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Bundle Containing Partial Flow Blockages

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TURBULENT FLOW IN A MODEL
NUCLEAR FUEL ROD BUNDLE CONTAINING
PARTIAL FLOW BLOCKAGES

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Abstract - Local velocity and turbulence intensity measurements were obtained with a laser Doppler anemometer near flow blockages in an unheated 7 x 7 rod bundle. Sleeve blockages were positioned on the center nine rods to create area reductions of 70 and 90 percent in the center four subchannels of the bundle. Experimental results indicated that severe flow disturbances existed downstream from the blockage clusters and showed that only minor disturbances can be expected upstream from the blockages. Recirculation zones for both 70 and 90 percent blockages were detected downstream from the blockage clusters and persisted for approximately three to five subchannel hydraulic diameters depending on blockage severity. The experimental velocity results obtained with blockage clusters located midway between grid spacers were successfully predicted using the COBRA subchannel computer program.

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NOMENCLATURE

E_{rms} ,	rms voltage;
E_{DC} ,	dc voltage;
f ,	bare rod friction factor;
f_D ,	Doppler frequency;
f_i ,	frequency of incident laser beam;
f_t ,	turbulent momentum factor;
K_{ij} ,	cross flow resistance;
K_{s1} ,	subchannel spacer loss coefficient;
K_{s2} ,	subchannel blockade loss coefficient;
Re ,	Reynolds number;
s/l ,	transverse momentum;
t ,	total transient time;
T ,	temperature;
$\bar{u}$,	local measured mean axial velocity;
U_B ,	bundle average velocity;
U_{sc} ,	subchannel average velocity;
$\bar{u}/U_B$,	ratio of local mean velocity to bundle average velocity;
u' ,	local rms fluctuating component of velocity;
$u'/\bar{u}$,	local intensity of turbulence;
x ,	x coordinate;
y ,	y coordinate;
z ,	z coordinate;

Greek Symbols

β ,	turbulent mixing parameter;
λ ,	wavelength;
θ ,	angle between incident laser beams.

1. INTRODUCTION

In the event of postulated accidents in nuclear reactors, fuel rod overheating may occur. As rod temperatures increase, internal fuel pressures may cause clad "swelling" which could lead to coolant blockages. It is important that flow and heat transfer phenomena near such blockages are well understood to permit detailed safety analyses to be performed for postulated accidents. Consequently, as a first step in gaining such an understanding, an experimental program was initiated to study the effects of blockages on flow distributions in rod bundles. The experiments were performed in water at 85°F at Reynolds numbers of 1.4×10^4 ($U_B = 2.7$ ft/sec), 2.9×10^4 ($U_B = 5.7$ ft/sec), and 5.8×10^4 ($U_B = 10.7$ ft/sec). These conditions modeled those of steam at a point in time during a postulated loss of coolant accident (LOCA) in a pressurized water reactor (PWR) where all of the reactor core reflood water (0.5, 1.0, and 2.0 in./sec) would be converted to steam. Dynamic similarity was ensured between the low Mach number steam and water by the equality of the Reynolds numbers.

To date, there has been limited research associated with determining the effects of blockages on flow distributions and turbulence intensity levels in rod bundles. In 1964, Carmody [1] used a hot-wire anemometer to measure mean velocities and turbulence intensities in air flow near a disk. The stream lines were traced in the recirculation region of the flow and increases in turbulence intensity to ~0.28 were measured. Bishop et al. [2] used existing hydrodynamic data [1,3,4,5,6] to determine and compare flow characteristics of local blockages in Liquid Metal Fast Breeder Reactor (LMFBR) fuel subassemblies. They initially concluded that the hydrodynamics of two blockages having the same area

could be significantly different and were dependent on the height and location of the blockages. Their calculations indicated considerable turbulence and entrained flow in the blockage wake. They concluded convective heat transfer would be important in the determination of fuel clad and coolant temperatures near blockages.

In 1973, Kirsch and Schleisiek [7] reported temperature distributions obtained downstream from a blockage with liquid sodium flowing in an annular channel, the inner part of which formed six subchannels. A recirculation zone was inferred by analysis of the temperature distribution and later verified by observing the flow pattern in a glass model with water. The dimensions of the recirculation zone were determined from static pressure profiles. The results confirmed that recirculation zone dimensions were independent of Reynolds number within wide limits.

Rowe et al. [8] used a laser Doppler anemometer (LDA) to measure local velocities and turbulence intensities near flow blockages in a simple four-subchannel rod bundle model. The LDA was used because the noncontact probing did not disturb the flow at the measurement location. The experimental results showed that significant flow redistribution accompanied by increases in turbulence intensities result from plate and tapered sleeve blockages. Flow reductions persisted well downstream from the blockages; however, flow redistribution was only detected short distances upstream from the blockages.

More recently, 1975, Vegter et al. [9] investigated the velocity distributions near two blockage configurations in a 39-rod bundle model of a LMFBF fuel subassembly. Air velocities were measured with a pitot-static probe in subchannels downstream and adjoining the blockages; a region of

separated flow was found to be five times a characteristic blockage height, consistent with other investigations [1,10]. A typical plot of normalized velocity as a function of distance downstream from the blockage is shown in Fig. 1. Immediately upstream of a 1/4-inch thick plate blockage, a significant decrease in axial velocity was detected. Evidently, Vegter et al. [9] were unable to obtain velocity measurements in the downstream recirculation zone of the blockage. The velocity distributions far downstream from the blockage indicate a reasonable recovery profile. The velocity recovered to approximately 83 percent of its upstream value 65 inches downstream from the blockage.

The purpose of this paper is to present local velocity and turbulence intensity results obtained in a flow blockage experiment conducted in water [12]. Comparisons of the data with predictions obtained using the COBRA program are provided. An abbreviated follow-on study [13] has been conducted in air to simulate the high quality steam environment expected during a LOCA and will be published in the open literature in the near future.

2. EXPERIMENTAL METHOD

2.1 EQUIPMENT

The basic equipment used to perform the flow blockage experiment consisted of a test assembly made up of a flow housing and an unheated 7 x 7 rod bundle, a laser Doppler anemometer, and signal processing instrumentation. The following sections briefly discuss the equipment used in the study.

2.1.1 Test Assembly

An assembly view of the test section is shown in Fig. 2. An 8-inch long flow conditioning section was placed at the test assembly inlet. The flow conditioner consisted of four eccentric perforated plates in a triangular array, followed by a bank of tubes 3-1/4 inches long. The plates distributed the flow uniformly across the test assembly cross section; the tubes served as flow straighteners to limit the scale of turbulence.

A cross-sectional view of the assembly at the blockage axial centerline is presented in Fig. 3. The flow housing body consisted of front and back plates containing nine windows and solid stainless steel side plates containing five pressure taps. The windows were 2 inches high by 4 inches wide, and were located on 6-inch axial intervals. The optically flat and parallel windows were fabricated from borosilicate crown glass, sealed with O-rings, and held in place by thick cover plates.

The model fuel bundle was an unheated square 7 x 7 rod array. Various sizes (rod numbers) of square arrays were considered during preliminary design to assure that the flow housing walls would not influence blocked subchannel flow rates. A pre-test analysis performed with the COBRA-IIIC program indicated that wall effects of a 7 x 7 rod bundle were negligible [12]. Therefore, a 7 x 7 rod array was chosen since an existing flow housing would accept it with rod diameters and rod pitches typical of those found in PWRs.

Model unheated rods were fabricated from 1/8-inch Sch 10S stainless steel pipe (OD = 0.392 inches) 57 inches long. Lower and upper brass tie plates positioned the 49 rods to form the bundle. Flow channels in the tie plates were sized to assure uniform velocity distributions over

the cross section of the bundle. A rod pitch of 0.539 inches was maintained with three simple "egg crate" spacers fabricated from brass.

Brass sleeves were placed on the center nine rods to model the blockage as shown in Fig. 4. The blockages were 3 inches long with 1-inch tapers at each end. Flow area reductions of 70 and 90 percent could be attained in the center four subchannels of the bundle. The 70 and 90 percent severities corresponded to area reductions of 35 and 45 percent in the subchannels adjacent to the sides of the cluster, and 17 and 22 percent in the subchannels next to the corners of the blockage, respectively. The shape, severity, and location of the blockage clusters used in the present experiment were not intended to define those that would actually exist during a LOCA. The shape of the blockage sleeves was formulated after considering experimental results of high temperature expansion and rupture behavior of Zircaloy tubing [14]. Severities of 70 and 90 percent were chosen to create gross flow disturbances in the rod bundle. Gross flow disturbances were required to adequately test the capability of the COBRA computer program for predicting such maldistributed flow profiles. Two area reductions were investigated to determine severity effects. Determination of more realistic blockage locations, shapes and severities must await results of experiments designed to obtain such information.

A movable support was provided at the top of the bundle to position the rod bundle in the flow housing. A vertical travel of 7 inches was possible and, because the windows were on 6-inch centerlines, data at any axial location within the bundle could be obtained.

2.1.2 Laser Doppler Anemometer

Turbulent flow measurements were performed with a laser Doppler anemometer (LDA), a highly advanced system used for obtaining measurements of local mean velocity and intensity of turbulence. The most notable advantage of an LDA system is that the noncontact probing does not disturb the flow. An important feature of all LDA systems is that the output signal is a calibration-free frequency linearly related to flow velocity. Single known components of flow velocity can be measured independent of other velocity components; furthermore, velocity measurements in reversing flows are possible.

The LDA system used in the present experiment is shown schematically in Fig. 5 and is discussed in detail by Brayton and Goethert [15]. The differential Doppler mode with frequency shifting was used throughout the experiments. The system is easily aligned and operates effectively where the intensity of scattered light is low. Frequency shifting removed the directional ambiguity and thus allowed measurements in regions of reverse flow. Natural contaminants in the loop water were used as light scattering particles in this experiment.

The measuring, or intersection, volume was located in the flow channel with a hydraulic lift/traversing table capable of positioning the laser and optics as an integral unit. The table was supported on precision linear ball bearings and driven by variable speed servo-motors. The motor speed control and position control made it possible to locate the beam intersection volume to within 0.001 inches in both the x and y coordinates in a horizontal plane. The hydraulic lifting capability of the table permitted the laser and optics to be positioned at desired axial locations.

2.1.3 Signal Processing Instrumentation

The signal processing instrumentation used to condition, interpret, and obtain the axial velocity and intensity of turbulence data from the Doppler signal consisted of a DISA Doppler signal processor, an oscilloscope, a digital voltmeter, and an rms voltmeter. The Doppler signal processor consisted of a preamplifier and frequency tracker which improved the signal-to-noise ratio of the Doppler signal and converted the frequency into an analog voltage. The analog voltage was proportional to local mean axial flow velocity by the relationship, $\bar{u} = 13.063 f_D$ ft/sec. The output of the processor also followed frequency fluctuations about the mean within each available frequency range thus giving an analog output for fluctuating turbulent velocity. A DC digital voltmeter was used to more accurately determine the mean value of the processor output voltage and thereby the mean velocity. An rms voltmeter measured the alternating component of the processor output voltage which, when normalized with respect to local velocity (DC voltage), was used to determine local turbulence intensity, i.e., $E_{rms}/E_{DC} = u'/\bar{u}$.

A low pass filter preceded the rms voltmeter to reject higher frequency signals. All data were obtained at a cutoff frequency of 4 kHz, and frequency used in [16] for similar flow conditions.

2.2 EXPERIMENTAL PROCEDURE

Loop flow and temperature were set at desired values. The LDA optical system was adjusted to produce an optimum Doppler signal as observed on an oscilloscope. Data acquisition was started approximately 0.100 inches from a window and continued incrementally, usually every 0.135 inches, along selected traverses across the rod bundle as shown in Fig. 6.

Only data obtained along the traverse at $y = 1.763$ inches are presented in this paper. Data obtained along each traverse are presented in [12].

At each data location, the frequency tracker (Doppler signal processor) was checked to assure proper adjustment and the rms voltmeter was nulled at the correct value. The DC voltmeter output (voltage representation of the Doppler frequency), rms output, x and y locations, and other pertinent loop information were then recorded. The lift/traversing table was then used to reposition the measuring volume. The above procedure was repeated at selected axial locations. Pressure drop data between taps 1-2, 2-3, 3-4, 4-5, 1-3, and 1-5 were obtained intermittently throughout the course of the experiment to determine bare rod friction factors and spacer and blockage loss coefficients.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 VELOCITY REDUCTION AND RECOVERY

Figures 7 through 9 present velocity profiles at specific axial locations along the length of the bundle. The data were obtained with a 90 percent blockage located midway between spacers #1 and #2 at an average bundle velocity of 5.7 ft/sec ($Re = 2.9 \times 10^4$). Each plot presents the ratio of local measured axial velocity-to-bundle average velocity as a function of distance from the wall (window). All velocity profiles are presented along an x traverse at $y = 1.763$ inches (refer to Fig. 6). Numbers in parentheses accompanying the data plane designations indicate respective distances from the blockage axial centerline. Negative axial locations correspond to data planes located upstream from the blockage.

The velocity profiles were well developed and very uniform upstream from the blockage cluster as shown in Fig. 7. The influence of the blockage was seen approximately three subchannel hydraulic diameters (1.8 inches) upstream from the blockage centerline, as indicated by the relatively low velocities in the inner subchannels and the higher velocities in the outer subchannels. This trend can be clearly seen in the velocity profile obtained in the tapered region of the blockage 1.3 inches upstream from the blockage centerline. Peak-to-average velocity ratios increased from ~ 1.1 to ~ 1.25 in the outer subchannels. Velocity ratios in the inner subchannels decreased, with the most significant decrease occurring in subchannel #1 (SC #1). This would be expected since SC #1 had an area reduction of 90 percent, whereas the subchannels on the periphery of the blockage cluster were somewhat less restricted as previously discussed.

Figures 8 and 9 present velocity profiles downstream from the blockage, with downstream designated by the plus sign preceding the distance values. Velocity profiles obtained immediately downstream from the blockage (Fig. 8) indicate negative flows and the existence of a recirculation zone in SC #1. The recirculation pattern persisted for at least 2.5 inches (~ 5 subchannel hydraulic diameters) downstream from the blockage centerline; however, flow reversals were not detected 3.5 inches (~ 7 diameters) downstream from the blockage centerline.* At

*No attempt was made to relate the length of the recirculation zone to a blockage characteristic length. Until sufficient data has been obtained with different blockage severities and dimensions, it is premature to "guess" the best blockage characteristic length that should be used to express the length of the recirculation zone.

an axial location 7.3 inches downstream from the blockage centerline, the velocity profile began to recover from the influence of the blockage cluster. Additional downstream velocity profiles shown in Fig. 9 indicate that the velocity profile was essentially recovered from the blockage disturbance approximately 25 inches, or 50 subchannel diameters, downstream from the blockage.

Velocity profiles at $U_B = 2.7$ ft/sec ($Re = 1.4 \times 10^4$) and 10.7 ft/sec ($Re = 5.8 \times 10^4$) were also obtained. The profiles indicate essentially the same trends as those obtained at $U_B = 5.7$ ft/sec as shown in Fig. 10, when normalized to the average bundle velocity. The velocity profiles in the outer subchannels agree exceptionally well. The velocity profiles in the inner subchannels show some scatter in the downstream tapered regions of the blockage. Farther downstream, the three velocity profiles are in good agreement. It can be concluded that velocity distributions resulting from the blockage disturbance were independent of Reynolds number over the range investigated. This conclusion is in agreement with Kirsch and Schleisiek [7].

Figure 11 presents measured SC #1 centroid velocities as a function of axial distance along the bundle of all three flow rates. The profiles are very similar to those obtained by Vegter et al. [9]. An abrupt flow reduction was detected just upstream from the blockage cluster, and a well-defined recovery profile existed downstream from the blockage. The profiles also indicate that the normalized velocity distributions at the entrance and exit regions to the blockage cluster were not strongly dependent on Reynolds number.*

*The downstream minima were actually "searched out" during data acquisition.

Data were also obtained with a 90 percent blockage cluster located immediately upstream and adjacent to spacer #2 and with a 70 percent blockage located midway between spacers. Figure 12 compares SC #1 centroid velocities near the three blockage clusters. The velocity profiles obtained with the 90 percent blockage located midway between spacers and adjacent to spacer #2 are essentially the same upstream of the cluster. It is evident that flow recovery downstream from the 90 percent blockage occurred over a much shorter distance when the blockage was midway between spacers.

The velocity profile in the entrance region to the 70 percent blockage cluster was similar to that obtained near the 90 percent blockage. At the exit region of the blockage, the velocity profile obtained with the 70 percent blockage exhibits a jetting characteristic that was not measured when using the 90 percent blockage. Jetting may not have been detected with the 90 percent blockage because the measuring volume could not be positioned as close to the blockage axial centerline as was possible with the 70 percent blockage. It was possible to locate a data plane only as close as 1.3 inches above the 90 percent blockage, while the data plane could be positioned as near as 0.8 inches above the 70 percent blockage axial centerline. The inability to measure velocities closer to the axial centerline of the 90 percent blockage would not appear to completely explain the absence of jetting. Possibly, the flow rates in the 90 percent blocked inner subchannels were extremely low and jetting was minimal or simply did not exist.

The velocity profiles immediately downstream from the blockage clusters indicate that the flow with the 90 percent blockage redeveloped

more rapidly than that with the 70 percent blockage when compared on a relative basis. That is, 1.5 inches downstream from the minima of the two profiles, the flow with the 90 percent blockage recovered from $\bar{u}/U_B = 0.05$ to 0.55, whereas the flow with the 70 percent blockage recovered from $\bar{u}/U_B = 0.62$ to 0.75. It is assumed that the shorter flow recovery length required for the 90 percent blockage was due to larger driving potentials present with the more maldistributed flow accompanying the more severe blockage. The influence of the blockage severities was nullified after the flow passed through spacer #2.

The velocity profile presented in Fig. 12 near the 70 percent cluster is somewhat misleading because the SC #1 centroid velocity did not approach zero. Figure 13 presents local velocity traverses obtained downstream of the 70 percent blockage. As shown, the relatively high SC #1 centroid velocities are accompanied by negative velocities in the subchannel gaps in the tapered region of the cluster (+0.8 inch). The recirculation regions persisted for less than three subchannel hydraulic diameters (<1.4 inches) downstream from the blockage axial centerline. Jetting was not detected four subchannel diameters downstream from the blockage cluster (+2.0 inches).

3.2 TURBULENCE INTENSITY

Turbulence intensity profiles at various axial locations along the bundle and at $y = 1.763$ inches are presented in Fig. 14. The intensity profiles were essentially independent of Reynolds number over the range investigated.

In the upstream tapered region of the cluster, the outer subchannel intensities were ~ 0.04 as would be expected, but the intensities obtained

in SC #1 increased to ~ 0.9 .* Note that the SC #1 centroid intensities were significantly higher than those in the rod gaps. Generally, higher values of intensity exist in decelerating flows and lower values accompany accelerating flows. Examination of the velocity profile of Fig. 7 reveals this to be the phenomenon that occurred in the upstream tapered region of the blockage, since SC #1 gap velocities were higher than the centroid velocity.

Downstream from the blockage, the lower intensity values, ~ 0.04 , persisted in the outer subchannels; higher values, up to ~ 10.0 , continued to exist in the innermost subchannels. This trend continued downstream ~ 2.5 inches (~ 5 diameters) but the intensity profile was essentially recovered ~ 3.5 inches (~ 7 diameters) downstream from the blockage centerline.

Axial intensity profiles obtained at the centroid of SC #1 with a 70 percent blockage and a 90 percent blockage are compared in Fig. 15. The profiles indicate that local intensity values were independent of blockage severity a few subchannel diameters upstream and downstream from the blockage cluster. However, in the close proximity of the cluster, intensities accompanying the 90 percent blockage were much greater than those resulting from the 70 percent blockage. The difference in intensity magnitudes is realizable because jetting occurred downstream from the 70 percent blockage, which created low intensities of turbulence, and flow deceleration was detected near the 90 percent blockage, explaining the relatively high intensity values.

*Intensity is defined on a local basis, i.e., $u'/\bar{u}$, not on an average bundle velocity basis, i.e., u'/U_B .

Lengths required for redevelopment of the intensity profiles correspond to those of the velocity profiles previously presented in Fig. 12. The axial intensity profiles also indicate that the length required for flow redevelopment was not strongly dependent on blockage severity.

4. COMPARISONS WITH COBRA PREDICTIONS

Comparisons of the measured velocity data with predictions obtained using the COBRA program are presented in this section. The comparisons are of major importance in verification and development of the COBRA program for subchannel analyses for postulated nuclear reactor accident conditions.

4.1 COBRA VERSION, INPUT MODEL, AND METHOD OF COMPARISON

Predictions of the data obtained with the 70 percent blockage were performed using COBRA-IIIC [11]. Data obtained near the 90 percent blockage could not be predicted with COBRA-IIIC using standard steady-state techniques since instabilities in the numerical solution were encountered. Therefore, predictions of the 90 percent data were performed with a modified version of COBRA-IIIC using a "two step" approach [12]:

- (1) Steady-state predictions with a 70 percent blockage were performed.
- (2) A transient solution, which extended the 70 percent blockage solution to a 90 percent blockage solution, was then performed. During each transient time increment, a slightly greater blockage severity was introduced into the input geometry. After a 90 percent severity was obtained, sufficient time steps were completed

to assure convergence to the correct solution. It is important to note that the solution was transient with respect to blockage severity only; all other input parameters remained constant with time.

The geometry model presented in Fig. 16 identifies the location of the subchannels. The model was a one-eighth sector of the total bundle cross section and was justifiable based on geometric symmetry. Dimensions of the model were as-built dimensions measured during and after bundle assembly. The sleeve blockages were modeled as flow area reductions. The area reductions in the tapered region of the blockage sleeves were assumed to vary linearly along the length of the tapers.

Prior to comparing the measured axial velocity profiles with COBRA predictions, the local measured velocity data were used to calculate subchannel average velocities. Subchannel average velocities were required because the COBRA code computes average values only.

For subchannels #1, #2, and #3, an area-weighting approach in conjunction with the assumption of highly turbulent flow was used to estimate subchannel average velocities from experimental local velocity data as described in detail in [12]. Average velocities for subchannels #4 through #10 were determined by inspecting the velocity profiles at non-disturbed data planes, e.g., #3, and estimating the ratio of the average subchannel velocity to the subchannel centroid velocity. Average subchannel velocities at undisturbed data planes were known to be approximately equal to the average bundle velocity. This approach was also used for subchannels #1, #2, and #3 at locations not influenced by the blockage cluster.

4.2 70 PERCENT BLOCKAGE MIDWAY BETWEEN SPACERS

COBRA-IIIC predictions of the velocity data obtained with the 70 percent blockage located midway between spacers #1 and #2 are presented in Figs. 17 and 18. In each figure, the ratio of average subchannel velocity to bundle average velocity is presented as a function of axial location along the bundle. The measured data points are actually subchannel average velocities calculated using measured local axial velocities as discussed in the previous section. Important COBRA input parameters used to predict the velocity data are presented in Table 1. Friction factor and loss coefficient values were determined using pressure drop data obtained during the experiment.

Predictions of the velocity data obtained in subchannels #1, #2, and #3 are shown in Fig. 17. COBRA predicted the axial velocity profiles upstream of the blockage cluster extremely well. The predicted locations of the minimum velocity points were in excellent agreement with experimental data.

Downstream from the blockage, the predicted locations and magnitudes of the minimum velocity points were also in good agreement with measured values. The jetting predicted by COBRA was measured experimentally in the downstream tapered region of the blockage. The flow recovery profiles were in good agreement with measured profiles.

Figure 18 presents COBRA predictions of SC #4, #5, and #6 average velocities. As indicated, the predicted subchannel velocities agree satisfactorily with measured values. COBRA predictions of SC #7 through #10 velocities, not presented herein, were also in excellent agreement with the experimental data.

Table 1. COBRA input parameters.

Parameter	COBRA Symbol	Value	
		70%	90%
Cross Flow Resistance	K_{ij}	0.02	0.02
Transverse Momentum	s/l	0.25	0.25
Turbulent Momentum Factor	ft	1.0	1.0
Bare Rod Friction Factor	f	$0.34 Re^{-0.25}$	$0.34 Re^{-0.25}$
Subchannel Spacer Loss Coefficient	K_{s1}	1.14	1.14
Subchannel Blockage Loss Coefficient	K_{s2}		
For Subchannel #1		0.5	0.5
For Subchannel #2		0.0	0.05
Other Subchannels		0.0	0.0
Model Length (in.)		40	40
Calculation Increment (in.)	Δz	0.5	0.5
Total Transient Time (sec)	t	0.0	2.0
Turbulent Mixing	β	0.02	0.02
Temperature (°F)	T	85.0	85.0

4.3 90 PERCENT BLOCKAGE MIDWAY BETWEEN SPACERS

COBRA predictions of the velocity data obtained with the 90 percent blockage located midway between spacers #1 and #2 are presented in Fig. 19. The predictions for SC #1 through #3 are in excellent agreement with the experimental data. Upstream from the blockage cluster in SC #1, COBRA predicted the location and magnitude of the severe velocity reduction, but the jetting effect predicted by COBRA was not detected experimentally. There are two possible reasons for jetting not being observed experimentally. First, the measuring volume could not be positioned in the "core" of the blockage cluster, i.e., close to the blockage axial centerline. This was caused by the geometrical restraint created by the angle between the laser beams and the restriction of the tapered region of the blockage cluster. Second, jetting may not have actually existed because the severity of the blockage in the center four subchannels may have "choked" the flow and forced the majority of the flow into the outer subchannels.

COBRA predictions agreed exceptionally well with experimental data obtained downstream from the blockage cluster. The predicted velocity recovery profiles in the reported subchannels essentially coincide with the experimental data. The velocity minimum measured in SC #1 was actually "searched out" and agrees nicely with the predicted location and value. Additional COBRA predictions presented in [12] of SC #4 through #10 velocities and predictions at other Reynolds numbers were in good agreement with the experimental data.

5. SUMMARY AND CONCLUSIONS

This experiment provides information regarding the turbulent flow structure in a model nuclear fuel rod bundle containing postulated sleeve

blockages. The information was obtained with a laser Doppler anemometer by measuring the local mean axial velocity and local intensity of turbulence at selected axial locations in the bundle.

The experimental data indicate that postulated blockages caused severe flow disturbances in the rod bundle. Axially, the flow was not influenced by a 90 percent blockage until the flow reached a location between three and six subchannel hydraulic diameters upstream from the blockage cluster. A recirculation zone existed for approximately five subchannel hydraulic diameters downstream from the cluster. The flow required approximately 50 subchannel hydraulic diameters to completely recover from the effects of the blockage. Local intensity of turbulence profiles were consistent with velocity profiles in that the intensity was relatively uniform upstream from the blockage, increased by three orders of magnitude downstream from the blockage, and was completely recovered from the blockage disturbance 50 subchannel hydraulic diameters downstream from the cluster. Both the velocity profiles and the intensity profiles were found to be essentially independent of Reynolds number over the range investigated.

In the lateral direction, the gross influence of the blockage was confined to those subchannels containing sleeve blockages. Flow increases were detected in the subchannels adjacent to the blockage cluster since flow was diverted around the blockage.

Effects of axial blockage location were studied by comparing data measured with a 90 percent blockage located midway between two spacers with data obtained with the blockage located adjacent to a spacer. The location of the blockage did not affect the flow in the immediate vicinity

of the blockage cluster; however, the downstream recovery profile was influenced. The required flow recovery length with the blockage adjacent to a spacer was significantly greater than when the blockage was located midway between spacers.

Blockage severity was investigated by comparing data obtained using 70 percent and 90 percent blockage clusters. The recirculation zone was shorter--less than three subchannel hydraulic diameters compared to approximately five diameters--for the less severe blockage. The required flow recovery lengths were essentially the same for the two blockage severities.

COBRA predictions of the experimental velocity data were exceptionally good for the cases with the 70 percent and 90 percent blockages located midway between two spacers. The COBRA program could not predict subchannel velocities when the blockage was located adjacent to a spacer since numerical instabilities were encountered.

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Fig. 1

Fig. 2

Fig. 3

BLOCKAGE CLUSTER

CORNER SLEEVE

SIDE SLEEVE

CENTER SLEEVE

(3) TAPPED HOLES
WITH SET SCREWS

REV 1924-1
Fig 5-5

1

NOTE: ALL DIMENSIONS IN INCHES

SUBCHANNEL NUMBERS

RODS WITH SLEEVE BLOCKAGES

--- DATA TRAVERSE LOCATIONS

• DATA POINT LOCATION

Fig. 7

Fig. 8

Fig. 9

Fig. 12

Fig. 14

Fig. 15

Fig. 16