0$ position was defined as the midpoint of the measured gap width, which was found to vary ± 0.010 in. from the nominal 0.100-in. gap. Specifications for the heater rod units called for 0.010 in./ft straightness and a ± 0.002 -in. tolerance on outside diameter.

The $X = 0.0$ reference plane was determined by traversing the probe volume in the X-direction until the frequency tracker displayed zero velocity (the 51.1 kHz differential Bragg cell shift frequency), indicating the probe volume was positioned at the inside surface of the window. Location of the $X = 0.0$ point was repeatable to ± 0.020 in.

When the optical system was positioned and reference coordinates established, the inlet flow and heater rod power levels were adjusted to the desired levels. The system was allowed to reach steady-state conditions before either steady-state velocity traverse data acquisition was begun or before a flow transient condition was initiated. All velocity, x-y position, inlet flow, pressure, rod power, and temperature measurements were recorded simultaneously on seven track magnetic tape and on a paper printer. For steady-state velocity profile measurement conditions, data scans were initiated manually while for transient flow test runs, data scan rates were controlled by a digital clock incorporating selectable scan intervals. All data reduction and tabulation was handled by a FORTRAN computer program.

3.3.1 Bundle Flow Measurements

A 1/2-in.-dia. extended-range (0.08–8.0 GPM) turbine flowmeter was used to measure total test section flow rates. The flowmeter had a 3-msec dynamic response time so that instantaneous flow rates could be accurately measured during the controlled flow transient.

4.0 OPERATING CONDITIONS

The operating conditions for this series of experiments were initially chosen to match the run conditions used by Quigley, McMonagle, and Bates (1977) for a 1:0 power gradient at low Reynolds number (~ 480). Selection of such previously studied steady-state conditions to serve as an end point for a transient flow condition allows better interpretation of the test results and adds additional credibility to the experimental measurements.

As discussed by Quigley et al. the complex and sometimes severe thermal gradients found in heated rod bundles at low flow rates add a certain degree of difficulty to LDA measurements. Further discussions of the problems of LDA measurements in flows containing time and spatially dependent index of refraction distributions are presented by Buchhave, George, and Lumley (1977) and Durst (1977).

4.1 LDA MEASUREMENT CAPABILITY

The index of refraction for water varies from 1.333 at 75°F (typical bundle inlet temperature) to 1.319 at 200°F (typical maximum observed rod wall temperatures in the heated bundle) (Weast [1971]; Tilton and Taylor [1978]). This index variation of $\sim 1.1\%$ can have appreciable effects on LDA measurements as discussed by Buchhave et al. (1979). This situation could hold true for a given instantaneous Doppler signal, but for a continuous LDA signal with 10^3 – 10^5 samples/second validation rate in a location with a nominal temperature gradient of zero, a tracking-type signal processor will give accurate velocity readings (indicated in the uncertainty analysis of Section 5).

Zones of time-averaged, non-zero temperature gradients normal to the beam path give rise to static beam deflections, and therefore a high degree of positional uncertainty for LDA measurements. Non-zero temperature gradients existed for the wall subchannels (subchannels 8 through 21 of Figure 3.2) of the 2 x 6 test bundle for all heated runs. Therefore the majority of velocity measurements in this study were confined to the $Y = 0.0$ axis of the bundle, the centerline of the central subchannels (subchannels 1 through 7) between the two rows of heater pins.

Quigley, McMonagle, and Bates (1977) report on similar problems with LDA measurements in heated flows. It should be noted that for the particular signal processor and optical arrangement used in the LDA setup of the earlier study, Quigley et al. were unable to get complete velocity traverse data at all axial levels for bundle bulk temperature rises of 33°F at $\text{Re} \approx 480$. However, the improved electronics and optics as well as the more powerful laser of the current study allowed for successful velocity measurements under much more severe conditions ($\Delta T_B \geq 186^{\circ}\text{F}$). Although dynamic deflections of the LDA probe volume due to time varying thermal gradients and plumes were observed, such deflection appeared much less severe than those reported earlier. A more geometrically symmetric arrangement of rods in the bundle assembly is the most probable explanation.

4.2 EXPERIMENTAL CONDITIONS

For the cases studied, velocity measurements were made along the $Y = 0.0$ axis, the centerline of the central subchannels. Some off-centerline measurements were made for comparison purposes. For the steady-state flow cases, complete velocity profile measurements were made with velocities measured every 0.067 in. in the X direction. Multiple readings were recorded to establish the degree of data scatter.

Velocity data were recorded at selected points along the central subchannel axial centerlines (centerpoints) for the transient flow cases. The LDA probe volume was positioned at the selected subchannel centerpoint; data acquisition at selected time intervals (generally 3 or 5 seconds) was initiated; and then the flow transient was begun. Data acquisition continued until steady-state conditions were established. The probe volume was then moved to the next subchannel centerpoint and the initial conditions re-established. The flow transient was then repeated. Numerous checks of data repeatability were performed and each data run was performed at least twice for all heated transient cases.

Table 4.1 is a summary of the various test cases, both steady-state and transient. Cases 1 and 2 are basically repeats of test conditions used by Quigley, McMonagle, and Bates (1977), and are presented for comparison of data

TABLE 4.1. Nominal Run Conditions

Case Number	W _i (GPM)	W _f (GPM)	Transient Time (sec)	Power Gradient	Q _H (kW/rod)	Q _L (kW/rod)	Re ^(a) (initial/final)	Gr* (initial/final)	Gr*/Re ² (initial/final)	ΔT (°F) (initial/final)
1	1.25	1.25	S.S.	0:0	0.0	0.0	490/490	0.0/0.0	0.0/0.0	0.0/0.0
2	1.25	1.25	S.S.	1:0	0.91	0.0	580/580	5.59x10 ⁴ / 5.59x10 ⁴	0.166/0.166	29.8/29.8
3	3.08	3.08	S.S.	0:0	0.0	0.0	1200/1200	0.0/0.0	0.0/0.0	0.0/0.0
4	3.08	3.08	S.S.	1:1	0.91	0.91	1390/1390	0.0/0.0	0.0/0.0	24.2/24.2
5	3.08	1.08	150	0:0	0.0	0.0	1200/420	0.0/0.0	0.0/0.0	0.0/0.0
6	3.08	1.08	150	1:0	0.91	0.0	1290/520	1.65x10 ⁴ / 7.04x10 ⁴	0.00/0.264	12.1/34.5
7	3.08	1.08	45	0:0	0.0	0.0	1200/420	0.0/0.0	0.0/0.0	0.0/0.0
8	3.08	1.08	45	1:0	0.91	0.0	1290/520	1.65x10 ⁴ / 7.04x10 ⁴	0.010/0.264	12.1/34.5
9	3.08	3.08	S.S.	1:0	0.91	0.0	1290/1290	1.65x10 ⁴ / 1.65x10 ⁴	0.010/0.010	12.1/12.1
10	1.08	1.08	S.S.	0:0	0.0	0.0	420/420	0.0/0.0	0.0/0.0	0.0/0.0
11	1.08	1.08	S.S.	1:0	0.91	0.0	520/520	7.04x10 ⁴ / 7.04x10 ⁴	0.264/0.264	34.5/34.5
12	3.08	1.08	45	2:1	0.91	0.455	1340/560	9.20x10 ³ / 4.56x10 ⁴	0.005/0.146	18.2/51.8
13	3.08	3.08	S.S.	2:1	0.91	0.455	1340/1340	9.20x10 ³ / 9.20x10 ³	0.005/0.005	18.2/18.2
14	1.08	1.08	S.S.	2:1	0.91	0.455	560/560	4.56x10 ⁴ / 4.56x10 ⁴	0.146/0.146	51.8/51.8
15	3.08	1.08	45	3:1	1.365	0.455	1390/630	2.06x10 ⁴ / 1.25x10 ⁵	0.011/0.320	24.2/69.1
16	3.08	3.08	S.S.	3:1	1.365	0.455	1390/1390	2.06x10 ⁴ / 2.06x10 ⁴	0.011/0.011	24.2/24.2
17	1.08	1.08	S.S.	3:1	1.365	0.455	630/630	1.25x10 ⁵ / 1.25x10 ⁵	0.320/0.320	69.1/69.1
18	3.08	1.08	45	4:1	1.820	0.455	1440/680	2.44x10 ⁴ / 2.38x10 ⁵	0.017/0.522	30.3/86.3
19	3.08	3.08	S.S.	4:1	1.820	0.455	1440/1440	2.44x10 ⁴ / 2.44x10 ⁴	0.017/0.017	30.3/30.3
20	1.08	1.08	S.S.	4:1	1.820	0.455	680/680	2.38x10 ⁵ / 2.38x10 ⁵	0.522/0.522	86.3/86.3

(a) Based on Bundle Average D_H = 0.0294 ft and average flow conditions (T,P) with T_{IN} = 75°F.

TABLE 4.1. (contd)

Case Number	W _i (GPM)	W _f (GPM)	Transient Time (sec)	Power Gradient	Q _H (kW/rod)	Q _L (kW/rod)	Re ^(a) (initial/final)	Gr* (initial/final)	Gr*/Re ² (initial/final)	ΔT (°F) (initial/final)
21	1.63	0.55	45	0:0	0.0	0.0	640/200	0.0/0.0	0.0/0.0	0.0/0.0
22	1.63	0.55	45	1:0	0.91	0.0	730/320	3.79x10 ⁴ / 2.44x10 ⁵	0.072/2.414	22.9/67.8
23	1.63	0.55	150	0:0	0.0	0.0	640/200	0.0/0.0	0.0/0.0	0.0/0.0
24	1.63	0.55	150	1:0	0.91	0.0	730/320	3.79x10 ⁴ / 2.44x10 ⁵	0.072/2.414	22.9/67.8
25	1.63	0.55	300	0:0	0.0	0.0	640/200	0.0/0.0	0.0/0.0	0.0/0.0
26	1.63	0.55	300	1:0	0.91	0.0	730/320	3.79x10 ⁴ / 2.44x10 ⁵	0.072/2.414	22.9/67.8
27	1.63	0.55	500	0:0	0.0	0.0	640/200	0.0/0.0	0.0/0.0	0.0/0.0
28	1.63	0.55	500	1:0	0.91	0.0	730/320	3.79x10 ⁴ / 2.44x10 ⁵	0.072/2.414	22.9/67.8
29	1.63	1.63	S.S.	0:0	0.0	0.0	640/640	0.0/0.0	0.0/0.0	0.0/0.0
30	1.63	1.63	S.S.	1:0	0.91	0.0	730/730	3.79x10 ⁴ / 3.79x10 ⁴	0.072/0.072	22.9/22.9
31	0.55	0.55	S.S.	0:0	0.0	0.0	200/200	0.0/0.0	0.0/0.0	0.0/0.0
32	0.55	0.55	S.S.	1:0	0.91	0.0	320/320	2.44x10 ⁵ / 2.44x10 ⁵	2.414/2.414	67.8/67.8
33	0.30	0.30	S.S.	0:0	0.0	0.0	120/120	0.0/0.0	0.0/0.0	0.0/0.0
34	0.30	0.30	S.S.	1:0	0.91	0.0	220/220	9.19x10 ⁵ / 9.19x10 ⁵	19.04/19.04	124.2/124.2
35	0.30	0.30	S.S.	2:1	0.91	0.455	280/280	9.11x10 ⁵ / 9.11x10 ⁵	11.86/11.86	186.34/186.34
36	0.55	0.55	S.S.	2:1	0.91	0.455	370/370	1.98x10 ⁵ / 1.98x10 ⁵	1.409/1.409	101.6/101.6
37	1.70	1.70	S.S.	0:0	0.0	0.0	660/660	0.0/0.0	0.0/0.0	0.0/0.0
38	1.70	1.70	S.S.	2:1	0.91	0.455	800/800	2.17x10 ⁴ / 2.17x10 ⁴	0.034/0.034	32.9/32.9

(a) Based on Bundle Average D_H = 0.0294 ft and average flow conditions (T,P) with T_{IN} = 75°F.

repeatability. The velocity data for windows 8 and 9 of Case 2 were not measured by Quigley et al. due to poor signal quality. They are presented here to complete the data set as well as show the improved LDA velocity measurement capability for heated flows.

Cases 3 and 4 present comparisons of isothermal and fully heated bundle velocity profiles. For a fully heated bundle (Case 4), no net power skew exists and therefore $Gr^* = 0.0$, indicating that only localized buoyancy effects should be observed. Case 4 demonstrates the ability to make accurate LDA measurements in heated-bundle flows.

Cases 5 and 6 represent transient flow conditions for isothermal (Case 5) and 1:0 bundle power skew (Case 6) conditions. In each case, bundle inlet flow was linearly decreased by 65% over a 150-second period. The end point flow conditions nearly match the Reynolds number of Case 2 reported by Quigley et al. It should be noted that the Reynolds number was matched at a lower total inlet flow due to an elevated inlet temperature (and thus a decreased kinematic viscosity term for $Re = \frac{UDH}{\nu}$, where U and ν are bundle average values). The Gr^*/Re^2 term for the flow transient conditions of Case 6 range from an initial value of ~ 0.01 to a final value of ~ 0.26 , bracketing the lower limit value of 0.025 where Khan et al. (1975) consider buoyancy effects to become important.

Cases 7 and 8 repeat the flow and rod power conditions of Cases 5 and 6, respectively, with a decreased flow transient time. By ramping the flow downward over a shorter, 45-sec period, the effect of flow "coastdown" rates could be compared.

Cases 9, 10, and 11 are investigations of the steady-state end-point conditions of the flow transients in Cases 5 through 8. The velocity profiles measured were obtained for comparison with the subchannel centerpoint velocities measured during the transient runs.

Cases 12 through 20 repeat the transient and steady-state flow conditions of cases 5 through 11 for various bundle power levels (i.e., 2:1, 3:1, and 4:1 power skews).

Cases 21 through 28 investigate flow transients over a lower Reynolds number range while also varying the ramp-down rate of the linear flow coast-down. Cases 29 through 32 are the steady-state conditions representing the end point flow-conditions of this lower Reynolds number transient flow range.

The steady-state flow conditions of Cases 33 through 35 examine isothermal and heated-bundle flow behavior for very low Reynolds number conditions.

The remaining Cases 36 through 38 look at the steady-state flow behavior for a given 2:1 power skew over a varying Reynolds number range.

Table 4.2 outlines the actual run conditions, including bundle average velocities, rod powers, and bulk fluid temperatures, for the steady-state flow cases. Table 4.3 is a similar presentation of data for the transient flow cases. The NOM subscripts in the tables refer to nominal values.

TABLE 4.2. Experimental Conditions – Steady-State Cases

Case	Power Skew	$\dot{W}_{NOM}$ (GPM)	$\bar{U}_{NOM}$ (ft/sec)	WIN Number	Measured $\bar{U}$ (ft/sec)	Rod Power (kW) Hot/Cold	Measured T_{IN} (°F)	Measured ΔT_B (°F)
1	Isothermal	1.25	0.164	7	0.160-0.168	0.0/0.0	75	--
				8	0.162-0.167	0.0/0.0	74	--
				9	0.161-0.165	0.0/0.0	75	--
2	1:0	1.25	0.164	7	0.162-0.168	0.910/0.0	75	29
				8	0.163-0.167	0.910/0.0	74	29
				9	0.162-0.166	0.910/0.0	75	29
3	Isothermal	3.08	0.406	2	0.407-0.412	0.0/0.0	78	--
				4	0.401-0.405	0.0/0.0		
				7	0.404-0.410	0.0/0.0		
				8	0.402-0.406	0.0/0.0		
				9	0.403-0.407	0.0/0.0	73	--
4	1:1	3.08	0.406	2	0.405-0.410	0.916/0.916	78	24
				4	0.405-0.410	0.920/0.920	75	25
				7	0.405-0.409	0.920/0.920	80	24
				8	0.401-0.405	0.925/0.925		
				9	0.402-0.410	0.917/0.917	74	25
9	1:0	3.08	0.406	9	0.401-0.412	0.914/0.0	72	12
10	Isothermal	1.08	0.142	7	0.140-0.145	0.0/0.0	75	--
				8	0.139-0.144	0.0/0.0	74	--
				9	0.141-0.145	0.0/0.0	72	--
11	1:0	1.08	0.142	7	0.139-0.144	0.912/0.0	75	34
				8	0.140-0.145	0.912/0.0	74	34
				9	0.137-0.147	0.913/0.0	72	34
13	2:1	3.08	0.406	9	0.405-0.409	0.914/0.461	56	18
14	2:1	1.08	0.142	7	0.140-0.144	0.913/0.458	75	50
				9	0.139-0.144	0.914/0.460	75	50
16	3:1	3.08	0.406	9	0.405-0.408	1.366/0.463	56	24
17	3:1	1.08	0.142	9	0.139-0.143	1.365/0.466	56	68
19	4:1	3.08	0.406	9	0.403-0.408	1.825/0.460	59	31
20	4:1	1.08	0.142	9	0.136-0.141	1.825/0.460	65	87
29	Isothermal	1.63	0.215	2	0.215-0.218	0.0/0.0	75	--
				8	0.215-0.217	0.0/0.0	74	--
				9	0.215-0.219	0.0/0.0	75	--
30	1:0	1.63	0.215	2	0.213-0.217	0.916/0.0	75	23
				8	0.213-0.216	0.914/0.0	74	
				9	0.214-0.218	0.910/0.0	75	23
31	Isothermal	0.55	0.073	2	0.073-0.077	0.0/0.0	75	--
				8	0.070-0.075	0.0/0.0	74	--
				9	0.071-0.075	0.0/0.0	75	--
32	1:0	0.55	0.073	2	0.071-0.076	0.916/0.0	75	58
				8	0.071-0.076	0.910/0.0	74	61
				9	0.071-0.075	0.906/0.0	75	64
33	Isothermal	0.30	0.040	2	0.038-0.041	0.0/0.0	61	--
				4	0.038-0.042	0.0/0.0	61	--
				7	0.037-0.043	0.0/0.0	60	--
				9	0.037-0.042	0.0/0.0	55	--
34	1:0	0.30	0.040	2	0.037-0.041	0.910/0.0	59	114
				9	0.035-0.046	0.910/0.0	64	109
35	2:1	0.30	0.040	2	0.037-0.041	0.915/0.466	63	151
				4	0.038-0.042	0.910/0.460	62	151
				7	0.037-0.042	0.914/0.458	60	155
				9	0.038-0.044	0.909/0.461	59	155
36	2:1	0.55	0.073	2	0.070-0.074	0.913/0.466	64	101
				4	0.070-0.075	0.910/0.460	62	100
				7	0.070-0.075	0.913/0.458	60	101
				9	0.072-0.076	0.917/0.464	55	98
37	Isothermal	1.70	0.224	9	0.222-0.226	0.0/0.0	55	--
38	2:1	1.70	0.224	9	0.221-0.225	0.917/0.464	56	33

TABLE 4.3. Experimental Conditions - Transient Cases

Case No.	Transient (sec)	Power Skew	$\dot{W}_{i,NOM}$ (GPM)	$\bar{U}_{t=0,NOM}$ (ft/sec)	$\dot{W}_{f,NOM}$ (GPM)	$\bar{U}_{f,NOM}$ (ft/sec)	Window No.	Measured Bundle Ave Velocities U_b ft/sec initial/final	Power (kW) Hot/Cold	Measured T_{IN} (°F)	Measured ΔT_B (°F)
5	150	Isothermal	3.08	0.406	1.08	0.142	2	0.401-0.411/0.134-0.153	0.0/0.0	72	0.0/0.0
							4	0.405-0.411/0.139-0.154		67	
							6	0.404-0.412/0.139-0.153		73	
							7	0.405-0.410/0.139-0.150		72	
							8	0.404-0.413/0.138-0.153		75	
	150	1:0	3.08	0.406	1.08	0.142	9	0.404-0.411/0.136-0.147	0.914/0.0	70	13/32
							2	0.403-0.410/0.137-0.146		67	
							4	0.392-0.410/0.137-0.155		72	
							6	0.403-0.409/0.137-0.156		70	
							7	0.403-0.410/0.139-0.152		73	
	45	Isothermal	3.08	0.406	1.08	0.142	8	0.404-0.410/0.139-0.146	0.913/0.0	70	12/28
							9	0.402-0.412/0.136-0.146		69	
							2	0.403-0.410/0.134-0.147		77	
							4	0.401-0.409/0.137-0.144		77	
							6	0.401-0.410/0.135-0.146		80	
	45	1:0	3.08	0.406	1.08	0.142	7	0.401-0.412/0.137-0.145	0.920/0.0	80	13/33
							8	0.399-0.410/0.136-0.144		72	
							9	0.402-0.409/0.134-0.152		72	
							2	0.402-0.410/0.134-0.154		77	
							4	0.401-0.408/0.134-0.151		78	
	45	2:1	3/08	0.406	1.08	0.142	6	0.403-0.408/0.136-0.148	0.923/0.0	79	19/47
							7	0.402-0.411/0.136-0.150		80	
							8	0.390-0.410/0.136-0.145		81	
							9	0.401-0.410/0.135-0.149		82	
							2	0.399-0.410/0.135-0.144	0.915/0.459	78	
	45	3:1	3.09	0.406	1.08	0.142	4	0.402-0.408/0.134-0.158		78	25/60
							6	0.401-0.409/0.135-0.142		79	
							7	0.399-0.408/0.134-0.154		79	
							8	0.405-0.410/0.137-0.149		72	
							9	0.401-0.410/0.133-0.142		75	
	45	3:1	3.09	0.406	1.08	0.142	2	0.404-0.412/0.136-0.148	1.359/0.460	60	25/61
							4	0.403-0.410/0.136-0.146		64	
							6	0.407-0.140/0.132-0.147		64	
							7	0.404-0.409/0.136-0.148		56	
							8	0.400-0.409/0.136-0.151		56	
	45	3:1	3.09	0.406	1.08	0.142	9	0.401-0.407/0.136-0.151	1.369/0.459	65	26/62
							2	0.404-0.412/0.136-0.148		60	
							4	0.403-0.410/0.136-0.146		64	
							6	0.407-0.140/0.132-0.147		64	
							7	0.404-0.409/0.136-0.148		56	
	45	3:1	3.09	0.406	1.08	0.142	8	0.400-0.409/0.136-0.151	1.365/0.457	65	26/62
							9	0.401-0.407/0.136-0.151		65	
							2	0.404-0.412/0.136-0.148		60	
							4	0.403-0.410/0.136-0.146		64	
							6	0.407-0.140/0.132-0.147		64	

TABLE 4.3. (contd)

Case No.	Transient (sec)	Power Skew	$\dot{W}_{i,NOM}$ (GPM)	$\bar{U}_{t=0,NOM}$ (ft/sec)	$\dot{W}_{f,NOM}$ (GPM)	$\bar{U}_{f,NOM}$ (ft/sec)	Window No.	Measured Bundle Ave Velocities U_x ft/sec initial/final	Power (kW) Hot/Cold	Measured T_{IN} (°F)	Measured ΔT_0 (°F)
18	45	4:1	3.08	0.406	1.08	0.142	2 4 6 7 9	0.403-0.408/0.135-0.147 0.403-0.407/0.135-0.149 0.401-0.410/0.135-0.149 0.401-0.405/0.136-0.151 0.400-0.404/0.135-0.151	1.812/0.457 1.812/0.460 1.822/0.458 1.819/0.455 1.834/0.462	61 63 60 56 65	31/74 32/74 33/76 32/78 34/80
21	45	Isothermal	1.63	0.215	0.55	0.073	2 8 9	0.218-0.221/0.068-0.074 0.221-0.233/0.067-0.076 0.214-0.216/0.070-0.078	0.0/0.0	78 78 63	0.0/0.0
22	45	1:0	1.63	0.215	0.55	0.073	2 8 9	0.216-0.221/0.066-0.073 0.216-0.223/0.067-0.075 0.211-0.215/0.069-0.075	0.910/0.0 0.915/0.0 0.916/0.0	78 78 63	24/56 23/55 25/55
23	150	Isothermal	1.63	0.215	0.55	0.073	9	0.215-0.222/0.069-0.078	0.0/0.0	57	0.0/0.0
24	150	1:0					9	0.217-0.223/0.069-0.080	0.910/0.0	68	25/55
25	300	Isothermal					9	0.208-0.220/0.071-0.074	0.0/0.0	61	0.0/0.0
26	300	1:0					9	0.214-0.217/0.071-0.078	0.926/0.0	61	25/55
27	500	Isothermal					9	0.214-0.217/0.067-0.077	0.0/0.0	62	0.0/0.0
28	500	1:0					9	0.214-0.218/0.071-0.080	0.917/0.0	63	25/57

5.0 DATA ACCURACY AND UNCERTAINTY ANALYSIS

An error analysis using the error and uncertainty method of Schenck (1961) was performed to estimate experimental data accuracy. Table 5.1 presents a summary of the results of the uncertainty analysis based on nominal test conditions for each test case. A more detailed description of the method and analysis appears in Appendix B.

Axial velocity measurements were found to have an estimated uncertainty ranging from ± 3.3 to $\pm 1.1\%$ corresponding to velocities between -0.21 and $+0.73$ ft/sec, respectively. In order to reduce the fluctuation of the tracker output in response to locally high velocity fluctuations caused by thermal-plume-induced mixing, the tracker was operated with an RC damping circuit on the analog output. While this circuitry served to reduce the fluctuations to a time-averaged value for steady-state cases, it also induced some lag to the velocity readings during transient flow cases. Values of calculated nominal time lag uncertainty for velocity measurements are also presented in Table 5.1.

Volumetric flow rate (and thus bundle average velocity, $\bar{U}$) was measured by means of a 100:1 range turbine flowmeter rated for 0.08 to 8.0 GPM with a 3-msec response rate to a step change in flow. Based on factory-supplied and subsequently lab-verified calibrations, the uncertainties in measurement of various flow rates are presented in Table 5.1. The stated $\pm 5\%$ fluctuations in steady-state flows and $\pm 10\%$ variations for transient flows are due to a combination of effects from various flow loop components. The loop flow control valve and positioner exhibited some minor inherent instabilities and discontinuous stem movement that induced a majority of the observed fluctuations, especially during flow coastdown transients ($\pm 10\%$ from nominal), [see Figure 5.1]. During steady-state runs with the flow control valve manually locked in position, fluctuations of less than $\pm 5\%$ from nominal were observed.

The overall measurement accuracy of subchannel temperatures was a function of the calibration accuracy of the thermocouple and the thermocouple position relative to the thermal plumes surrounding the heated rods.

TABLE 5.1. Uncertainty Values

	NOMINAL VALUE	Uncertainty	
		Value	Percent
Volumetric flow rate, $\dot{W}$	3.08 GPM	± 0.06 GPM	± 1.9
	1.63 GPM	± 0.03 GPM	± 1.9
	1.25 GPM	± 0.02 GPM	± 1.9
	1.08 GPM	± 0.02 GPM	± 1.9
	0.55 GPM	± 0.02 GPM	± 3.5
	0.30 GPM	± 0.03 GPM	± 10.0
Fluctuation bounds for $\dot{W}$			
for transient flows			± 10
for steady-state flows			± 5
Mean local velocity, U ($f_D = 20$ to 160 kHz)	-0.208 ft/sec	± 0.007 ft/sec	± 3.3
	0.729 ft/sec	± 0.008 ft/sec	± 1.1
RC time lag for transient velocity measurements (assuming nominal $\bar{U}$ and $\tau = RC \approx 5$ sec)			
for 150-sec ramp	0.406 $\rightarrow$ 0.142 ft/sec	± 0.009 ft/sec	$\pm 2.2 \rightarrow 6.3$
for 45-sec ramp	0.406 $\rightarrow$ 0.142 ft/sec	± 0.029 ft/sec	$\pm 7.1 \rightarrow 20.4$
for 45-sec ramp	0.215 $\rightarrow$ 0.073 ft/sec	± 0.016 ft/sec	$\pm 7.4 \rightarrow 21.9$
X, Y data point location (Isothermal)		± 0.001 in.	
Point location for $X = 0$		± 0.020 in.	
Point location for $Y = 0$		± 0.050 in.	
Axial location, Z		± 0.050 in.	
Transient times for 45-sec transient		± 2 sec	± 4.4
for 150-sec transient		± 3 sec	± 2
for 300-sec transient		± 5 sec	± 1.6
for 500-sec transient		± 10 sec	± 2
Rod power - watt transducers			± 3.4
Temperatures		$\pm 1^\circ\text{F}$	
Nondimensional temperature, T^* ,	0.5	± 0.0653	± 13.1
for $\Delta T_B \approx 12.1^\circ\text{F}$	1.0	± 0.0826	± 8.3
	2.0	± 0.1307	± 6.5
	3.0	± 0.1848	± 6.7

$$T^* = \frac{T - T_{in}}{(T_{out} - T_{in})} \quad t=0$$

FIGURE 5.1. Fluctuations from Nominal Flow During Linear Flow Coastdowns

The thermocouples of the rake assembly were positioned to within ± 0.050 in. of the particular subchannel centerpoint for the interior subchannels 2 through 6.

The time response of the temperature measurement system tended to time average small-scale fluid temperature fluctuation; however, the overall combined temperature fluctuation/system time response can be seen in Figures 5.2 and 5.3. These figures qualitatively demonstrate the very dynamic nature of the temperature gradients (i.e., thermal plumes) surrounding the heated pins. Both figures represent 1:0 power skews in the bundle (~ 0.91 kW/Heated rod) for the $Z^* = 0.875$ axial level with Figure 5.1 showing data obtained at 3.08 GPM ($Re \approx 1290$) and Figure 5.3 showing data obtained at 1.08 GPM ($Re \approx 520$). Comparison of the two figures illustrates the enhanced dynamic nature of the thermal plumes at the lower Reynolds number.

FIGURE 5.2. Subchannel Centerpoint Temperatures for Steady-State Conditions (Case 9)

FIGURE 5.3. Subchannel Centerpoint Temperatures for Steady-State Conditions (Case 11)

6.0 COBRA WHOLE CORE COMPUTER PROGRAM

The COBRA-WC computer program (George et al., 1980), a modified version of the COBRA-IV-I code (Wheeler et al. 1976) has been specifically developed for predicting core-wide steady-state and transient temperature and flow distributions in LMFBR assemblies on a subchannel basis. One of the basic objectives of this study was to evaluate and improve the COBRA-WC transient models at low-flow conditions and also to evaluate the flow recirculation model.

Some of the features of COBRA-WC that are substantial improvements over those of COBRA-IV-I are:

- Flow recirculation calculations are much faster than for COBRA-IV-I.
- Input is modified for multiassembly problems.
- Flexibility is provided to reduce computation times by implementing:
 - variable axial step size
 - direct solution scheme for momentum equation as well as an iterative scheme
 - different user-definable forcing functions
 - variable time step size
 - fully implicit solution of the energy equation for predicting coolant, cladding, duct, and fuel temperature distribution.

The experimental geometry was initially modeled with the 21-channel model shown in Figure 3.2. Four additional peripheral subchannels were later added to allow modeling of the duct wall heat capacity and radial heat loss effects. Prior to predicting the data, the sensitivity of COBRA-WC predictions was investigated relative to a large number of parameters. It was found that the effect of wall viscosity correction, as applied to the friction factor, had a very small effect on the bundle velocity and temperature distribution. The presence of spacer grids was found to affect flow and temperature fields minimally. The effect of using two different fluid property tables (ASME and

NASA-WASP; Weast 1971) was also small, although improvement in the predicted velocity distribution was found using the ASME steam tables.

6.1 IMPROVEMENT IN THE COBRA-WC TURBULENT MIXING MODEL

It was found that COBRA-WC predictions could be improved by modifying the turbulent mixing model for flow transients below a Reynolds number of ~450. The standard turbulent mixing model used in COBRA-WC is:

$$w' = \beta s G \quad (1)$$

where

β = mixing coefficient

s = gap between adjacent rods, and

G = bundle average axial mass flux.

During each flow transient as the Reynolds number was reduced, the intensity of the turbulent plumes was visually observed to increase. The dynamic thermal plumes surrounding the rods interacted with each other, promoting turbulence and mixing between channels. This was especially noticeable below a Reynolds number of ~450. These thermal plumes are zones of locally heated fluid which rise more rapidly than the bulk fluid in the subchannel because of their lower density. Thus superimposed upon a bundle global buoyant phenomenon is a local (intrachannel) buoyancy effect which complicates the analysis of the data. It was found that most data above a Reynolds number of 450 were predicted well using COBRA if $w' = 0.0$ (no turbulent mixing) was assumed. However, below a Reynolds number of 450, it was necessary to include the effect of thermal-plume-induced variations on w' to accurately predict velocity and temperature distribution. Thus w' was correlated against the parameter $\frac{Gr}{Re^2} \cdot \hat{Q}_p$, where $\hat{Q}_p$ is the local-to-bundle average heat generation ratio. If the rate of heat generation in rods 1 through 6 in Figure 3.2 is symbolized as Q_H and in rods 7 through 12 as Q_C , then $\hat{Q}_p = Q_H / [(Q_H + Q_C)/2]$ for rods 1 through 6. During the transient, $\frac{Gr}{Re^2}$ increases with a resulting increase in w' . If it is assumed that β is a constant, as is commonly done in COBRA analysis, the turbulent mixing parameter w' would decrease with time (due to decreases in $\bar{G}$) and would have one uniform value for the entire assembly. However, this is

contrary to the observed thermal-hydraulic phenomena, especially for the case where part of the bundle is unheated. Since $\hat{Q}_p$ depends upon the local heat generation rate, the turbulent cross flow mixing rate, w' , is not uniform across the bundle. This non-uniform turbulent mixing rate between subchannels was incorporated in the COBRA-WC code. It was found that improved predictions were obtained for transients where the Reynolds number was less than ~450 if the turbulent mixing parameter, w' , is given by Equation (2).

$$w' = 0.01 \frac{Gr}{Re^2} \hat{Q}_p. \quad (2)$$

A similar parameter, Gr^*/Re^2 , was related to the inception of recirculation during any transient flow condition. Gr^* is the product of Gr , the bundle Grashof number based on the bundle mixed mean temperature rise, and $(\hat{Q}_p-1)$. The factor $(\hat{Q}_p-1)$ has a range $0 \leq (\hat{Q}_p-1) \leq 1$, indicating the severity of the lateral power skew from a uniform distribution, [where $(\hat{Q}_p-1) = 0$] to an infinite (half the bundle unheated) distribution, [where $(\hat{Q}_p-1) = 1$]. During transient conditions, recirculation zones were observed to form for relatively high values of Gr^*/Re^2 , as discussed in the following sections.

6.2 COBRA-WC CODE INPUT

The input to the COBRA-WC code in addition to geometry, includes water property tables, operating conditions of bundle heat generation rate, total flow, inlet temperature (or enthalpy), inlet pressure, power skew, and input correlations. Table 6.1 lists the standard COBRA-WC input. The input parameters/correlations that were needed for the present problem included the following:

- Friction factor correlation
- Nusselt number correlation for rod-to-fluid heat transfer
- Mixing correlation between channels

- Nusselt number correlations for heat transfer between housing wall and fluid both inside and outside the wall (radial heat loss model)
- Temperature (or enthalpy) of source fluid entering a recirculation zone.

TABLE 6.1. Standard COBRA-WC Input

Geometry	21 channels, 12 rods bundle length = 60.0 in. heated length = 48.0 in. axial node size = 2.0 in. time step size = 1 sec Time step during flow recirculation mode is determined by code.
Power Distribution	axially uniform power in first 48 in. radial power skew is 1:0, 2:1, 3:1, 4:1
Inlet Flow or Temperature	specified
Input Correlations	friction factor - maximum of $64/Re$ or $0.184/Re^{0.2}$
Heat Transfer Correlations	$Nu = 0.023 Re^{0.8} Pr^{0.4}$
Mixing Correlations	see text
Transient Forcing Function	constant inlet temperature constant bundle power linear reduction in inlet flow rate

The correlations for friction factor and Nusselt number for the rod-coolant interface were taken from the work of Quigley, McMonagle, and Bates (1977), who tried several friction factor correlations before determining that the most appropriate correlation was the maximum of smooth tube laminar and turbulent friction factors (Table 6.1).

Only small differences in predicted velocities and temperatures were observed in the rod bundle when the inlet flow split was based on hydraulic diameter rather than uniform mass velocity. Predicted velocities and temperatures were only slightly affected when the first 12 in. of unheated bundle length were included in the input model.

It was therefore decided to model the upper 60 in. of the bundle, the first 48 in. being specified as the bundle heated length.

Parametric studies on the heat transfer coefficients between the test section wall and fluid on either side of the wall showed that channel temperatures were essentially unaffected by as much as $\pm 50\%$ change in heat transfer coefficients about a mean value. However, wall heat capacity did affect the coolant temperatures, and this was taken into account in the COBRA-WC model.

7.0 EXPERIMENTAL RESULTS AND DISCUSSION

Representative experimental results for the various test cases outlined in Table 4.1 are presented in the following sections. Predictions obtained with the COBRA-WC computer code for both transient velocity and temperature are also shown for most cases as plots superimposed on the experimental data. The COBRA-WC predictions represent subchannel average values of temperature or velocity, while the experimental data represent local, point measurements at selected locations on the axial subchannel centerline. Steady-state velocity profiles within a subchannel were measured at different Reynolds numbers to provide an estimate of the ratio of the subchannel average velocity to the subchannel centerline velocity. These results allow comparisons of the subchannel centerline measured velocities with the COBRA-WC subchannel average predicted velocities.

Both measured and COBRA-WC-predicted velocities are presented in dimensionless form; $U/\bar{U}$. Velocity is nondimensionalized with respect to the bundle average velocity, $\bar{U} = \dot{W}/a$, where $\dot{W}$ is either the initial ($\bar{U}_{t=0} = \dot{W}_i/a$) or final steady-state ($\bar{U} = \dot{W}_f/a$) bundle flow rate for transient test conditions. For steady-state velocity profile plots $\bar{U}_{t=0}$ refers to the initial steady-state conditions of a transient, $\bar{U}$ refers to the final steady-state conditions.

Temperatures were nondimensionalized as $(T-T_{in})/(T_{out}-T_{in})_{t=0}$ where $T-T_{in}$ is the axial temperature rise at any given time and $(T_{out}-T_{in})_{t=0}$ is the fluid bulk temperature rise across the bundle at initial steady state conditions ($t = 0$).

7.1 Steady State Cases 1 and 2

To provide continuity with the experimental results reported by Quigley, McMonagle, and Bates (1977) and to insure that the geometry, and flow conditions were similar and repeatable, Case 2 experimental conditions exactly repeat the steady-state flow conditions of Case 2 reported by Quigley et al.: namely, a 1:0 power gradient with 0.91 kW/rod on the hot side and no heating on the cold side and a flow rate ($\dot{W}$) of 1.25 GPM.

The axial level of window number 7 ($Z^* = 0.750$), was the uppermost axial level for which Quigley et al. obtained velocity data for the conditions of Case 2. These data were plotted^(a) and compared with the more recent data as shown in Figure 7.1. The isothermal flow profile is also shown for comparison. The two heated profiles for the 1:0 power skew at $Re \approx 580$ are nearly identical, although the cumulative effects of positional uncertainties and asymmetric geometries are apparent. The comparison confirmed the similarity of flow and power conditions, as well as approximate geometric similarity for the two independent tests.

With the improved LDA system (optics and electronics) used in this study, Case 2 velocity profiles were also measured for the axial levels of windows 8

FIGURE 7.1. Repeatability Comparison with the Case 2 Steady-State Conditions of Quigley, McMonagle, and Bates (1977)

(a) The "hot" and "cold" sides of the 2×6 bundle were transposed in the two studies; Quigley's velocity sample is shown inverted from the original data plot.

and 9 ($Z^* = 0.875$ and 1.00 , respectively), where Quigley, McMonagle, and Bates (1977) were unable to make reliable velocity measurements. These velocity profiles are presented in Figures 7.2 and 7.3, with the corresponding Case 1 isothermal profiles. As buoyancy forces continued to develop at these downstream axial levels, the typical profile of velocity peaks at subchannel centerlines and of velocity minimums at gaps between adjacent rods (most clearly seen in the isothermal velocity profiles) became less apparent. The hot side and cold side profiles become more nearly uniform as the thermal plumes developed and interacted. For the $Z^* = 1.00$ axial level of window 9, the buoyancy-induced flow redistribution was so severe that axially stagnant, zero-velocity flow was induced on the cold side (as the measured velocities of Figure 7.3 show).

FIGURE 7.2. Isothermal (Case 1) and Heated Bundle (Case 2) Velocity Profiles ($Z^* = 0.875$)

FIGURE 7.3. Isothermal (Case 1) and Heated Bundle (Case 2) Velocity Profiles ($Z^* = 1.00$)

Also included in the plots of Figures 7.1 through 7.3 are COBRA code predictions of subchannel velocities for the flow conditions of Case 2. The horizontal bars represent predicted subchannel average velocities. In contrast, local LDA measured velocity distributions were obtained along the $Y = 0.0$ subchannel centerline axis. As previously discussed, severe thermal gradients precluded the accurate measurement of off-centerline velocities in most heated bundle cases. Thus it was not possible to calculate subchannel average velocities from the experimental data. A simple numerical average of the centerline velocity distribution does, however, provide a reasonable "average" velocity to which comparisons can be made. Note that the COBRA predictions for Case 2 incorporate the $w' = 0.0$ crossflow mixing term as used by Quigley et al.

For the Case 2 steady-state conditions, COBRA velocity predictions show excellent agreement with the experimental data, particularly in the cold-side,

low-velocity regions and the steep velocity gradient zone between the heated and unheated sides of the 2 x 6 bundle. For the hot-side, higher-velocity flows, comparisons between the LDA measured local velocities and the COBRA-code-predicted subchannel average velocities are more difficult to interpret, but in general the measured and predicted values show good correlation.

7.2 ISOTHERMAL (CASE 3) AND UNIFORMLY HEATED (CASE 4) BUNDLE STEADY-STATE VELOCITY PROFILES

The experimental data presented in Figure 7.4 represent measurements obtained to check bundle symmetry and to check LDA measurement capability in heated flows. The nominal and actual run conditions for Case 3 (isothermal) and Case 4 (uniformly heated bundle) velocity profiles are given in Tables 4.1 and 4.2. Figures 7.4 through 7.9 show profiles of the nondimensional local axial velocity $U/\bar{U}$ relative to the X coordinate (Figure 3.2) along a $Y = 0.0$

FIGURE 7.4. Isothermal (Case 3) and Uniformly Heated (Case 4) Bundle Velocity Profiles ($Z^* = 0.125$)

FIGURE 7.5. Isothermal (Case 3) and Uniformly Heated (Case 4) Bundle Velocity Profiles ($Z^* = 0.375$)

FIGURE 7.6. Isothermal (Case 3) and Uniformly Heated (Case 4) Bundle Velocity Profiles ($Z^* = 0.750$)

FIGURE 7.7. Isothermal (Case 3) and Uniformly Heated (Case 4) Bundle Velocity Profiles ($Z^* = 0.875$)

FIGURE 7.8. Isothermal (Case 3) and Uniformly Heated (Case 4) Bundle Velocity Profiles ($Z^* = 1.00$)

traverse between the rod rows of the 2 x 6 rod bundle. Measurements for several axial levels were obtained. The uniformity of both the isothermal and heated bundle profiles indicates reasonable symmetry in the test bundle. The superimposed heater rod positions clearly show that peak velocities in any subchannel occur at the subchannel centers and that the minimum velocities occur in the gaps between adjacent rods.

The heated and isothermal profiles exhibited the same general characteristics. For the heated cases, the upward buoyancy forces in the subchannels adjacent to the walls were smaller than in the central subchannels of the bundle because of the presence of the cold walls. Consequently, flow redistribution occurred, and at the end of the heated length ($Z^* = 1.00$) the central subchannels showed a slightly higher flow rate as compared to isothermal conditions (Figure 7.8). Although there were no problems in velocity and velocity profile measurements for the central subchannels (1 through 7) there was considerable difficulty in measuring wall subchannel velocities for the heated cases. This was because severe thermal gradients existed in the wall subchannels because of the presence of the cold walls. Resultant variations in the fluid refractive index caused deflections in the LDA beams which resulted in probe volume positional uncertainties and distorted velocity profiles (Figure 7.9).

The two data sets of Figure 7.10, demonstrate the excellent repeatability of the LDA velocity measurements in heated flows. The profiles are for the steady state, fully heated bundle conditions of case 4 at the bundle end-of-heated length ($Z^* = 1.00$) for a $Y = 0.0$ traverse.

FIGURE 7.9. Isothermal (Case 3) and Uniformly Heated (Case 4) Bundle Velocity Profiles for Side Subchannels ($Y = +0.581 \text{ in.}$)

FIGURE 7.10. Velocity Profile Repeatability Check, Case 4 ($Z^* = 1.00$)

7.3 FLOW TRANSIENT CASES 5 AND 6

The flow coastdown curve for these transient cases was a linear decrease of the bundle average flow from 3.08 GPM to 1.08 GPM over a 150-sec time period. These conditions were not intended to model any particular prototypic reactor conditions, but were chosen as an initial test of transient velocity and temperature measurement capability. The conditions provided an initial transient data base to compare with COBRA-WC predictions of transient mixed-convection flows. However, the Reynolds number range of the transient, ~1290 to ~520, for the 1:0 power skew heated cases, was within the expected range for LMFBR flow coastdowns to natural-convection conditions. The measured non-dimensionalized centerpoint velocity histories for subchannels 2, 4, and 6 are shown in Figure 7.11 for the $Z^* = 0.125$ axial level at isothermal conditions. Velocity history curves for other axial levels and other central subchannels were very similar and are presented in Appendix C. The data show the repeatability and linearity of the flow coastdown to be satisfactory. The LDA signal processor RC time constant problem discussed earlier showed only minor effects on the measured transient velocities. For this, and all subsequent transient velocity and temperature plots, the transient was initiated at time $t = 0$.

The isothermal transients also demonstrated that the ratio of the subchannel centerpoint velocities to bundle average velocities changed as the flow transient progressed as shown in Figure 7.12. For $Re = 1200$ at time $t = 0$, the centerpoint-to-average ratio was approximately 1.6. However, as the flow coastdown progressed, this ratio increased to a maximum value of approximately 2.0, as is shown in Figure 7.12 by the $U/\bar{U}$ reference lines showing the range $U/\bar{U} = 1.0$ to $U/\bar{U} = 2.0$. The ratio $U/\bar{U}$ as used for the reference lines is the ratio of subchannel centerpoint velocity to the instantaneous bundle average velocity. This behavior agrees with hydraulic theory in that the flow regime is moving to a more laminar condition. Pipe flow theory predicts for a fully laminar flow profile that the centerline peak-to-average velocity ratio should be ~2.0. Rod bundle subchannel flows appear to behave quite similarly.

Case 6 centerpoint velocity histories for subchannels 2, 4, and 6 are shown in Figure 7.13 through 7.15 for the $Z^* = 0.125$, 0.625, and 1.00 axial

FIGURE 7.11. Measured Subchannel Centerpoint Velocity Histories During Isothermal, 150-sec Flow Coastdown (Case 5)

FIGURE 7.12. Ratio of Subchannel Centerpoint Velocity to Bundle Average Velocity for Range of Transient, $Re = 1200 \rightarrow 420$ (Case 5)

FIGURE 7.13. Measured and COBRA-Predicted Subchannel Velocity Histories, Case 6 ($Z^* = 0.125$)

FIGURE 7.14. Measured and COBRA-Predicted Subchannel Velocity Histories, Case 6 ($Z^* = 0.625$)

FIGURE 7.15. Measured and COBRA-Predicted Subchannel Velocity Histories, Case 6 ($Z^* = 1.00$)

levels. Data for other axial levels are presented in Appendix C. The data were obtained at a 1:0 power skew during a 150-sec flow transient. At the $Z^* = 0.125$ level (Figure 7.13) 6 in. along the heated length, the velocities are essentially indistinguishable from the isothermal case (Figure 7-11) at time $t = 0$. At $Z^* = 0.625$, (Figure 7.14) 30 in. along the heated length, the flow skew becomes increasingly more pronounced, with decreased flows in subchannels 2 and 4 and increased flows in the hot-side subchannel 6. The most notable feature observed at the $Z^* = 1.00$ axial level (Figure 7.15) were negative velocities ($U/\bar{U}_{t=0} = -0.1$) measured near the end of the flow transient in subchannel 2, indicating that a recirculation zone was formed. The inception of recirculation occurred at $Gr^*/Re^2 \approx 0.24$. Increases in velocities were detected in subchannel 4 at the $Z^* = 1.00$ axial level ($U/\bar{U} = 0.6-0.7$) when compared to those for the $Z^* = 0.625$ axial level ($U/\bar{U}_{t=0} = 0.4 - 0.5$).

Figure 7.16 demonstrates the excellent repeatability of local velocity measurements in heated, transient flows. The plot shows two repetitions of

FIGURE 7.16. Repeatability of Subchannel Centerpoint Velocity Measurements, Case 6 ($Z^* = 1.00$)

subchannel centerpoint velocity measurements for the test conditions of Case 6 at the $Z^* = 1.00$ axial level. The two sets of data show excellent agreement. Equally good comparisons of data repeatability were found for each test case of the study.

Included in Figure 7.13 are COBRA-WC predictions of the velocity histories for subchannels 2, 4, and 6. Although wide differences exist between the code-predicted subchannel average velocities and the experimentally measured local subchannel centerpoint velocities, general comparisons of the code predictions to the trends and magnitudes of the measured data are possible.

For the $Z^* = 0.125$ axial level shown in Figure 7.13, neither the experimental data or code predictions of subchannel velocities show any significant effect of the 1:0 rod power skew. Comparison with the isothermal data of

Figure 7.11 shows that very little flow redistribution occurred. The ratio between the measured subchannel centerpoint and the code predicted subchannel average velocities is apparent.

At the $Z^* = 0.625$ axial level (Figure 7.14) buoyancy induced flow redistribution was apparent and became more prominent as the flow coastdown progressed. With the exception of the overpredicted velocity for subchannel 4 at $t \geq 150$ sec, COBRA-WC predictions compare satisfactorily with the data.

At the $Z^* = 1.00$ axial level (Figure 7.15) where buoyancy effects became most prominent, COBRA-WC predictions continue to compare well with the measured data. Subchannel 6 predictions appear to be somewhat low initially then somewhat high at times $t \geq 150$ sec, the end point of the flow coastdown. COBRA-WC predictions of the velocity history for subchannel 2 appear excellent, showing both the inception of recirculation and its subsequent recovery.

Figure 7.17 shows a velocity vector map of the buoyancy-induced recirculation pattern in the 2 x 6 rod bundle as inferred from axial velocity measurements. The map aids visualization of the overall bundle flow pattern.

As discussed earlier, subchannel centerpoint temperature measurements were also made for the transient flow conditions using a thermocouple rake assembly. The non-dimensionalized temperature histories for the three uppermost axial levels ($Z^* = 0.750, 0.875, \text{ and } 1.00$) are shown in Figures 7.18, 7.19 and 7.20. COBRA-WC code predictions for turbulent exchange mixing crossflow, $w' = 0.0$ are also shown. Inception of cold-side recirculation can be detected by a departure from the inlet temperature in subchannel 2. This increase in temperature occurred at the exit of the heated bundle at approximately 160 sec into the transient. This corresponds to the time at which negative velocities were detected (Figure 7.15). It appears that the induced recirculation transported hot fluid into the cold side subchannels. This caused lateral temperature differences to be decreased and relative buoyancy forces between the hot and cold sides of the bundle to be reduced. This subsequently resulted in flow recovery on the cold side of the bundle. COBRA-WC models this behavior accurately.

FIGURE 7.17. Buoyancy-Induced Flow Recirculation Pattern

Subchannel 4, the interface subchannel between the hot and cold sides of the bundle, had very large fluctuations in centerpoint temperature caused by the very dynamic thermal plumes visually observed to form around the heated rods, as shown in Figures 5.2 and 5.3 for steady-state flow conditions. It is further postulated that the shear flow between the very buoyant thermal plumes and the bundle bulk flow led to the formation of local eddies which alternately entrained hot fluid from the hotter side of the bundle and cold fluid from the opposite side, resulting in the observed temperature fluctuations. Such localized phenomena cannot be predicted by a subchannel analysis code such as

FIGURE 7.18. Measured and COBRA-Predicted Subchannel Temperature Histories, Case 6 ($Z^* = 0.750$)

FIGURE 7.19. Measured and COBRA-Predicted Subchannel Temperature Histories, Case 6 ($Z^* = 0.875$)

FIGURE 7.20. Measured and COBRA-Predicted Subchannel Temperature Histories, Case 6 ($Z^* = 1.00$)

COBRA-WC. However, the code does appear to predict the average subchannel temperatures satisfactorily. In particular, it can be seen that the large increase in the temperature of subchannel 2, which occurred after the end of the actual flow transient, is well predicted by COBRA-WC (Figure 7.20).

7.4 Flow Transient Cases 7 and 8

The test conditions of Cases 7 and 8 were similar to those of Cases 5 and 6 respectively, with the exception that the flow transient time was decreased from 150 sec to 45 sec. Figure 7.21 shows the isothermal velocity histories for Case 7 at the $Z^* = 1.00$ axial level. The consistency of the velocity magnitudes from subchannel to subchannel and the linearity of the velocity histories are evident. Isothermal (Case 7) velocity histories for other axial levels are presented in Appendix C.

Figure 7.22 shows the effect of heat addition on subchannel centerpoint velocity histories obtained in Case 8 for the $Z^* = 1.0$ axial level. Plots for additional axial levels are presented in Appendix C. Rods 1 through 6

FIGURE 7.21. Measured Subchannel Centerpoint Velocity Histories During Isothermal, 45-sec Flow Coastdown, Case 7 ($Z^* = 1.00$)

FIGURE 7.22. Measured and COBRA-Predicted Subchannel Velocity Histories, Case 8 ($Z^* = 1.00$)

were unheated and rods 7 through 12 were heated at 0.91 kW/rod. The behavior is nearly identical to that of Case 6, including the development of a recirculation zone and its subsequent disappearance at long times. Inception of recirculation occurred at $Gr^*/Re^2 \approx 0.27$.

The subchannel centerline temperature histories for the 45 sec transient at the $Z^* = 1.00$ axial level (Figure 7.23) again exhibit a high degree of similarity with the 150 sec transient data (Case 6). Recirculation of fluid on the cold side is again detectable by the rapid temperature increase in subchannel 2. This increase occurred approximately 10 sec after the flow transient had terminated, as it did for Case 6.

7.5 STEADY STATE CASES 9, 10, AND 11

Figures 7.24 and 7.25 show a comparison of the $Z^* = 1.0$ axial level steady-state velocity profiles in the heated and unheated bundle cases at 3.08

FIGURE 7.23. Measured and COBRA-Predicted Subchannel Temperature Histories, Case 8 ($Z^* = 1.00$)

FIGURE 7.24. Isothermal (Case 3) and Heated Bundle (Case 9) Velocity Profiles for Initial Steady-State Conditions of Cases 5, 6, 7, and 8 ($Z^* = 1.00$)

FIGURE 7.25. Isothermal (Case 10) and Heated Bundle (Case 11) Velocity Profiles for Final Steady-State Conditions of Cases 5, 6, 7, and 8

and 1.08 GPM. Data for other axial levels are presented in Appendix C. These conditions model the initial and final steady state conditions of flow transient cases 5 and 7 (isothermal) and cases 6 and 8 (1:0 power skew). The 3.08 GPM flowrate corresponds to a Reynolds number of 1290 for the heated bundle and 1200 for the unheated bundle due to the effect of temperature on fluid properties. The properties used to calculate the Reynolds number were evaluated at the bundle average axial mixed mean coolant temperature. The 1.08 GPM flowrate (with $Re = 420$ unheated and $Re = 520$ heated) steady-state velocity profile for the heated bundle (Case 11) shows dramatic evidence of the buoyancy-induced flow redistribution. The plot of Figure 7.25 is shown with two non-dimensional velocity scales. The $U/\bar{U}$ scale references the local velocity data to the 1.08 GPM flowrate bundle average velocity corresponding to the final steady-state conditions of transient cases 5 and 7. The $U/\bar{U}_{t=0}$ scale references the 3.08 GPM flow-rate of the initial steady-state conditions of the Case 5 and 7 transients. This allows the steady-state data to be easily correlated with the transient test data. The horizontal bars in Figures 7.24 and 7.25 are the COBRA-WC predictions of the respective subchannel average velocities. For final steady-state conditions results from COBRA-WC slightly underpredict velocities in the cold side and interface subchannels, but the average velocity in the hot side subchannel is predicted well.

7.6 FLOW TRANSIENT CASE 12 AND STEADY-STATE CASE 13 AND 14

Case 12 was a 45-sec flow transient similar to that of Case 8 except the rod bundle was operated at a 2:1 power skew. Rods 1 through 6 were operated at ~ 0.45 kW/rod and rods 7 through 12 were operated at ~ 0.91 kW/rod. Due to the smaller power skew of this case as compared to the 1:0 power skew cases, flow redistribution within the bundle was much less severe, as shown in Figure 7.26 for the $Z^* = 1.00$ axial level. The buoyancy forces, described by the parameter Gr^*/Re^2 , were smaller than for Cases 6 and 8 (Table 4.1) and did not produce flow reversals in the bundle. COBRA-WC predictions of the initial and final steady-state subchannel average velocities for the $Z^* = 1.00$ axial level are shown in Figure 7.27 and 7.28. The measured velocity profile clearly shows that a much less severe flow redistribution occurred for the 2:1 power skew. Temperature measurements at the $Z^* = 1.00$ axial level are shown

FIGURE 7.26. Measured and COBRA Predicted Subchannel Velocity Histories, Case 12 ($Z^* = 1.00$)

FIGURE 7.27. Isothermal (Case 3) and Heated Bundle (Case 13) Velocity Profiles for Initial Steady-State Conditions of Cases 7 and 12

FIGURE 7.28. Isothermal (Case 10) and Heated Bundle (Case 14) Velocity Profiles for Final Steady-State Conditions of Cases 7 and 12 ($Z^* = 1.00$)

FIGURE 7.29. Measured and COBRA Predicted Subchannel Temperature Histories, Case 12 ($Z^* = 1.00$)

in Figure 7.29. The measured, as well as COBRA-WC predicted, temperatures show a much less severe lateral temperature difference for the 2:1 power skew. Case 12 velocity and temperature histories at other axial levels are presented in Appendix C.

7.7 FLOW TRANSIENT CASE 15 AND STEADY STATE CASES 16 AND 17

Case 15 was again a 45-sec flow transient similar to that of Cases 8 and 12, except the power skew was increased to 3:1. With rods 1 through 6 powered at 0.45 kW/rod and rods 7 through 12 powered at 1.365 kW/rod, the magnitude of the differential buoyancy forces (indicated by the Gr^*/Re^2 term of Table 4.1) is somewhat greater than for the 1:0 power skew condition (Case 8). The sub-channel velocity histories for the Case 15 conditions are shown in Figure 7.30. Comparison with data of previous cases shows a flow redistribution more severe than for the 2:1 skew (Case 12, Figure 7.26), but less severe than and totally lacking the reverse flow recirculation observed for the 1:0 power skew case (Case 8, Figure 7.22). This observation is not consistent with Gr^*/Re^2 criterion for the nominal conditions assumed for the values in Table 4.1.

Reference to Table 4.3, which presents the actual run conditions for Cases 8 and 15 reveals that the runs of Case 15 were performed with an inlet temperature 15 to 20°F lower than for Case 8. The volumetric thermal expansion term, α , is quite sensitive to absolute temperature. A 20°F decrease in inlet temperature can decrease the value of $GR = g\alpha\Delta T_B D_H / \nu^2$ by up to 20 . Thus the decreased inlet temperature of the Case 15 data runs could be responsible for the lack of observed recirculating flow. In fact, at the time of minimum velocity for subchannel 2 (see Figure 7.30), i.e., at $t \cong +66$ sec, $Gr^*/Re^2 \cong 0.19$ for the actual run conditions measured. This is significantly less than $Gr/Re^2 \cong 0.27$ for Case 8 or $Gr^*/Re^2 \cong 0.24$ for Case 6 inceptions of recirculation.

COBRA-WC predictions for Case 15 conditions are superimposed on the data of Figure 7.30. COBRA predictions indicate recirculation in subchannel 2 for the 3:1 power skew at $t = \sim 45$ sec while the experimental measurements showed the centerpoint velocity of subchannel 2 remained slightly positive. However, the code predictions compare favorably with the experimental measurements of the "hot" and "cold" subchannel fluid temperatures (Figure 7.31).

FIGURE 7.30. Measured and COBRA-Predicted Subchannel Velocity Histories
Case 15 ($Z^* = 1.00$)

FIGURE 7.31. Measured and COBRA-Predicted Subchannel Temperature Histories,
Case 15 ($Z^* = 1.00$)

Measured and code-predicted velocities for both initial and final steady-state flows are shown in Figures 7.32 and 7.33 respectively. For the final steady-state conditions in particular, the agreement between the code-predicted subchannel average velocity and the LDA-measured velocity profile is quite good.

Additional transient data and code predictions for the Case 15 3:1 power skew at other axial levels are contained in Appendix C.

7.8 FLOW TRANSIENT CASE 18 AND STEADY-STATE CASES 19 AND 20

Case 18 imposed a 4:1 power skew on the 2 x 6 bundle (1.820 kW/rod for rods 7 through 12, 0.455 kW/rod for rods 1 through 6) during the same 45-sec linear flow transient used for previous cases. Figure 7.34 presents velocity data for the $Z^* = 1.00$ axial level. Subchannel temperature data are presented in Figure 7.35. Comparisons between COBRA-WC predictions and experimental measurements are acceptable with both the code simulation and the LDA measurements showing a transient-induced flow reversal in subchannel 2. Inception of recirculation for the conditions of Case 18 occurs for $Gr^*/Re = 0.25$; this is consistent with previous cases of recirculation.

Initial and final steady-state velocity profiles (Cases 19 and 20) for the 4:1 power skew condition are presented in Figures 7.36 and 7.37. Note that for the 4:1 power skew condition the hot-side and cold-side rod powers differ by $1.82 - 0.455 = 1.365$ kW/rod. For the 1:0 power skew condition (Case 11) the difference was only $0.91 - 0.0 = 0.91$ kW/rod. However, in comparing the 4:1 power skew at 1.08 GPM flow (Figure 7.37) with the 1:0 skew at 1.08 GPM flow (Figure 7.25), the 1:0 skew results in the greater amount of buoyancy-induced flow redistribution. The cold-side heating obviously promotes thermal plume formation and a subsequent increase in mixing. The velocity and thermal profiles of the bundle are thus less skewed. Heating of the cold-side rods may also have some effect on local friction factors that can further effect flow distribution. Consistency of data for the 2:1, 3:1, and 4:1 power skew cases as compared to the 1:0 power skew case suggest that 1:0 or other overly large power skews may dictate a special set of correlations.

FIGURE 7.32. Isothermal (Case 3) and Heated Bundle (Case 16) Velocity Profiles for Initial Steady-State Conditions of Cases 7 and 15 ($Z^* = 1.00$)

FIGURE 7.33. Isothermal (Case 10) and Heated Bundle (Case 17) Velocity Profiles for Final Steady-State Conditions of Cases 7 and 15 ($Z^* = 1.00$)

FIGURE 7.34. Measured and COBRA-Predicted Subchannel Velocity Histories, Case 18 ($Z^* = 1.00$)

FIGURE 7.35. Measured and COBRA-Predicted Subchannel Temperature Histories, Case 18 ($Z^* = 1.00$)

FIGURE 7.36. Isothermal (Case 3) and Heated Bundle (Case 19) Velocity Profiles for Initial Steady-State Conditions of Cases 7 and 18 ($Z^* = 1.00$)

FIGURE 7.37. Isothermal (Case 10) and Heated Bundle (Case 20) Velocity Profiles for Final Steady-State Conditions of Cases 7 and 18 ($Z^* = 1.00$)

7.9 FLOW TRANSIENT CASES 21 AND 22

The initial and final Reynolds numbers for Case 22 ($Re = 730$ and $Re = 320$, respectively for 1:0 power skew) are lower by approximately one-half than those for the previous cases as shown in Table 4.1. The power input to the bundle and the power skew across the bundle are the same as for Cases 6 and 8 (1:0). However, due to the lower flow rate, larger buoyancy effects were expected during Case 22 runs than existed during Cases 6 and 8. Table 4.1 shows that the magnitude of the parameter Gr^*/Re^2 for Case 22 was increased by approximately an order of magnitude compared to the previous cases.

Figure 7.38 shows the isothermal centerpoint velocity histories for Case 21 at $Z^* = 1.00$. The velocity magnitudes for channels 2, 4, and 6 were nearly equal as expected for the isothermal case. The velocity histories decreased linearly with time from time $t = 0$ and respond very closely to the controlled inlet flow rate.

FIGURE 7.38. Measured Subchannel Centerpoint Velocity Histories During Isothermal, 45-sec Flow Coastdown, Case 21 ($Z^* = 1.00$)

Addition of heat to the bundle results in large differences in the measured velocities as shown in Figure 7.39 for Case 22. The increase in buoyancy-induced flow redistribution for Case 22 resulted in an earlier flow reversal (at $t = 30$ sec) with a larger maximum negative velocity ($U/\bar{U} \approx -0.6$) than for Cases 6 and 8 ($U/\bar{U} \approx -0.1$). The inception of recirculation occurred at $Gr^*/Re^2 \approx 0.30$ and caused flow from a higher temperature region to enter the cold side of the bundle. Increases in the temperature of the cold side caused the magnitude of the negative velocity on the cold side to decrease until it became very slightly positive at time $t = 160$ sec. Recirculation zones of the type described earlier did not develop during steady-state conditions even though attempts were made to produce recirculation.

Subchannel temperature measurements were also made for the transient conditions of Case 22. Data for the $Z^* = 1.00$ axial level are shown in

FIGURE 39. Measured and COBRA-Predicted Subchannel Velocity Histories, Case 22 ($Z^* = 1.00$)

Figure 7.40. The inception of recirculation sharply decreased the lateral temperature difference between the hot and cold sides of the 2 x 6 bundle. Temperature as well as velocity measurements for other axial levels are presented in Appendix C.

COBRA-WC predictions for the Case 22 data provide the best example of the sensitivity of the predictions to the type of turbulent mixing model used. COBRA predictions for previous cases (such as Cases 6, 8, and 12) compared favorably with the experimental data using the default input parameters in COBRA-WC and a turbulent crossflow mixing rate of $w' = 0.0$ during the transient. However, using the same parameters, COBRA-WC did not predict the velocity and temperature distributions well for Case 22. Figure 7.41 shows the COBRA-WC predictions for $w' = 0.0$. The $Z^* = 0.875$ axial level is presented as a representative example. The shapes of the velocity distribution curves for subchannels 4 and 6 are not predicted well. As shown, the predicted velocity for subchannel 4 goes to zero at 50 sec whereas the data was well above zero. It was also found that the measured temperature distributions were not predicted well if w' is equal to zero (see Figure 7.40).

FIGURE 7.40. Measured and COBRA-Predicted Subchannel Temperature Histories, Case 22 ($Z^* = 1.00$)

FIGURE 7.41. Measured and COBRA-Predicted (Using Various Turbulent Mixing Models) Velocity Histories, Case 22 ($Z^* = 0.875$)

Observation of the bundle flow during a transient showed that thermal plumes were formed within the bundle adjacent to the heated rods. It was also observed that as the Reynolds number was reduced, the intensity of the thermal plumes increased. The thermal plumes grew in the transverse direction as they moved upwards, and neighboring thermal plumes were visually observed to interact and promote local turbulence within the bundle. Thermal plume interaction appears to have promoted turbulent mixing between subchannels which contained heated rods. The effect of the thermal plumes in promoting turbulent mixing was most evident for Case 22 when the Reynolds number was below ~ 450 . Since mixing increased during the transient of Case 22, a model was developed to correlate w' against the parameter $(Gr/Re^2)\hat{Q}_p$ which also increased during the transient.

The COBRA code was modified to provide a laterally non-uniform turbulent mixing parameter, w' , within the bundle. The gaps between subchannels

which contain heated rods have a value of $w' > 0.0$, whereas $w' = 0.0$ for the rest of the bundle. It was found that velocity predictions matched the data best when $w' = 0.01 (Gr/Re^2) \hat{Q}_p$ as shown in Figure 7.41. As Gr/Re^2 increased during the transient, w' also increased and attained a maximum value after the end of the flow coastdown. This was because the average mixed mean assembly temperature rise, ΔT_B , had not attained its maximum value at the end of the flow coastdown. The value of ΔT_B continued to increase until the fluid entering the bundle at the end of the flow coastdown reached the end of the bundle heated length; i.e., ΔT_B continued to increase for a duration equal to the residence time of the fluid in the heated length.

Since enhanced mixing due to the interactions of thermal plumes occurred only in the vicinity of the heated rods, it was necessary to account for non-uniform lateral turbulent mixing within the bundle. This was done by correlating w' with $\hat{Q}_p$, the local rod power peaking factor.

COBRA-WC predictions incorporating the new w' model were also made for Case 6, 8, and 12. Results were found to be as good as the $w' = 0.0$ predictions, and the new model was incorporated in all subsequent COBRA-WC simulations. The new model is designed to be self-correcting in that its effect becomes more dominant at increasing values of $(Gr/Re^2) \hat{Q}_p$.

7.10 FLOW TRANSIENT CASES 23 THROUGH 28

In order to investigate possible effects of flow coastdown rates on mixed-convection flow redistribution, the same power and flow conditions ($Re = 730 \rightarrow 320$) as those for Case 22 were repeated with varying flow ramp-off rates. Specifically, the test conditions included 150-sec (Case 24), 300-sec (Case 26) and 500-sec (Case 28) linear flow ramp-off transients. No detailed COBRA-WC code predictions for these cases were made--the objective of the test series was to make experimental observations of the effect of flow coastdown rate.

Velocity history plots for subchannels 2, 4, and 6 are presented for each ramp-off rate under both isothermal and 1:0 power skew heated bundle conditions (Figures 7.42 thru 7.47). It can be seen from the series of figures that the magnitude of observed recirculation for the cold-side subchannel No. 2

FIGURE 7.42. Measured Subchannel Centerpoint Velocity Histories During Isothermal, 150-sec Flow Coastdown, Case 23 ($Z^* = 1.00$)

FIGURE 7.43. Measured Subchannel Velocity Histories, Case 24 ($Z^* = 1.00$) 1:0 Power Skew, 150-sec Flow Coastdown, $Re = 730 \rightarrow 320$

FIGURE 7.44. Measured Subchannel Centerpoint Velocity Histories During Isothermal, 300-sec Flow Cooldown, Case 25 ($Z^* = 1.00$)

FIGURE 7.45. Measured Subchannel Velocity Histories, Case 26 ($Z^* = 1.00$), 1:0 Power Skew, 300-sec Flow Cooldown, $Re = 730 > 320$

FIGURE 7.46. Measured Subchannel Centerpoint Velocity Histories During Isothermal, 500-sec Flow Coastdown, Case 27 ($Z^* = 1.00$)

FIGURE 7.47. Measured Subchannel Velocity Histories, Case 28 ($Z^* = 1.00$), 1:0 Power Skew, 500-sec Flow Coastdown, $Re = 730 > 320$

decreased with increasing transient coastdown times. This trend seems consistent with the previous observation of recirculation being detected only for transient flows and not for steady-state conditions. The increasing transient coastdown times show increasing tendencies toward steady-state behavior, i.e., decreasing recirculation.

However, the criterion for inception of recirculation appears to be generally consistent with the earlier observations. For the 150-sec coastdown (Figure 7.43), recirculation was observed at $t = 84$ sec; $Gr^*/Re^2 = 0.26$. For the 300-sec flow coastdown (Figure 7.45) inception of recirculation was found at $t = 145$ sec; $Gr^*/Re = 0.19$. And lastly, for the 500-sec coastdown (Figure 7.47) recirculation began at $t = 290$ sec; $Gr^*/Re^2 = 0.27$. All values of Gr^*/Re^2 are close to the $Gr^*/Re^2 > 0.2$ criterion suggested earlier for the inception of recirculation. The Case 24 (300 sec coastdown) value appears somewhat low but is well within the uncertainty band expected for this study.

7.11 STEADY STATE CASES 29 THROUGH 32

Cases 29 and 30 represented the initial ($t = 0$) steady-state conditions, isothermal and 1:0 power skew respectively, for flow transient Cases 21 through 28. Similarly, Cases 31 and 32 were studies of the final steady-state conditions of transient Cases 21 through 28. Figure 7.48 shows the measured velocity distributions for Cases 29 and 30. It is apparent by comparison with velocity profiles of the higher Reynolds number initial conditions (e.g., Figure 7.24) of the $3.08 \rightarrow 1.08$ GPM transients, that the initial flow distribution for the $1.63 \rightarrow 0.55$ GPM transients ($Re \approx 730 \rightarrow 320$) was much more skewed. Sub-channels 2, 4, and 6 centerpoint velocities correlate nicely with the initial velocities observed in the transient runs.

Final steady-state conditions for the flow transients of Case 21 through 28 resulted in the LDA-measured velocity profiles of Figure 7.49. Most obvious are the near-zero velocities measured in the cold-side subchannel number 2, which is consistent with the final velocities measured at long times for the corresponding flow transients. Even for this low Reynolds number ($Re \approx 320$), no significant steady-state flow recirculation was measurable for the central channels 1 through 7.

FIGURE 7.48. Isothermal (Case 29) and Heated Bundle (Case 30) Velocity Profiles for Initial Steady-State Conditions of Cases 21 Through 28 ($Z^* = 0.875$)

FIGURE 7.49. Isothermal (Case 31) and Heated Bundle (Case 32) Velocity Profiles for Final Steady-State Conditions of Cases 21 Through 28 ($Z^* = 0.875$)

COBRA-WC code predictions of subchannel velocities for the initial and final steady-state flows are also included on the plots of Figures 7.48 and 7.49. Comparisons between COBRA's subchannel average and the LDA measured subchannel centerline velocity values are easily evidenced. Velocity profile plots of Cases 29 through 32 for other axial levels are included in Appendix C.

7.12 STEADY-STATE FLOW CASES 33 AND 34

Cases 33 and 34 examine the detailed flow behavior of very low Reynolds number flows in the 2 x 6 rod bundle facility. The tests were performed in an attempt to examine the conditions whereby steady state flow recirculation might be established. Figure 7.50 shows the velocity profiles obtained for the Case 33 isothermal condition ($Re \approx 120$) and the Case 34 1:0 power skew ($Re \approx 220$). As seen from the plot, there was some recirculation on the unheated side of the bundle at $X \leq 0.7$ in. However, there was a stronger, somewhat erratic (as evidenced by the wide data scatter) recirculation on the hot-side of the bundle at $X \geq 3.1$ in. Such behavior is totally contrary to any expected behavior for

FIGURE 7.50. Isothermal (Case 33) and Heated Bundle (Case 34) Velocity Profiles for Low Reynolds Number ($Re = 220$) Steady-State Conditions ($Z^* = 1.00$)

a 1:0 power skew condition. The isothermal profile indicates essentially undisturbed flow with no geometry problems apparent. We postulate that some combination of the horizontal side-discharge geometry and associated heat losses from the discharge line restructured the flow field near the bundle end-of-heated-length. This anomolous recirculation at the $Z^* = 1.00$ axial level persisted for virtually any rod power configuration for low (≤ 250) Reynolds numbers.

To investigate what effects this anomolous flow behavior might have had on the transient test results, the end point flow (0.55 GPM) profile of the lowest-Reynolds-number-range ($Re = 730 \rightarrow 320$) transient was detailed for both a normal 1:0 power skew and an inverted 0:1 power skew. In the 0:1 power skew case, rods 1 through 6 were heated at 0.91 kW/rod, while rods 7 through 12 were unheated. The flow profiles thus obtained would be mirror images if there were no asymmetric thermal-hydraulic forces at work. As demonstrated by the data of Figure 7.51, the 1:0 and 0:1 power skew flow profiles for $Re \approx 320$ show no anomalous behavior. These findings lend further confidence to the transient test results.

FIGURE 7.51. Comparison of 1:0 and Inverted 0:1 Power Skew for Case 32 Conditions ($Z^* = 1.00$)

7.13 STEADY-STATE CASES 35 THROUGH 38

The steady-state flow distributions for a 1:0 power skew condition has been examined in previous sections. Cases 35 through 38 examine steady-state flow distributions for the less severe 2:1 power skew. Case 35 modeled a low Reynolds number flow (0.30 GPM, $Re = 280$). As seen in Figure 7.52, the rather unexpected condition of hot-side recirculating flow was again observed. For both the 1:0 and 2:1 power skew conditions, this behavior was confirmed by visual observation of entrained particles as well as the LDA measurements. As before, some combination of discharge geometry and associated heat losses are thought to account for this interesting behavior. This anomalous behavior was confined to the window 9 end-of-heated-length region ($Z^* = 1.00$), which lends further support to the hypothesis. Figure 7.53 shows the velocity profile measured at the window 7 ($Z^* = 0.750$) axial level for the conditions of Case 35. The flow distribution is more "normal" with elevated velocities in the hot-side subchannels, and reduced (but still positive) flows on the cold side. Velocity profiles for additional axial levels of Case 35 conditions are included in Appendix C.

Comparison of the Case 36 ($Re = 370$) and Case 38 ($Re = 800$) velocity profiles of Figures 7.54 and 7.55 gives an indication of the thermal plume enhanced mixing that becomes more pronounced at lower flow rates. While the Case 38 profile (Figure 7.55) does show an overall skew attributable to the 2:1 power gradient, the velocity profile exhibits behavior very similar to the isothermal condition; very definite velocity peaks at subchannel centers and velocity minimums at gaps between adjacent rods. The Case 36 profile (Figure 7.54) in comparison shows a much flatter profile with no distinguishable local velocity maximums and minimums. This turbulent flow-like, flat velocity profile was generated by the induced mixing of the bouyant thermal plumes formed near the heated rods. This postulated mechanism of thermal plume enhanced mixing was given further credibility by the improved predictive capability of the COBRA-WC code incorporating a turbulent crossflow mixing term coupled directly to the bouyancy-related parameter, Gr/Re^2 .

FIGURE 7.52. Isothermal (Case 33) and Heated Bundle (Case 35) Velocity Profiles for Low Reynolds Number ($Re = 280$) Steady-State Conditions ($Z^* = 0.750$)

FIGURE 7.53. Isothermal (Case 33) and Heated Bundle (Case 35) Velocity Profiles for Low Reynolds Number ($Re = 280$) Steady-State Conditions ($Z^* = 0.750$)

FIGURES 7.54. Isothermal (Case 31) and Heated Bundle (Case 36) Velocity Profiles for Steady-State Flow ($Re = 370$; $Z^* = 1.00$)

FIGURE 7.55. Isothermal (Case 37) and Heated Bundle (Case 38) Velocity Profiles for Steady-State Flow ($Re = 800$; $Z^* = 1.00$)

7.14 SUMMARY OF TRANSIENT MIXED CONVECTION RESULTS

Buoyancy can affect flows within a fuel bundle in three ways: 1) buoyancy forces can alter the total bulk flow rate in the bundle (Singer, Kerian and Parkinson 1972); 2) buoyancy forces can cause flow redistribution within a bundle (Quigley, McMonagle and Bates 1977); or 3) buoyancy forces can induce both of the aforementioned effects within a bundle. In the present study the inlet flow into the bundle was controlled during the transients, and the total inlet flow into the bundle could not increase due to buoyancy. The present study focused on flow redistribution within a bundle and extended the work of Quigley et al. to include flow transients. The study on "combined" effects of buoyancy is reported in Section 8.0 on natural circulation in a 2 x 6 rod bundle.

Transient velocity measurements in hot, cold, and interface channels were taken at 6-in. intervals along the 4-ft heated length of the test bundle. The inlet flow to the bundle was reduced from initial steady-state conditions while maintaining a constant rod power level. During the transient there was an increase in flow redistribution within the bundle. Decreasing velocities were observed at the 48-in. axial level (bundle end of heated length) for channels 2 and 4 (the cold and interface subchannels.), which for the 1:0 and 4:1 power skew cases led to flow reversals in subchannel 2. In some cases, for a reduced bundle flow rate, the recirculation zone was observed to penetrate to the midplane of the heated length.

It is hypothesized that the formation of a recirculation zone caused hot fluid to be transported to the colder regions of the bundle thereby increasing the cold-side temperature. As the cold-side temperature increased, lateral temperature differences between hot and cold sides decreased, thus decreasing the effective differential buoyancy forces. The magnitude of the cold-side negative velocity gradually decreased until, for steady-state conditions, it was approximately zero. No recirculation flow patterns were observed within the bundle for steady-state conditions. For the 1:0 power skew transients the

inception of recirculation occurred when the dimensionless ratio $Gr/Re^2(\hat{Q}_p - 1) \geq \sim 0.2$. This criterion was not exceeded at any time during certain power skew/flow transient cases and no recirculation was detected.

The COBRA-WC code was used in making a comparative analysis of the data. Velocity and temperature histories were predicted well, including the time of inception for recirculation flow. In certain cases, no adjustments were made to the COBRA-WC input parameters, and turbulent mixing was set to zero ($w' = 0.0$). The exceptions were the low-Reynolds-number transient cases where it was found that COBRA-WC predictions could be substantially improved by including the effect of turbulent mixing due to the interacting effect of thermal plumes. Thus, it appears that the turbulent mixing crossflow rate, w' , did not remain constant during the transient but increased with time as turbulent plumes developed and interacted. It was found that w' can be correlated with the dimensionless group $(Gr/Re^2)\hat{Q}_p$ [$w' = 0.01 (Gr/Re^2)\hat{Q}_p$].

For all test conditions in Table 4.1 with $Re \geq 300$, flow reversal occurred within the bundle only during a transient. During a transient an increase in buoyancy forces caused an increase in crossflow from the colder to the hotter regions of the bundle. It has been hypothesized that as the axial velocity of the colder subchannel approached zero, the inertia of the fluid in the transverse direction caused it to undershoot below zero. The subsequent increase in temperature of the colder side of the bundle was partially responsible for the flow recovery.

The magnitudes of the dimensionless ratio Gr^*/Re^2 at the time of flow reversal for the various cases are presented in the table below. Based on other similar runs it appears that if the parameter $Gr^*/Re^2 > \sim 0.2$ at any time during transient, flow recirculation can be expected to occur. This is a preliminary conclusion.

TABLE 7.1. Gr^*/Re^2 at Inception of Recirculation

Case Number	Flow Transient Time (sec)	Power Skew	Initial Gr^*/Re^2	Final Gr^*/Re^2	Inception of Time (sec)	Recirculation Gr^*/Re^2
6	150	1:0	0.010	0.264	160	0.24
8	45	1:0	0.010	0.264	55	0.27
12	45	2:1	0.005	0.146	-	-
15	45	3:1	0.011	0.320	-	-
18	45	4:1	0.017	0.522	52	0.25
22	45	1:0	0.072	2.414	30	0.30
24	150	1:0	0.072	2.414	84	0.255
26	300	1:0	0.072	2.414	145	0.192
28	500	1:0	0.072	2.414	290	0.272

8.0 NATURAL CIRCULATION IN THE 2 x 6 ROD BUNDLE

8.1 NATURAL CIRCULATION TEST FACILITY

The test facility as described in Section 3.1 was modified for use to perform the natural circulation tests (see Figure 8.1). For these tests, developed buoyancy forces provided the sole source of coolant flow through the heated 2 x 6 rod bundle. For this test series only steady-state flow conditions were considered.

The 3000-gal supply tank was connected to the test section inlet using large 4-in.-dia piping. This large-diameter piping resulted in extremely low pressure drops at the low flow rates required. The test section discharge was fitted with a head balance tank assembly that allowed a static fluid level balance between the test section discharge and the supply tank. A 0 to 5 in. H₂O differential pressure transducer was connected between the supply tank and the balance tank to monitor the relative levels. A constant level in the supply tank was maintained by a continuous feed with a fixed-elevation overflow drain fitted on the tank. As a buoyancy head was developed by addition of heat in the test section, a small self-priming pump was used to pump coolant from the head balance tank to maintain a balanced level with the supply tank. The pump discharge was routed through a 10- μ m filter to the same small turbine flow meter used for the mixed-convection studies. The flow rate thus measured was (effectively) the buoyancy-driven natural-convection flow for the heated bundle.

8.2 EXPERIMENTAL PROCEDURE

The primary purpose of conducting the steady-state natural circulation tests was to obtain data for comparison with the mixed-convection data at similar rod power configurations and bundle average Reynolds numbers. Table 8.1 outlines the various test cases.

For each test case, conditions were allowed to reach steady-state before a $Z^* = 1.00$ centerline velocity traverse with the LDA was made. Subchannel centerline temperature measurements were also obtained for selected axial levels.

FIGURE 8.1. Test Facility-Natural Circulation Test Configuration

TABLE 8.1. Natural Circulation Test Conditions

Case Number	$\dot{W}$ (GPM)	Power Gradient	Q_H (kW/rod)	Q_L (kW/rod)	Re^a	Compare to Mixed-Convection Case number
39	1.04	1:0	0.91	0.0	500	11
40	1.08	2:1	0.91	0.455	560	14
41	1.08	3:1	1.365	0.455	630	17

^a Based on bundle average $D_H = 0.0294$ ft and bundle average flow conditions (T,P) with $T_{in} = 75^\circ F$

A typical run was initiated by turning on the rod powers to desired levels. As the fluid in the test section was heated and became less dense, the level in the discharge balance tank began to rise (as monitored by the differential pressure transducer). The small transfer pump was then started and the flow adjusted (by means of a needle valve on the pump discharge line) such that the balance between the supply tank and the balance tank was maintained. For Case 39, 1.04 GPM was the maximum natural circulation flow obtainable. However, for Cases 40 and 41 (2:1 and 3:1 power skews) sufficient buoyancy forces existed to give more than 1.08 GPM total flow. For these cases the pump discharge was maintained at 1.08 GPM, and the level in the balance tank was allowed to rise. This mode of operation limited the natural circulation flow to a level matching that of earlier mixed convection tests.

8.3 STEADY-STATE NATURAL CIRCULATION TEST RESULTS

Experimental data for the natural circulation tests are presented in the accompanying figures. For the 1:0 power skew (Case 39), 1.04 GPM ($Re \approx 500$) was the maximum obtainable thermally driven flow. The non-dimensionalized ($U/\bar{U}$) velocity profile for the $Z^* = 1.00$ axial level is shown in Figure 8.1 and compared to the 1.08 GPM ($Re \approx 520$) mixed convection data. Within the limits of experimental error, the data are essentially identical.

Data for the 2:1 and 3:1 power skew conditions are similarly presented and compared to the mixed convection profiles in Figures 8.2 and 8.3 respectively. In both instances, the natural convection and mixed convection velocity profiles are very similar.

Based on this very limited comparison, it can be concluded that the local behavior of thermally driven convective flows is indistinguishable from mixed convection flows for similar Reynolds Numbers.

In addition to the local velocity data obtained by the LDA, a short test sequence was completed which measured bundle average temperature use and maximum thermally driven bulk flow for a range of total power input to the 2 x 6 gundle. For uniformly heated bundle power levels of 0.5, 1.0, 1.5, 2.0, 2.5

FIGURE 8.2. Natural Circulation Velocity Profile (Case 39) and Mixed-Convection Velocity Profile (Case 11) for a 1:0 Power Skew, $Re \approx 500$ ($Z^* = 1.00$)

FIGURE 8.3. Natural Circulation Velocity Profile (Case 40) and Mixed-Convection Velocity Profile (Case 14) for a 2:1 Power Skew, $Re \approx 550$ ($Z^* = 1.00$)

FIGURE 8.4. Natural Circulation Velocity Profile (Case 41) and Mixed-Convection Velocity Profile (Case 17) for a 3:1 Power Skew, $Re \approx 600$ ($Z^* = 1.00$)

and 3.0 kW/rod, the temperature rise across the bundle, ΔT_B , and the thermally driven bulk flow rate were measured. These data are plotted in Figures 8.5 and 8.6.

The data of Figure 8.5 indicate that the slope of the curve of coolant temperature rise versus total bundle power is positive but tends to decrease with increasing power. Thus increased power levels increase the peak coolant temperature, but simultaneously the larger axial temperature rise increases the bulk convective flow due to the increased buoyancy of the hotter, less dense fluid. Similar results have been reported by Gillette et al. (1979) for actual in-reactor tests.

FIGURE 8.5. Effect of Bundle Power Level on Coolant Bulk Temperature Rise for Natural Circulation Flows

FIGURE 8.6. Effect of Bundle Power Level on Natural Circulation (Buoyancy-Driven) Flow Rates

REFERENCES

- Buchave, P., W. K. George, Jr. and J. L. Lumley. 1979. "The Measurement of Turbulence with the Laser-Doppler Anemometer." Annual Review of Fluid Mechanics, 11:443-503.
- Creer, J. M., D. S. Rowe, J. M. Bates and A. M. Sutey. 1976. Effects of Sleeve Blockages on Axial Velocity and Intensity of Turbulence in an Unheated 7 x 7 Rod Bundle. BNWL-1965, 1976, Pacific Northwest Laboratory, Richland, Washington.
- Durst, F. 1977. "Hot-Wire and Laser-Doppler Techniques in Turbulence Research." Lecture presented at the Conference: Turbulent Transport Processes in Fluids, October 17-20, 1977, Sarajewo, Yugoslavia.
- George, T. L., K. L. Basehore, C. L. Wheeler, W. A. Prather and R. E. Masterson. 1980. COBRA-WC: A Version of COBRA for Single-Phase Multiassembly Thermal Hydraulic Transient Analysis. PNL-3259, Pacific Northwest Laboratory, Richland, Washington.
- Gillette, J. L., R. M. Singer, J. V. Tokar and J. W. Sullivan. 1979. "Experimental Study of the Transition from Forced to Natural Circulation in EBR-II at Low Power and Flow." Paper No. 79-HT-10, American Society of Mechanical Engineers, New York, New York, August 1979.
- Hendricks, R. C., I. C. Peller and A. K. Baron. 1973. "WASP - A Flexible Fortran IV Computer Code for Calculating Water and Steam Properties." NASA Technical Note, NASA TN D-7391, National Aeronautics and Space Administration, Washington, D.C.
- Khan, E. U., W. M. Rohsenow, A. A. Sonin and N. E. Todreas. 1975. "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Rod Assemblies Operating in Combined Forced and Free Convection." Nuc. Eng. and Des., (35):199-211.
- Markley, R. A., R. D. Coffield and E. U. Khan. 1979. "Natural Convection Analyses and Verification for LMFBR Codes. In Proceedings of the IAEA Conference on Thermal Dynamics of Fast Breeder Reactor Fuel Assemblies Under Nominal and Non-nominal Conditions. Karlsruhe, West Germany.
- Quigley, M. S., C. A. McMonagle and J. M. Bates. 1977. Investigation of Combined Free and Forced Convection in a 2 x 6 Rod Bundle. BNWL-2216, Pacific Northwest Laboratory, Richland, Washington.
- Schenck, H., Jr. 1961. Theories of Engineering Experimentation. McGraw-Hill Book Company, New York, New York.

- Singer, R. M., J. L. Kerian and T. F. Parkinson. 1972. "An Experimental Study of Combined Liquid Metal Heat Transfer During Flow Transients." Paper No. 72-WA/HT-45, American Society of Mechanical Engineers, New York, New York.
- Tilton, L. W. and S. K. Taylor. 1938. "Refractive-Index and Dispersion of Distilled Water for Visible Radiation at Temperatures 0 to 60°C." Research Paper PP. 1085, Journal of Research of the National Bureau of Standards. Vol. 20.
- Tsai, C., A. A. Bishop and R. A. Markley. 1973. "Effects of Buoyancy Force on the Velocity and Temperature Distributions in an LMFBR Radial Blanket Fuel Rod Assembly." Paper No. 73-HT-58, American Society of Mechanical Engineers, New York, New York.
- Weast, R. C., ed. 1971. Handbook of Chemistry and Physics. 52nd edition. The Chemical Rubber Co., Cleveland, Ohio.
- Wheeler, C. L., C. W. Stewart, R. H. Cena, D. S. Rowe and A. M. Sutey. 1976. COBRA-IV-I: An Interim Version of COBRA for Thermal Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements and Cores. BNWL-1962, Pacific Northwest Laboratory, Richland, Washington.

APPENDIX A
NOMENCLATURE

NOMENCLATURE

C	damping circuitry capacitance
D_H	bundle hydraulic diameter
F_s	Bragg cell induced frequency shift
F_D	Doppler frequency
G	bundle average axial mass flux
Gr	Grashof number, $(g\alpha\Delta T_B D_H^3/\nu^2)$
Gr^*	modified Grashof number = $Gr (\hat{Q}_p - 1)$
Gr/Re^2	$(g\alpha D_H \Delta T_B)/\bar{U}$
L	rod bundle heated length
Pr	Prandtl number
Q_C	cold-side heat flux
Q_H	hot-side heat flux
$\hat{Q}_p$	local-to-average power ratio, e.g., $Q_H/[(Q_H + Q_C)/2]$
R	damping circuitry resistance
Re	Reynolds number, $(\bar{U} D_H/\nu)$
T	temperature
T^*	nondimensionalized local temperature $T-T_{in}/(T_{out}-T_{in})_{t=0}$
T_{in}	test section inlet temperature
T_{out}	test section outlet temperature
ΔT_B	temperature rise across bundle, $(T_{out}-T_{in})$
U	local mean axial velocity
$\bar{U}$	bundle average velocity
$\dot{W}_i$	initial volumetric flow rate (at $t=0$)
$\dot{W}_f$	final volumetric flow rate
Z^*	Z/L , nondimensional axial level
a	rod bundle flow area
d	rod diameter
g	gravitational constant
m	slope of flow coastdown curve
s	gap width between adjacent rods
t	time from start of transient, sec

w'	turbulent crossflow mixing parameter
X	positional coordinate
Y	positional coordinate
α	thermal expansion coefficient, $1/^\circ\text{F}$
β	mixing coefficient
θ	laser beam intersection angle
λ	laser light wavelength
ν	kinematic viscosity
π	density
τ	damping circuitry time constant for signal processor
ω	uncertainty interval

APPENDIX B
UNCERTAINTY ANALYSIS

APPENDIX B
UNCERTAINTY ANALYSIS

Accuracies of the results of the combined free- and forced-convection transient flow study were estimated using the uncertainty method presented by Schenck (1961). Consider the general case of a result R , which is a function of the two measured variables X_m and Y_m :

$$R + r = F(X_m + x, Y_m + y)$$

If this function is continuous and differentiable, it can be shown that the result R lies within the uncertainty interval ω such that

$$\omega_r^2 = (\partial R / \partial X_m)^2 \omega_x^2 + (\partial R / \partial Y_m)^2 \omega_y^2 .$$

where ω for this analysis is that precision index enclosing 95 percent of all readings or values.

VELOCITY UNCERTAINTY

For the laser anemometer, the axial velocity is directly related to the Doppler frequency (F_D) by the relationship

$$U = \frac{(F_D - F_s)\lambda}{2 \sin \theta/2}$$

with

$$\omega_U^2 = (\partial U / \partial \lambda)^2 \omega_\lambda^2 + (\partial U / \partial F_D)^2 \omega_{F_D}^2 + (\partial U / \partial F_s)^2 \omega_{F_s}^2 + (\partial U / \partial \theta/2)^2 \omega_{\theta/2}^2$$

It was assumed that the uncertainty of the wavelength of the laser light ($5145 \text{ \AA} = 1.688 \times 10^{-6} \text{ ft}$) is negligible so that the first term above goes

to zero. By considering instrument accuracies, the Doppler frequency uncertainty was estimated to be $\omega_{F_D} \cong \pm 1.0$ kHz from 0 to 150 kHz. The Bragg cell-induced shift frequency of 51.1 kHz is assumed accurate to $\omega_{F_S} = \pm 0.2$ kHz. The half angle of the laser beam intersection was determined to be $\theta/2 = 7.24^\circ \pm 0.04^\circ$ (0.0007 rad) by the above uncertainty methods. For the nominal Doppler frequency range encountered in this study, $20.0 \text{ kHz} < F_D < 160 \text{ kHz}$.

$$\omega_U^2 = (\lambda/2 \sin \theta/2)^2 \omega_{F_D}^2 + (-\lambda/2 \sin \theta/2)^2 \omega_{F_S}^2 + \left(\frac{-\lambda(F_D - F_S)}{2} \csc \frac{\theta}{2} \cot \frac{\theta}{2} \right)^2 \omega_{\theta/2}^2$$

where $\lambda = 5.145 \text{ Å} = 1.688 \times 10^{-6} \text{ ft}$, $\omega_\lambda = 0.0$

$\theta/2 = 7.24^\circ$, $\omega_{\theta/2} = \pm 0.0007 \text{ rad}$

$F_S = 51.1 \text{ kHz}$, $\omega_{F_S} = \pm 0.2 \text{ kHz}$

at: $F_D = 20. \text{ kHz}$, $\omega_{F_D} = \pm 1.0 \text{ kHz}$

$$\begin{aligned} \omega^2 &= [1.688 \times 10^{-6}/2 \sin (7.24)]^2 (1 \times 10^3)^2 \\ &\quad + [-1.688 \times 10^{-6}/2 \sin (7.24)]^2 (0.2 \times 10^3)^2 \\ &\quad + \left[\frac{-1.688 \times 10^{-6} (20 - 51.1) 10^3}{2} \csc (7.24) (\cot 7.24) \right]^2 (0.0007)^2 \\ &= 4.485 \times 10^{-5} + 1.794 \times 10^{-6} + 1.317 \times 10^{-6} \\ &= 4.796 \times 10^{-5} \end{aligned}$$

$\omega_U = \pm 0.0069 \text{ ft/s}$

$U = -0.208 \text{ ft/s}$ (for $F_D = 20 \text{ kHz}$)

$\omega_U = \pm 3.3\%$

at: $F_D = 160 \text{ kHz}$, $\omega_{F_D} = \pm 1.0 \text{ kHz}$

$$\omega_U^2 = 4.485 \times 10^{-5} + 1.794 \times 10^{-6} + 1.614 \times 10^{-5} = 6.279 \times 10^{-5}$$

$$\omega_U = \pm 0.0079 \text{ ft/sec}$$

$$U = 0.729 \text{ ft/sec (for } F_D = 160 \text{ kHz)}$$

$$\omega_U = \pm 1.1\%$$

As a conservative estimate, assume $\pm 6\%$ error on bundle average velocity (initial or final steady-state flows), based on the sum of the uncertainties for cross-sectional flow area ($\pm 1\%$) and bundle total flow ($\pm 5\%$ variation from nominal). Therefore, the total uncertainty for the nondimensional velocity $U/\bar{U}$ can be estimated at $< \pm 10\%$ (Schenck 1961).

An additional source of error for velocity measurements during a flow coastdown transient was the resistance-capacitance (RC) time lag of signal processor readings of instantaneous Doppler frequency. As shown in Figure B.1, the RC time constant, $\tau = 5 \text{ sec}$, can be seen to result in positive biasing error for velocity measurements obtained during a flow coastdown condition. The 45-sec transient curve shown in Figure B.1 represents the steepest flow coastdown curve used in the present study. For these operating conditions, the RC lag induced bias is

$$\Delta \frac{U}{U_{t=0}} < +0.1,$$

as shown below.

For the RC damping circuit used on the signal processor:

$$\begin{aligned} \tau &= \text{circuit time constant} \\ &= R \cdot C \\ &= 5.0 \text{ seconds.} \end{aligned}$$

FIGURE B.1. Signal Processor First Order Response to Ramp Change in Flow Rate

For local subchannel centerline velocity ramping from

$$\frac{U}{U_{t=0}} = 1.52$$

to

$$\frac{U}{U_{t=0}} = 0.69 \text{ in 45 seconds}$$

the slope m of the flow coastdown curve (assuming a linear 45-sec rampdown of local flow velocity in response to a linear 45-sec rampdown of inlet flow rate) is given by

$$m = \frac{1.42 - 0.69}{45 \text{ sec}} = 0.018/\text{sec}$$

The induced lag (due to first order response of signal processor) in the measurements is therefore

$$\Delta \frac{U}{U_{t=0}} = m = 0.018/\text{sec} (5 \text{ sec}) = +0.092.$$

$$\text{or at } t = 45 \text{ sec: } \frac{0.092}{0.690} = +13.3\%$$

This biasing error only applies to transient flow conditions, and has no effect on steady-state velocity measurements.

TEMPERATURE UNCERTAINTY

The accuracy of the thermocouple temperature measurement based on calibration checks was $\omega_T \approx \pm 0.9^\circ\text{F}$. The thermocouple referencing unit

induced an additional error of $<0.1^{\circ}\text{F}$. For the temperature difference between two thermocouple locations, $\Delta T = T_2 - T_1$, the uncertainty is:

$$\omega_{\Delta T}^2 = (1.0)^2 + (1.0)^2 = 2.0$$

$$\omega_{\Delta T} = \pm 1.414^{\circ}\text{F}$$

The nondimensional temperature for any location was defined as:

$$\frac{T - T_{in}}{(T_{out} - T_{in})_{t=0}} = T^*$$

for

$$\Delta T_B = (T_{out} - T_{in})_{t=0} = 12.10^{\circ}\text{F} \text{ and } T^* = 1.0$$

$$\omega_{T^*}^2 = \left(\frac{1}{\Delta T_B}\right)^2 \omega_{\Delta T}^2 + \left(-\frac{\Delta T}{\Delta T_B^2}\right) \omega_{\Delta T_B}^2$$

$$= \left(\frac{1}{12.10}\right)^2 (1.414)^2 + \left(\frac{-12.10}{12.10^2}\right)^2 (1.414)^2$$

$$= 0.0137 + 0.0137$$

$$= 0.0273$$

$$\omega_{T^*} = 0.1653$$

or

$$\frac{\omega_{T^*}}{T^*} = 16.53\%$$

For other values of T^* with $\Delta T_B = 12.10^\circ\text{F}$:

$T^* = 0.5$	$\omega_T = \pm 26.1\%$
1.5	$\pm 14.1\%$
2.0	$\pm 13.1\%$
3.0	$\pm 12.3\%$

For $\Delta T_B \cong 18.2^\circ\text{F}$:

$T^* = 0.5$	$\omega_T = \pm 17.4\%$
1.0	$\pm 11.0\%$
1.5	$\pm 9.4\%$
2.0	$\pm 8.7\%$
3.0	$\pm 8.2\%$

For $\Delta T_B \pm 22.9^\circ\text{F}$:

$T^* = 0.5$	$\omega_T = \pm 13.8\%$
1.0	$\pm 8.8\%$
1.5	$\pm 7.4\%$
2.0	$\pm 6.9\%$
3.0	$\pm 6.5\%$

REFERENCE

Schenck, H., Jr. 1961. Theories of Engineering Experimentation. McGraw-Hill
Book Company, New York, New York.

APPENDIX C
DATA PLOTS

FIGURE C.1. Case 5, $Z^* = 0.375$ Velocity Histories

FIGURE C.2. Case 5, $Z^* = 0.625$ Velocity Histories

FIGURE C.3. Case 5, $Z^* = 0.750$ Velocity Histories

FIGURE C.4. Case 5, $Z^* = 0.875$ Velocity Histories

FIGURE C.5. Case 5, $Z^* = 1.00$ Velocity Histories

FIGURE C.6. Case 6, $Z^* = 0.375$ Velocity Histories

FIGURE C.7. Case 6, $z^* = 0.750$ Velocity Histories

FIGURE C.8. Case 6, $z^* = 0.875$ Velocity Histories

FIGURE C.9. Case 6, $Z^* = 0.125$ Temperature Histories

FIGURE C.10. Case 6, $Z^* = 0.375$ Temperature Histories

FIGURE C.11. Case 6, $Z^* = 0.625$ Temperature Histories

FIGURE C.12. Case 7, $Z^* = 0.125$ Velocity Histories

FIGURE C.13. Case 7, $Z^* = 0.375$ Velocity Histories

FIGURE C.14. Case 7, $Z^* = 0.625$ Velocity Histories

FIGURE C.15. Case 7, $Z^* = 0.750$ Velocity Histories

FIGURE C.16. Case 7, $Z^* = 0.875$ Velocity Histories

FIGURE C.17. Case 8, $Z^* = 0.125$ Velocity Histories

FIGURE C.18. Case 8, $Z^* = 0.375$ Velocity Histories

FIGURE C.19. Case 8, $Z^* = 0.625$ Velocity Histories

FIGURE C.20. Case 8, $Z^* = 0.750$ Velocity Histories

FIGURE C.21. Case 8, $Z^* = 0.875$ Velocity Histories

FIGURE C.22. Case 8, $Z^* = 0.125$ Temperature Histories

FIGURE C.23. Case 8, $Z^* = 0.375$ Temperature Histories

FIGURE C.24. Case 8, $Z^* = 0.625$ Temperature Histories

FIGURE C.25. Case 8, $Z^* = 0.750$ Temperature Histories

FIGURE C.26. Case 8, $Z^* = 0.875$ Temperature Histories

FIGURE C.27. Cases 10 and 11, $Z^* = 0.750$ Velocity Profiles

FIGURE C.28. Cases 10 and 11, $Z^* = 0.875$ Velocity Profiles

FIGURE C.29. Case 12, $Z^* = 0.125$ Velocity Histories

FIGURE C.30. Case 12, $Z^* = 0.375$ Velocity Histories

FIGURE C.31. Case 12, $Z^* = 0.625$ Velocity Histories

FIGURE C.32. Case 12, $Z^* = 0.750$ Velocity Histories

FIGURE C.33. Case 12, $Z^* = 0.875$ Velocity Histories

FIGURE C.34. Cases 10 and 14, $Z^* = 0.750$ Velocity Profiles

FIGURE C.35. Case 12, $Z^* = 0.375$ Temperature Histories

FIGURE C.36. Case 12, $Z^* = 0.625$ Temperature Histories

FIGURE C.37. Case 12, $Z^* = 0.750$ Temperature Histories

FIGURE C.38. Case 12, $Z^* = 0.875$ Temperature Histories

FIGURE C.39. Case 15, $Z^* = 0.125$ Velocity Histories

FIGURE C.40. Case 15, $Z^* = 0.375$ Velocity Histories

FIGURE C.41. Case 15, $Z^* = 0.625$ Velocity Histories

FIGURE C.42. Case 15, $Z^* = 0.750$ Velocity Histories

FIGURE C.43. Case 15, $z^* = 0.875$ Velocity Histories

FIGURE C.44. Case 18, $z^* = 0.125$ Velocity Histories

FIGURE C.45. Case 18, $Z^* = 0.375$ Velocity Histories

FIGURE C.46. Case 18, $Z^* = 0.625$ Velocity Histories

FIGURE C.47. Case 18, $Z^* = 0.750$ Velocity Histories

FIGURE C.48. Case 21, $Z^* = 0.125$ Velocity Histories

FIGURE C.49. Case 21, $Z^* = 0.875$ Velocity Histories

FIGURE C.50. Case 22, $Z^* = 0.125$ Velocity Histories

FIGURE C.51. Case 22, $Z^* = 0.375$ Temperature Histories

FIGURE C.52. Cases 29 and 30, $Z^* = 0.125$ Velocity Profiles

FIGURE C.53. Cases 29 and 30, $Z^* = 1.00$ Velocity Profiles

FIGURE C.54. Cases 31 and 32, $Z^* = 0.125$ Velocity Profiles

FIGURE C.55. Cases 31 and 32, $Z^* = 1.00$ Velocity Profiles

FIGURE C.56. Cases 33 and 35, $Z^* = 0.125$ Velocity Profiles

FIGURE C.57. Cases 33 and 35, $Z^* = 0.375$ Velocity Profiles

FIGURE C.58. Cases 31 and 36, $Z^* = 0.125$ Velocity Profiles

FIGURE C.59. Cases 31 and 36, $Z^* = 0.375$ Velocity Profiles

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