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COOLANT MIXING IN LMFBR ROD BUNDLES

Quarterly Progress Report, March 1 1974-May 31, 1974

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Cambridge, Massachusetts

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COOLANT MIXING IN LMFBR ROD BUNDLES

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March 1, 1974 - May 31, 1974

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Reports Issued Under This Contract

A. Quarterly Progress Reports

COO-2245-1 Period June 1, 1972 - November 30, 1972
COO-2245-2 Period December 1, 1972 - February 28, 1973
COO-2245-3 Period March 1, 1973 - May 31, 1973
COO-2245-6 Period June 1, 1973 - August 31, 1973
COO-2245-7 Period September 1, 1973 - November 30, 1973
COO-2245-8 Period December 1, 1973 - February 28, 1974
COO-2245-10 Period March 1, 1974 - May 31, 1974

B. Topical Reports

E. Khan and N. Todreas, "A Review of Recent Analytical and Experimental Studies Applicable to LMFBR Fuel and Blanket Assembly Design," COO-2245-4 TR, MIT, Sept. 1973.

E. Khan, W. Rohsenow, A. Sonin and N. Todreas, "A Simplified Approach for Predicting Temperature Distribution in Wire Wrapped Assemblies," COO-2245-5 TR, MIT, Sept. 1973.

T. Eaton and N. Todreas, "Instrumentation Methods for Interchannel Coolant Mixing Studies in Wire-Wrap Spaced Nuclear Fuel Assemblies," COO-2245-9 TR, MIT, June 1974.

"Coolant Mixing in LMFBR Rod Bundles"

Contract AT(11-1)-2245

Quarterly Progress Report

March 1, 1974 - May 31, 1974

The work of this contract has been divided into the following Tasks:

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

TASK IA: Assessment of Available Data

TASK IB: Experimental Bundle Water Mixing Investigation

TASK IC: Experimental Bundle Peripheral Velocity Measurements (Laser Anemometer)

TASK ID: Analytic Model Development - Bundles

TASK II: SUBCHANNEL GEOMETRY (BARE RODS)

TASK IIA: Assessment of Available Data

TASK IIB: Experimental Subchannel Water Mixing Investigation

TASK IIC: Experimental Subchannel Local Parameter Measurements (Laser Anemometer)

TASK IID: Analytic Model Development - Subchannel

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

TASK IA: Assessment of Available Data (Ehsan Khan)

The assessment and analysis of data was continued within the framework of development of analytic methods and is discussed under TASK ID.

TASK IB: Experimental Bundle Water Mixing Investigations

1) Development of Instrumentation Techniques (Tom Eaton)

This work has been completed and was reported in the last quarterly report (COO-2245-8). The topical report describing this work was released to ORNL for publication and will be issued as:

T. E. Eaton and Neil E. Todreas,
"Instrumentation Methods for Interchannel Coolant
Mixing Studies in Wire-Wrap Spaced Nuclear Fuel
Assemblies," COO-2245-9 TR, MIT, June, 1974.

2) 61-Pin Experiments (Alan Hanson)

During this quarter essentially all of the fabrication for the first 61-pin bundle was completed. This first bundle is prototypic of LMFBR fuel assemblies. Some rework on the 6-inch wire-wrap lead rods constructed during the previous quarter was necessary in order to obtain a more uniform wire-wrap lead. Fabrication of the connecting pins between the wire-wrapped rods and the instrumentation support plates was completed and these connector pins were securely fastened to the rods. A trial assembly of the instrumentation system with a few probes was made on the 6-inch lead bundle. This assembly showed that the connecting pins and support plates successfully perform their function of precisely locating the conductivity probes in the subchannels between adjacent rods. A full set of 120 conductivity probes was finished during the quarter; this completed the fabrication of components for the instrumentation system. Work on two injector rods for each wire-wrap lead bundle was continued. Care was taken in the fabrication of these injectors to assure proper positioning of the injection needle both axially and radially in the injection rod. Fabrication of all components should be completed by July when the injector rods are wrapped and some modification to the probe support plates is made to properly align the conductivity probes.

The flow housing accumulated many hours of operation during LDA experimentation with both the 6-inch and the 12-inch lead rods. The epoxy coating on the housing walls has held up very well except at the corners where it adjoins the plexiglass faceplates. The aluminum corrosion problem has thus been reduced to a manageable level. A recoating of the corners and periodic cleaning will be necessary.

Delays in delivery of some electronic components in short supply and the need to make thousands of wired connections have delayed the completion of the new data acquisition system. By the end of this quarter the wiring of the multiplexor switching system was finally completed. During the next quarter interconnection of the system components--conductivity probes, multiplexor, bridge, power supply, digital voltmeter, and teletype--will be accomplished. It is anticipated that a fairly lengthy period of time may be necessary for debugging the electronic circuitry and testing of the completed system but that it will be ready for operation in the middle of the next quarter. While this debugging is being done, hydraulic testing will be done in the bundle with the instrumentation in place to confirm loop capabilities relative to design.

Preliminary work has been initiated on a computer code to handle the large mass of data which will be generated by our experiments. This code must generate a calibration curve for each conductivity probe, fit data to the calibration curves, do a flow-split hydraulic analysis, and check for a mass balance on the injected salt tracer. This code will be written and tested during the next quarter.

Planning for the next bundle, which will be prototypic of LMFBR blanket assemblies, has begun. Some redesign of the flow housing to avoid corrosion problems and to reduce the weight of this much larger bundle is necessary. Design and fabrication of components for this blanket bundle will begin next quarter.

TASK IC: Experimental Bundle Peripheral Velocity Measurements
(Laser Anemometer) (Yi Bin Chen and Ka-Lam Ip)

Measurements of the velocity field were made in the edge subchannels of 61 pin wire-wrapped fuel assemblies having 12 inch and 6 inch wire axial pitches, pin diameters of 0.250 inches, and wire diameters of 0.0625 inches. The laser doppler velocimeter was arranged in the differential-doppler mode on backward-scattered light to measure velocity components $\pm 45^\circ$ from axial. The measurement point sample volume was approximately an ellipsoid with dimensions .00208 in (.053 mm), .00206 (.052), .0145 (.37) having the larger dimension oriented perpendicular to the duct wall.

The results of experiments performed in water in both laminar ($Re \approx 640$) and turbulent ($Re \approx 4500$) regimes are:

1. Length for flow development -- For 12 inch axial pitch in both flow regimes, the axial velocity seems to have fully developed within the second axial pitch while the transverse velocity still appears to be developing in the second pitch.
2. Transverse gap velocity (Fig. 1) -- For the 12 inch pitch in both flow regimes, the axially averaged transverse gap velocity, V_T , was about 13% of the bundle average velocity, V_B . For the 6 inch pitch, the corresponding value was 26%.
3. Subchannel averaged axial velocity (Fig. 2) -- For the 12 inch pitch, this velocity, V_A , was 1.04 and 1.19 times the bundle average velocity, V_B , for turbulent and laminar cases respectively. For the 6 inch pitch, the corresponding values were 1.02 and 1.24.

The estimated accuracy of individual velocity measurements is a strong inverse function of the transverse to axial velocity ratio. For a 10% ratio, the accuracy of the axial component was 3% and of the transverse component, 14%. These results confirm the estimated range of average transverse gap velocities being used in prediction codes but establish that theoretically calculated flow splits yield erroneously high edge subchannel velocities.

A complete presentation of the results will be made in the topical report noted below which will be issued next quarter.

Y.B. Chen, K. Ip and N. Todreas, "Velocity Measurements in Edge Channels of Wire-Wrapped LMFBR Fuel Assemblies," Report COO-2245-11 TR

TASK ID: Analytical Methods Development (Ehsan Khan)

In the last quarterly progress report it was mentioned that the ENERGY code was modified so that salt injection and hot water injection data can be analysed. Analysis of various sets of data which cover a wide spectrum of fuel and blanket assembly geometry (i.e., wide range of h/d and p/d) is required to determine ϵ_H and C_1 , the two empirical constants in ENERGY. Table I shows the various sets of data that have been analysed to date. Analysis of the General Electric (GE-127 pin) data⁽¹⁾, and the French (7 pin) data⁽²⁾ are reported here. Others have been reported previously.

Results: Figure 3 shows the variation of ϵ_H with $1/(h/d)$, where d is the rod diameter and h is the helical wire pitch. Different types of data (heated pins, salt injection and hot water injection) covering a large range of h/d and p/d and various bundle sizes were used for determining ϵ_H . The Reynolds number in each of these experiments was greater than 10000, i.e., highly turbulent flow. Figure 3 should be adequate for determining ϵ_H for fuel assembly calculations in the steady state. A similar plot for ϵ_H for the blanket assemblies is required; unfortunately data on blanket assemblies is scarce if not non-existent. Figure 4 shows a cross-plot from Figure 3. ϵ_H is plotted against p/d for three different values of h/d . It is interesting to note that there is a maximum in ϵ_H near the design value of $p/d = 1.25$. However it is also important to note that each set of data analysed has an error-bar associated with it (not shown in Figures 3 and 4 to retain clarity), and these overlap. The selection of the most probable value of ϵ_H in a specified range depends, to a certain extent, on the authors' judgement. Our ability in determining ϵ_H from the data was limited to a certain extent by the enhanced eddy diffusivity model in ENERGY. Thus the ϵ_H found from the German (Baumann and Hoffman) data is much more reliable than the French (SKOK) data because the German experimental data was reported 3 wire wrap pitch downstream of inlet whereas the French data was reported only one wire wrap pitch downstream.

Figure 5 shows the variation of C_1

($C_1 = \frac{\text{velocity in gap between rod and wall}}{\text{avg. bundle velocity}}$) with h/d .

After considerable deliberation it has been concluded that in our model, as long as region II (the wall region) is greater in width than the gap between rod and wall (g), C_1 is independent of the choice of width of region II. (Fig 6)

The reason for not choosing the width of region II smaller than 'g' is due to the boundary layer effects at the wall and the consequent difficulty in determining the average axial velocity in this region.

Figures 5a and 5b show the ORNL data along with two different sets of ANL data and the HEDL data. The German, Japanese and GE experiments cannot yield any information on swirl flows since injection of salt or hot water in the Japanese and GE experiments respectively was confined to the central regions. The German experiments contained a single heated pin at the center of the bundle and thermocouples were not located around the circumference in the wall region. The information on swirl flows obtained from the 7-pin Skok experiment have not been reported because C_1 could not be obtained easily from the limited reported data and in obtaining it indirectly an error band of +100% was required. In addition it was necessary to make many assumptions before C_1 could be extracted out of the data.

However Figure 5 shows our predictions for C_1 for values of h/d from 14 to 44 for which only the M. I. T. laser data exists. These predictions were determined as follows: We found by analysis of ORNL and ANL data that the average swirl flow in the wall region (region II) follows closely the wire wrap angle. This logic was extended to lower h/d ratios. The average swirl flow is given by $w_s = \rho \bar{v}_s S$. This is (by continuity) equal to the swirl flow rate in the gap since our model assumes uniform swirl flow in the wall region. Then

$$\rho \bar{v}_s S = \rho \bar{v}_g g$$

or

$$C_1 \equiv \frac{\bar{v}_g}{\bar{v}} = \frac{\bar{v}_s}{\bar{v}} \cdot \frac{S}{g} \quad (1)$$

Although the choice of 's' is quite arbitrary in our model, one can intuitively choose the most convenient 's' based on prior knowledge of axial and transverse velocity in the wall channels. Thus the wall region chosen corresponds to a width $(d + g)$ in the actual bundle

(see Figure 6). Since $\frac{\bar{v}_s}{\bar{v}}$ is assumed to follow the

wire wrap angle (as h/d gets smaller, the deviation from the wire wrap angle is larger), then C_1 can be calculated from equation 1. This C_1 is only approximate at h/d ratios less than 20. due to slippage of flow over the wire.

Analysis of Data:

1. GE-127 Pin Hot Water Injection Data Analysis

Figure 7 shows a cross-section of the GE-127 pin bundle. Hot water was injected at 161.40 F into the six central channels at approximately the same flow rate as in the surrounding channel. Several bundles were tested but data was only available (through the courtesy of Dr. P. Magee) for the bundle with $p/d = 1.28$, $d = 0.25$, $h = 6$ in. to 65 in. at increments of 1 in. For further details see Reference 1.

It is obvious from Figure 7 that estimation of swirl flow in the wall regions cannot be made from this setup. Therefore the effort was concentrated on determining ϵ_H^* for the particular geometry and flow conditions.

Only one complete set of data was available. The Reynolds number for this set of data was approximately 55000.

In order to determine ϵ_H^* for salt and hot water injection experiments, the following general procedure was adopted as a first step in the analysis. The temperature rise for various channels is determined from the ENERGY code by varying the input parameter ϵ_H^* . Figure 8 shows a plot of temperature rise versus ϵ_H^* for several channels, at the 12 in. axial level and at the 36 in. level. On the same figure the recorded data is plotted showing a $\pm 1^\circ$ F spread due to assumed thermocouple accuracy. It is interesting to note that the slope of the curve in Figure 8 for the injection channel at 12 in. is large but for other channels the slope is not large at 12 in. At 36 in. the slope of all the curves are small. The only meaningful estimate of the range of ϵ_H^* can be obtained from the injection channel data at 12 in. For other channels, when a $\pm 1^\circ$ F spread on data is superimposed on the plotted computer curves, it is seen that almost any value of ϵ_H^* should predict a temperature rise within the data range. Thus usefulness of the data 6 to 14 in. beyond injection is limited. The value of ϵ_H^* so determined was found to lie between 0.050 and 0.068. The procedure described above is only the first step in data analysis. The next step, a refinement of Step I, is described below.

Since at the injection point there is a perturbation of the main flow stream due to injection of salt or hot water, it is quite conceivable that these perturbation effects may last several inches downstream of injection point. The data is then analysed by taking the inlet plane in the computer program to be several inches downstream of the injection point in the experiment. For

this data, inlet was assumed to be 12 in. downstream of injection point and data at this 12 in. location was assumed as the initial channel condition. Figure 9 shows the data for the injection channel and also the predictions of ENERGY for five different cases. Set I shows the predictions for the case where the inlet to ENERGY is at the same plane as the injection point. For other curves the 12 in. level in the experiment is the starting point for the calculations. It is seen that curves I and II do not match although $\epsilon_H^* = 0.062$ for both. This was found to be due to a lack of energy balance in the data between inlet and 12 in. level. The total energy at the 12 in. level, as calculated by taking the sum of the product of flow and enthalpy over all channels was found to be greater than the total energy in the injection plane. The data at 12 in. is probably more reliable and free of any inlet perturbations. The inlet energy balance was corrected to match that at the 12 in. level. A $\pm 1^\circ$ F error band on the data in Figure 7 was superimposed which yielded a range for ϵ_H^* between 0.040 and 0.070 or an approximate average of 0.055 ± 0.015 .

2. Skok 7-Pin Hot Water Injection Data⁽²⁾

These experiments were performed using a 7-rod bundle (wire-wrapped) to determine the effect of Reynolds number, h/d and p/d on mixing between various subchannels within the bundle. Hot water was injected into various channels and attenuation of temperature in the injection channel and increase in temperature in the channels adjacent to the injection channel were measured by thermocouples. The rods within the bundle are hollow. As a result heat is not transferred through them. The distance between injection and detection point is one wire wrap pitch for all runs. Table II shows the various configurations tested. Figure 10 and Figure 11 show the temperature variation of the injection and neighboring channels for bundle 2 (wire-lead $h = 30$ cm. or 11.8 in.), for two different injection channels, no. 1 and no. 4. Let us for the time being focus attention on the temperature attenuation in the injection channel. One finds that under exactly similar conditions the temperature attenuation is different for the channels 1 and 4. This may be attributed to the location of the wire wrap position with respect to the injection channel. For example, in the injection plane the wire is located at the 7 o'clock position with respect to the center of channel 1 and it is about to enter channel 1. However the wire is located at the 5:30 position with respect to channel 4. Whereas the temperature attenuation after one pitch of the hellicoid wire is about 80% for channel 1, it is 90% for channel 4. There is an ambiguity as to which one of these two temperature attenuations

corresponds to the bundle average temperature attenuation for injection into an interior channel. In the text⁽²⁾ a definite impression is conveyed that this average attenuation is 80% for the injection channel. However Figure 4 (corresponds to Figure 11 here) in Reference 2 is labeled as representing the average temperature attenuation rate for the injection channel.* It was found on analysis of the data that the mixing coefficient ϵ_H^* in ENERGY was very sensitive to the temperature attenuation rate. We chose Figure 4 of Reference 2 to be representative of the average attenuation rate because ϵ_H^* so found was consistent with other results.

In analysing the Skok data using ENERGY we were faced with a problem. The modeling of sweep flow by an enhanced eddy-diffusivity is expected to hold good only after one wire wrap pitch. The data being analysed was given for a length of only one wire-wrap pitch. The ENERGY assumption would not be bad for an interior injection channel. This is because for the injector channel every wire traverse (three traverses per lead length) of the subchannel causes mixing between the uniform cold temperature of the adjacent channels and the hot injection temperature and, hence, degradation of the injection channel temperature. For a wall channel, however, there are only two traverses per lead length that cause mixing between adjacent channels and ENERGY models would not yield meaningful results. Skok obtained data for injection in both interior and wall subchannels.

Within the limitations of our analytical models the analysis of the data proceeded as follows. The two empirical constants in ENERGY are ϵ_H^* and C_1 . Data for each interior channel of bundle 2 show a distinct effect of wire wrap position with respect to injection point. Two sets of data, one for the minimum and one for average attenuation of salt into the injection channel is reported. For analysis of interior channels it was found that ϵ_H^* and C_1 are independent, i.e., varying C_1 effects ϵ_H^* for interior injection, very slightly. ϵ_H^* is varied in the code until the best possible match is obtained with the experimental data (temperature attenuation). Figures 10 and 11 also show the computer predictions along with the data. It is clear that $(\epsilon_H^*)_{avg.}$ as obtained from Figure 11 is much larger than $(\epsilon_H^*)_{min.}$, which is obtained from Figure 10. Obviously (ϵ_H^*) is very sensitive to the temperature attenuation rate. Consequently large error bar must be associated with these values of ϵ_H^* , so obtained. The error bars on (ϵ_H^*) (Bundle 2) were estimated to be $(\epsilon_H^*)_{min.} = 0.033 \pm 0.01$ and $(\epsilon_H^*)_{avg.} = 0.083 \pm 0.020$ assuming a thermocouple accuracy of $\pm 1.0^\circ$ F.

* A similar ambiguity exists for the wall channels.

Data with injection in the wall channel was analysed by assuming the same $(\epsilon_H^*)_{avg.}$ between wall-interior channels as was obtained between the interior-interior channels. Then C_1 was varied until the data and prediction matched. It is obvious that, as discussed before, our ability to analyse the wall channel is limited by our model. Consequently C_1 so obtained would not be representative of the true swirl flow in the bundle. Due to these reasons we believe that any value of C_1 so determined is meaningless and hence will not be reported. Our predictions for variation of C_1 with h/d based on other data has already been discussed and is shown in Figure 5.

All the results reported are for $(\epsilon_H^*)_{avg.}$ based on analysis of the interior injection channel in bundles 1 through 5. Figure 3 shows the $(\epsilon_H^*)_{avg.}$ for the various bundles. No significant effect of Reynolds number on was found. There appeared to be a maxima in ϵ_H^* between $p/d = 1.14$ and $p/d = 1.355$.

TASK II: SUBCHANNEL GEOMETRY (BARE RODS)

TASK IIA: Assessment of Available Data

Quarterly report COO-2245-6 presented an extensive review of available data. No new work was accomplished on this task during this quarter.

TASK IIB: Experimental Investigation (Joseph Kelly)

In this task an experimental measurement of turbulent interchange between two interior triangular array subchannels is planned. Existing correlations for turbulent interchange do not reliably cover triangular arrays because of the lack of existing data for these geometries.

Mixing tests were conducted using the present test section, and yielded unacceptable results. For several Reynolds' numbers, the turbulent mixing coefficient w_j/u was found to be ~ 160 . Since this was an order of magnitude higher than the expected results, an investigation into the exactness of the test section geometry was begun.

First, water displacement tests showed discrepancies in subchannel area up to 15%. Next, we inserted .1593" diameter rods in the subchannels to "force" the geometry. This attempt was unsuccessful and made it clear that the present test section is not satisfactory.

A new test section was designed (taking into account the failings of the previous one). It is presently being constructed and will be ready for use in September. At that time, a complete description of the new test section and the changes in the loop will be presented.

**TASK IIC: Experimental Subchannel Local Parameter Measurements
(Laser Anemometer) (Pedro Carajilescov)**

A parametric study of the measuring system (Laser Doppler Anemometer, LDA) was performed in order to obtain the optimum operating situation for the measurements we are going to perform.

Before a parametric study can be performed, it is necessary to define the LDA operation mode. The dual scattered beam mode with forward scattering was selected. Figure 12 shows this mode and defines the parameters involved in its operation. This operation mode was selected for three basic reasons:

- it is easy to align the beams
- it works well for low seeding particle concentrations
- forward scattered light intensity is higher than backscattered light intensity for the same incident light intensity.

The dual scattered mode is also called the "fringe mode" because interference fringes are formed in the probe volume. Figure 13 shows the fringes of interference of two beams with the same wavelength λ crossing each other, with polarization in the same plane, as well as the light intensity in the interference region. A particle crossing this region will scatter light of intensity proportional to the light intensity of the particular point it is located in at that time.

The distance between fringes is given by (3)

$$d_f = \frac{\lambda}{2 \sin \theta} \quad (1)$$

and the time for a particle to cross two consecutive fringes

$$\Delta t = \frac{d_f}{U_{\perp}} = \frac{\lambda}{2 U_{\perp} \sin \theta} \quad (2)$$

where $U_{\perp}$ is the particle velocity component perpendicular to the fringes.

The doppler frequency detected by the PMT is

$$\Delta v_D = \frac{1}{\Delta t} = \frac{2 U_{\perp} \sin \theta}{\lambda} \quad (3)$$

The probe volume is shown in Figure 14 and its dimensions are assumed to be those of an ellipsoid formed by the intersection of the two beams:

$$l = \frac{\sqrt{2} r_o}{\sin \theta}$$

$$w = \frac{\sqrt{2} r_o}{\cos \theta}$$

$$h = 2 r_o$$

(4)

where

$$r_o = 1.22 \frac{\lambda f_o}{D_L} \quad (\text{Airy disc radius, from diffraction theory})$$

and D_L = laser beam diameter.

The total number of fringes in the probe volume is

$$N_f = \frac{w}{d_f} \quad (5)$$

Since our measurements are to be performed in water instead of air, the angle θ of equations (4) has to be corrected by the water refractive index, n_w

$$n_{air} \cdot \sin \theta = n_w \cdot \sin \theta^* \quad (6)$$

θ^* should be used in those equations.

Our optical unit (DISA 55L01) has three beam focusing lenses available with focal lengths 130 mm., 300 mm. and 600 mm., and allows beam separation, a , from 18 mm. to 54 mm.

This gives us

$$\theta = \arctan \left(\frac{a}{2 r_o} \right) \quad (7)$$

Figure 15 shows plots of the distance between fringes, d_f (in μ), number of fringes, N_f and the length l (in mm) of the probe volume as a function of θ .

These parameters are important for the following reasons:

- (a) d_f determines the optimum size of the seeding particles, D_p , that should be used. It is recommended that $D_p \leq \frac{d_f}{4}$
- (b) it is desirable to have a large number of fringes in the probe volume, so that our signal can be processed by a spectrum analyser or a

frequency tracker. Usually the electronics of these components require a minimum number of cycles to give a valid response. Also the larger the number of cycles, the larger is the number of data points validated;

- (c) λ is important from the point of view of our geometry. Since the gap between two rods is small (our case $P/D = 1.10$ and $D = 2.00$ ", which gives gap = $.10$ " = 2.54 mm.), it is necessary to have a small λ so that our spatial resolution is good and such that velocity gradients do not give large errors.

Based on this analysis, it was chosen to use $f = 130$ mm., $a = 50$ mm. ($\theta = 11^\circ$), and $D_p = .5\mu$. This yields $df(u) = 1.6$, $N_f = 44$, $\lambda(\text{mm}) = .35$ and $w = .2$ mm. The seeding particles will be polystyrene ($\rho = 1.0 \rho_{\text{water}}$)

The light collecting system is also very important to reduce the noise that goes into the PMT. The diameter of the region where the two beams cross each other seen by the collecting system is given by

$$w_c = \frac{f_s}{f_p} D_{ph} = \frac{D}{M} \quad (\text{See Fig. 1}) \quad (8)$$

Our equipment has $f_p = 105$ mm., three values for f_s : 200 mm., 333 mm. and 600 mm., and two values for D_{ph} : .10 mm. and .15 mm. The best situation occurs with $f_s = 200$ mm. ($M = .525$) and pin hole, $D_{ph} = .10$ mm., which gives $w_c = .19$ mm.

This value is within the criterion $w_c \leq w$ recommended for good reduction of noise.

The concentration of seeding particles will determine whether or not superimposition of signal from a large number of particles in the probe volume will occur. For the dual scattered beam mode, it is better to have very low particle concentration. So the concentration is taken in the range

$$\left[\frac{1}{V_p}; \frac{2}{V_p} \right]$$

where V_p is the probe volume. So, in our case, C_v should be of the order of 10^6 particles/cm³.

The test section for this experiment is being assembled and measurements will begin in August when measuring equipment becomes available from the completion of task IC.

TASK IID: Analytic Model Development - Subchannel (Hisashi Ninokata and Pedro Carajilescov)

This task has two principal facets: A) the interrelation of lumped parameter and distributed parameter methods of analysis. This interrelation is aimed at extending the results of distributed parameter methods to perform predictions of exchange coefficients needed for lumped parameter methods. B) The development of a distributed parameter method to predict subchannel parameters including secondary flow effects.

SUBTASK A

A unified treatment of the turbulent and the molecular effects on the mixing coefficients has been accomplished and the momentum exchanged coefficient $\overline{W_{ij}^{*M}}$ evaluated for small rod bundles (19 pins and 37 pins) with clean triangular geometries based on the output of the computer code "VELASCO" which performs the calculation of the velocity distribution within a fuel rod array.

Specifically this was accomplished by first obtaining momentum exchange coefficients along subchannel boundaries as a function of radial distance from the wall of fuel pin or duct of channel. Second these distributed values were averaged along the boundary to give an overall momentum exchange coefficients $\overline{W_{ij}^{*M}}$ between two subchannels.

The method of obtaining $\overline{W_{ij}^{*M}}$ was extrapolated from Appendix A of Ref. 4. The VELASCO code has been used in the numerical application of this method which restricts the present results symmetric bare rod configuration with fully developed, turbulent flow and limited secondary flow consideration. Furthermore, since VELASCO employs some basic assumptions and general expressions for the radial distribution of axial velocity (see Ref. 5 or Ref. 6 for the details) it should be noticed that the momentum mixing is calculated based on a velocity distribution given by VELASCO, not on a momentum balance equation itself. In spite of these limitations, the result should be a good prediction of the spatial variation of exchange coefficients and will provide users of subchannel analysis code with alternate input data than from empirical approaches.

Figures 16 and 17 identify the boundaries in 19 and 37 pin bundles. Figure 18 presents the exchange coefficients for each boundary and thereby gives an indication of the spatial variation of these exchange coefficients. This study will be completed next quarter.

SUBTASK B

The development of a distributed parameter method to predict subchannel parameters is being attempted as described in previous reports.

Basically the method will deal with predictions of the velocity field (axial and secondary flows) and the turbulence kinetic energy distribution. In the discussion to follow, all analytical results were obtained for $P/D = 1.217$ and compared to the experimental data measured by Kjellstrom⁽⁷⁾, however the computation will be repeated for $P/D = 1.10$ and compared to the experimental results of Task IIC when they become available. Since we are primarily concerned with the velocity field and, particularly, with the axial velocity distribution, the results to be presented are only for such parameters.

The work has been divided into four phases:

- (1) Solution of momentum equation for laminar flow. Results for this case have already been presented.
- (2) Solution of the momentum equation for turbulent flow neglecting secondary flow effects. This was accomplished assuming the Prandtl-Kolmogoroff formula for the turbulent viscosity

$$\nu_T = c_v k^{1/2} l \quad (9)$$

with $l \equiv$ mixing length given by Buleev's equation.⁽⁸⁾

The turbulence kinetic energy was obtained by using Bobkov's approximation⁽⁹⁾:

$$k^{1/2} = U^* |0.85 e^{-1.27\xi}| \quad (10)$$

where

$$U^* = v_z \left[1 - \frac{v_{avg}}{v_{max}} \right]$$

$$\xi = \frac{r - r_0}{\hat{r} - r_0}, \text{ with } \hat{r} = \frac{P}{2 \cos \theta}$$

Problems with steep gradients of the parameters near the wall were solved assuming a radial mesh space distribution, in that region, of the type

$$\xi(1) = r(1) - \frac{D}{2} = \left(\frac{P}{2} - \frac{D}{2} \right) \cdot \left(\frac{1-l}{m-1} \right)^f$$

where P = pitch

D = rod diameter

m = mesh space number for $r = \frac{P}{2}$

The exponent f is given as an input in the program. In this case, f was taken equal to 1.7. Uniform radial mesh space distribution was assumed for $r(1) > P/2$

Figures 19a, b and c show the results for this case compared to experimental data⁽⁷⁾. We note that the variation in velocity as a function of θ is much more accentuated in our analytical results due to the neglect of secondary flow effects.

- (3) This third case is the same as the previous one but now assuming that secondary flow is given by Nijssing's approximation⁽¹⁰⁾, i.e.,

$$v_\theta = F \left[\left(\frac{\tau_w}{\rho} \right)^{1/2}, \Delta\theta_{max} \right] \cdot F \left(\frac{r}{r_0} \right) \quad (11)$$

where

$$F \left[\left(\frac{\tau_w}{\rho} \right)^{1/2}, \Delta\theta_{max} \right] = 2 C_{sec} \left(\frac{\tau_{w,av}}{\rho} \right)^{1/2} \frac{d(\tau_w/\tau_{w,av})^{1/2}}{d\theta} \cdot \Delta\theta_{max}$$

and

$$F \left(\frac{r}{r_0} \right) = \cos \left[\frac{(r-r_0)\pi}{(\hat{r}-r_0)} \right]$$

with $C_{sec} = 0.57$

Figures 19a, b and c also show the results for this case. The results are closer to the experimental data⁽⁷⁾ than those of the previous case, but they do not predict the secondary flows, since the secondary flows represent an input in the calculation.

- (4) This last phase will be directed toward prediction of the velocity field and the secondary flows, assuming the same hypotheses of case (2) but now solving the momentum equation along with the vorticity and stream function equations.

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TABLE I

Experimenter	Bundle Size	Bundle No.	P/d	h/d	Re	Experimental Type
1. Skok	7-pin	1	1.355	26.5	4.2x10 ⁴	Hot Water Inj.
		2	1.142	14.3	2.5-5.5x10 ⁴	
		3	1.142	21.4	4.2x10 ⁴	
		4	1.142	28.6	4.2x10 ⁴	
		5	1.065	19.5	4.2x10 ⁴	
2. Fontana	19-pin	1	1.24	.52	> 14000	Heated Pins
3. Baumann and Hoffmann	61-pin	1	1.315	16	14-35x10 ³	Heated Pins
		2	1.315	34	14-35x10 ³	
		3	1.315	50	14-35x10 ³	
4. Okomoto et al.	91-pin	1	1.20	45	8000	Salt Inj.
5. Lorenz et al.	91-pin	1	1.24	48	9-24x10 ³	Electrolyte Tracer Inj.
6. Pederson	91-pin	1	1.20	48	9-24x10 ³	Hot Water Inj.
7. Marion & Hines	127-pin	1	1.28	24	55x10 ³	Hot Water Inj.
8. Wheeler et al	217-pin	1	1.24	52	> 14x10 ³	Salt or Electrolyte Inj.

Bundle No.	Dia. of Pin In.	Dia. of Wire In.	Helicoidal Pitch, h In.	Infection Channel No.
1	0.667	0.23	17.7	1/10
2	0.827	0.118	11.8	1/4/10
3	0.827	0.118	17.7	1/10
4	0.827	0.118	23.6	1/10
5	0.906	0.059	17.7	1/10

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FIG. 1: AXIALLY AVERAGED TRANSVERSE GAP VELOCITY MEASUREMENTS

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FIG. 2: SUBCHANNEL AVERAGED AXIAL VELOCITY MEASUREMENTS

FIG. 3. E_n vs (d/h) for VARIOUS (P/d) OBTAINED BY USING ENERGY

FIG. 5A VARIATION OF C_1 vs h/d

FIG. 5b VARIATION OF C_1 w d/R .

$$s = \text{AREA OF WALL SUBCHANNEL (HATCHED REGION)} / p^{(1)}$$

NOTE: CHOICE OF "s" IS ARBITRARY IN MODEL HOWEVER FOR THIS PARTICULAR APPLICATION "s" IS DEFINED BY (1).

FIG. 6 Modelling of Wall Region in ENERGY

FIG. 7 Cross Section of Dummy Fuel Bundle

FIG. 8 PARAMETRIC STUDY FOR TEMP. RISE VS. $\overline{EH^*}$

FIG. 12. MEASURING SYSTEM : LDA

- DUAL SCATTERED MODE (FRINGES)
- ONE COMPONENT

FIG. 13. FRINGES OF INTERFERENCE

FIG. 14. PROBE VOLUME

FIG. 15 DESIGN OF THE LDA SETUP

Fig. 16. Subchannels in a subarray representative for a nineteen rod array
(case # 1, 2, 3, 4, 5)

Fig. 17 - Subchannels in a subarray representative for a thirty-seven rod array

(case # 6, 7)

FIG 19. TURBULENT FLOW VELOCITY DISTRIBUTION