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COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Progress Report

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REPORTS AND PAPERS PUBLISHED UNDER
MIT COOLANT MIXING IN LMFBR ROD BUNDLES PROJECT

A. Quality Progress Reports (Available from:
National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22151)

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
COO-2245-13	Period June 1, 1974 - August 31, 1974
COO-2245-14	Period September 1, 1974 - November 30, 1974
COO-2245-15	Period December 1, 1974 - February 28, 1975
COO-2245-23	Period March 1, 1975 - May 31, 1975
COO-2245-25	Period June 1, 1975 - August 31, 1975
COO-2245-26	Period September 1, 1975 - November 30, 1975
COO-2245-28	Period December 1, 1975 - February 29, 1976
COO-2245-30	Period March 1, 1976 - May 31, 1976
COO-2245-31	Period June 1, 1976 - August 31, 1976
COO-2245-34	Period September 1, 1976 - November 30, 1976
COO-2245-38	Period December 1, 1976 - February 28, 1977
COO-2245-50	Period March 1, 1977 - May 31, 1977
COO-2245-53	Period June 1, 1977 - August 31, 1977
COO-2245-60	Period September 1, 1977 - November 30, 1977
COO-2245-63	Period December 1, 1977 - February 28, 1978
COO-2245-64	Period March 1, 1978 - May 31, 1978
COO-2245-65	Period June 1, 1978 - August 31, 1978
COO-2245-66	Period September 1, 1978 - November 30, 1978

COO-2245-69 Period December 1, 1978 - February 28, 1979
COO-2245-70 Period March 1, 1979 - May 31, 1979
COO-2245-71 Period June 1, 1979 - August 31, 1979
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- * Revised - See Section B.2

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C. Chiu, J. Hawley, W. M. Rohsenow and N. Todreas, "Pressure Drop Measurements in Wire Wrapped Blanket Assemblies", COO-2245-42TR, July 1977.

C. Chiu, W. M. Rohsenow and N. Todreas, "Missing Experiments in LMFBR Wire Wrapped Blanket Assemblies", COO-2245-43TR, April 1978.

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* Revised - See Section B.2

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COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Contract AT(11-1)-2245

QUARTERLY PROGRESS REPORT

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-Subchannels

TASK III: LMFBR OUTLET PLENUM FLOW MIXING

TASK IIIA: Analytical and Experimental Investigation
of Velocity and Temperature Fields

TASK IV: THEORETICAL DETERMINATION OF LOCAL TEMPERATURE FIELDS
IN LMFBR FUEL ROD BUNDLES

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

I.A Assessment of Available Data

No work done on this task this quarter. This work was last reported in Progress Report COO-2245-72 dated September 1, 1979 - November 30, 1979.

I.B Experimental Bundle Water Investigations

I.B.1 61 Pin Fuel Bundles - Turbulent Flow

(Paul Symolon)

No additional progress has been made on the 61 pin bundle in the turbulent flow regime. A topical report will be issued later in the following quarter that will present the data and analysis.

I.B.2 61 Pin Fuel Bundles - Laminar and Transition Flow

(Paul Symolon)

No additional progress has been made on the 61 pin bundle in the laminar and transition flow regime. A topical report will be issued next quarter presenting the data and analysis.

I.B.3 217 Pin Fuel Bundle

(Paul Symolon)

During this quarter, flow split measurements were completed on the 217 pin bundle. The data is presented in Figure 1. As discussed in the previous quarterly report, the turbulent flow data is in good agreement with the correlation of reference 1. Also shown in Figure 1 is the correlation values for laminar and turbulent flow, along with the transition flow splits calculated from:

$$x_1 = \left(\frac{f_b}{f_1} \frac{De_1}{De_b} \right)^{.5} \quad x_2 = \left(\frac{f_b}{f_2} \frac{De_2}{De_b} \right)^{.5}$$

The new laminar flow data follows the predicted trend, but the experimental results for x_2 are above the correlation, while x_1 is quite close.

The mixing test was also run on the 217 pin bundle. Salt was injected into an edge subchannel at axial levels of 12, 24, and 36 inches at various flow rates to investigate injection depth effects. For a 12 inch injection run, the salt solution injection flow rate was varied to determine if this affects the calibrated swirl velocity ratio. Salt solution was also injected into the side pressure taps to see if direction of injection has any effect.

The mixing data was not reduced due to a hardware problem with the data reduction computer system. The data is expected to be reduced next quarter. Supporting software was written to allow the data reduction programs to be run on the new JCF Computer, and the data reduction programs were modified to run for the 217 pin mixing test.

Reference 1: Hawley, J. T., Chiu, C., Rohsenow, W. M., and Todreas, N. E., "Subchannel and Bundle Friction Factors in Laminar, Transition and Turbulent Flow", Paper to be presented at the ANS Saratoga Meeting, October 1980.

I.B.4 61 Pin Blanket Bundles

Work on these bundles was completed and reported in a series of topical reports by C. Chiu which are listed under B.1 Original Topical Reports and under C. Papers and Summaries.

I.B.5 Shaved Wire 61 Pin Blanket Bundle

(Song Feng Wang)

No work was done on this task during this quarter. The available data will be reported and analyzed in the next progress report.

I.B.6 37 Pin (P/D = 1.15) Bundle
(Kevin Burns)

Pressure drop experiments were performed in order to determine subchannel and bundle average friction factors. Particular attention was paid to possible improvements in experimental technique, especially for laminar flow pressure measurements (see TASK I.B.8). The results for the bundle average friction factors are presented as a function of Reynolds number as:

$$f_b = \frac{60}{Re_b} \quad , \quad Re_b < 400 \quad (\text{laminar})$$

$$f_b = \frac{0.33}{Re_b^{0.25}} \quad , \quad Re_b > 4000 \quad (\text{turbulent})$$

It was found that the turbulent pressure drop data agreed well with the results obtained earlier by T. Chiu on the same 37 pin bundle. The laminar data, however, deviates from T. Chiu's due to an improvement in the experimental measuring apparatus. The laminar correlation presented above is recommended, since a manometer was used instead of a differential pressure gage, thereby improving the experimental accuracy.

Salt tracer mixing experiments have been performed on the 37 pin bundle in order to determine the sweeping flow parameters ϵ_{1L}^* and C_{1L} . A good deal of data was taken in

laminar flow to support the development of a laminar mixing correlation (see TASK I.D.3). There has been a considerable delay, however, in reducing the data due to problems associated with the floppy disk drive. The disk drive is needed to run the initialization code in preparation for the experiments, as well as to run the intermediate data processing code. The experiment was performed in spite of an improperly initialized floppy disk, with the understanding that the data would have to be transcribed by hand and keypunched. In addition, the intermediate data processing code needed to be modified in order to accept punched card input. All steps up to and including this intermediate data processing are now complete. Presently, the SUPER~~SH~~ERGY-DRV code is being modified for use with the 37 pin bundle data, prior to its use in the determination of the mixing parameters, ϵ_{1L}^* and C_{1L} .

I.B.7 Experimental Method for Flow Split Determination

(James T. Hawley)

The work on the flowsplit manual continued on two fronts this quarter.

First, quite a bit of experimental work was done in order to quantify the behavior of the flowsplit collector (sampler) design which is currently in use. Specifically, experiments were done in order to determine: the topology of the pressure field in the upper plenum in the absence of the sampler; the magnitude of the disturbance to the surrounding flow field due to the presence of the sampler; and the variation in the extracted flowrate for variations in the pressure differences between the interior and exterior regions of the sampler. The reduction and analysis of this data is not yet complete.

Second, a theoretical justification of the current experimental methodology was achieved. The analysis proceeds by applying the energy equation twice to the control volume shown in Figure 1, both when the sampler is present and when it is absent. The mechanical energy equations for the given control volume and the two specified conditions are:

Sampler Absent:

$$P_1^* - P_2^* = K_{12} \frac{\rho V_1^{*2}}{2g_0} + \frac{\rho g}{g_0} (z_2 - z_1) + \frac{\rho}{2g_0} (\alpha_2^* V_2^{*2} - \alpha_1^* V_1^{*2}) \quad (1)$$

Sampler Present:

$$P_1 - P_2 = K_{12} \frac{\rho V_1^2}{2g_0} + \frac{\rho g}{g_0} (z_2 - z_1) + \frac{\rho}{2g_0} (\alpha_2 V_2^2 - \alpha_1 V_1^2) + f \frac{L_{12}}{De_2} \frac{\rho V_2^2}{2g_0} \quad (2)$$

where * $\equiv$ symbol used to denote the absence of the sampler
(i.e. undisturbed flow)

$K_{12} \equiv$ expansion coefficient from level 1 to level 2

$\alpha_1, \alpha_2 \equiv$ kinetic energy coefficients (at levels 1 and 2
respectively (account for the non-uniformity of
the velocity profiles at these cross-sections)).

The following assumptions and/or simplifications are made to
these equations:

1. the expansion coefficients for the two cases are
taken equal because the flow areas are the same;
2. all of the kinetic energy coefficients are assumed
to have the same value because the detailed
velocity profiles needed to evaluate them are
not available;
3. the velocities are transformed into volumetric
flowrates via the continuity equation;
4. the following definitions are made in order to
ease writing of the above equations:

$$A \equiv \frac{\rho}{2g_O} \left(\frac{K_{12} - \alpha}{A_1^2} + \frac{\alpha}{A_2^2} \right) \quad (3)$$

$$B \equiv f \frac{L_{12}}{De_2} \frac{\rho}{2A_2^2 g_O} \quad (4)$$

Equations (1) and (2) are then added together to yield a final
result of:

$$Q^{*2} + \frac{1}{A}(P_1 - P_1^*) = (1 + \frac{B}{A})Q^2 + \frac{1}{A}(P_2 - P_2^*) \quad (5)$$

The so-called isokinetic condition states that the quantity Q^* equals Q if and only if P_1^* equals P_1 . This is equivalent to stating that the flowrate which existed in the subchannel before the installation of the sampler is measured when one returns the disturbed pressure field to the undisturbed condition. If we apply this condition to Equation (5), we obtain the following relationship between Q and $(P_2 - P_2^*)$ which must be satisfied at the undisturbed condition:

$$\begin{array}{ll} \text{at isokinetic} & B Q^2 = P_2^* - P_2 \\ \text{condition} & \end{array} \quad (6)$$

Data of Q versus $P_2^* - P_2$ allows one to iteratively solve Equation (6) for Q (hence Q^*). This result can be compared to the value of Q measured at the condition employed in the current measurement methodology (which is setting P_2^* equal to P_2) and the results of such a comparison show that the measured values of Q^* differ from the exact value by less than one part in a thousand. . Since this is much less than experimental accuracy we conclude that the current methodology yields accurate enough results.

Figure 1. Control Volume Used for Energy Equation Analysis of Flow Split Experimental Methodology

I.B.8 Experimental Method for Pressure Drop Determination
 (Kevin Burns)

The recommended procedures for pressure drop experiments are outlined in a "Laboratory Manual for Static Pressure Drop Experiments in LMFBR Wire Wrapped Rod Bundles", to be released in the form of a topical report in the Spring 1980. An error analysis which estimates the error in the experimentally determined friction factors will also be presented in this topical report.

I.C. Experimental Bundle Peripheral Velocity
 Measurements (Laser Anemometer)
 No work is being done on this Task at present.

I.D. Analytical Model Development - Bundles

I.D.1 Steady State SUPERENERGY
 (Kerry Basehore)

This work was reported on in the previous progress report.

I.D.2 Transient TRANSENERGY
 (Tom Greene)

Descriptions of the TRANSENERGY-S and TRANSENERGY-M codes are being prepared. They will be presented as topical reports very shortly.

I.D.3.0 Models for Forced Convection Analysis

Pressure Drop and Flow Split Models

(James T. Hawley)

The final representation of the laminar and turbulent pressure drop models was decided upon this past quarter.

In laminar flow it was decided to formulate the overall subchannel pressure drop as the sum of a term representing skin friction loss for a bare-rod bundle with P/D equal to one and a term representing the pressure loss for all effects associated with the wire. This latter term is formulated by considering the form loss for flow over the wire and then allowing an unspecified constant which results from this analysis to vary with P/D and H/D. The final result of this model is:

$$\Delta P_{iTot} = \frac{1}{Re_i} \left[C_1^* \left(\frac{A'_{si}}{A_{si}} \right) \left(\frac{De_i}{De'_i} \right) + C_{\alpha i} \left(\frac{A_{ri}}{A'_{si}} \right) \left(\frac{De_i}{H} \right) \left(1 - \frac{D_w}{2De'_i} \right) \right] \frac{L}{De_i} \frac{\rho V_i^2}{2g_o} \quad (7)$$

where: $C_1^* = .40$

$C_2^* = 37.4$

' $\equiv$ symbol used to denote bare-rod bundle equivalent quantity

$C_{\alpha i}$'s are not yet determined

All other terms are defined in Report COO-2245-17TR,

Rev. 1 of 5/79.

In turbulent flow the final edge subchannel pressure drop model is as reported in the previous progress report except that a final formulation of the quantity C_{f2} which appears there has been obtained. It was decided to fit simple power curves to C_{f2} in order to improve the accuracy of the correlation. The resulting functions are:

$$C_{f2} = .235 (P/D)^{.685} (H/D)^{.094}, \text{ all } N_p; .196 \text{ in.} < D < .250 \text{ in.} \quad (4a)$$

$$C_{f2} = .477 (P/D)^{.656} (H/D)^{.333}, N_p > 19 \quad (4b)$$

.472 in. < D < .525 in.

$$C_{f2} = .475 (P/D)^{.645} (H/D)^{.356}, N_p = 19 \quad (4c)$$

I.D.3.1 Models for Forced Convection Analysis - Mixing

(Kevin Burns)

A flow sweeping model applicable to the laminar flow regime is currently being developed. There is essentially no laminar mixing data at this time. Hence the recent laminar mixing data for the 37 and 217 pin bundles will be relied on heavily.

A turbulent mixing model has been developed by C.Chiu (COO-2245-55TR, Rev. 1). This model assumed that the pressure force acting between the low pressure wake region directly downstream of the wire in a particular subchannel and the relatively high pressure in an adjacent subchannel, is the driving force for crossflow. This model is not expected to extend to purely laminar flow, however, since a low pressure wake directly downstream of the wire is virtually non-existent. Rather, since laminar flow is characterized by an increased dominance of the inertia forces by viscous forces, it is postulated that the driving force for sweeping flow is the pressure drop due to viscous drag over the wire. Thus, an attempt is being made towards utilizing the laminar pressure drop correlation of Hawley and Chiu (see I.D.3, Pressure Drop) in a sweeping flow model.

I.D.4.0 Models for Mixed Convection

(Song Feng Wang)

Work on this task was completed and reported in COO-2245-TR73 which is listed in the front of this report.

I.D.4.1. Models for Mixed Convection-Subchannels

(Song-Feng Wang)

During this quarter, a systematic analysis of aiding and opposing flow in finite triangular and square rod assemblies was performed to investigate the fluid flow and heat transfer behavior under mixed convection conditions. The result of radial velocity distributions, cell friction factors, the criterion for local flow recirculation and the criterion for transition to turbulence was summarized in a paper presented at the Specialists Meeting on Decay Heat Removal and Natural Convection in FBR's, BNL, February 1980. The paper is included in Appendix A for reference.

The calculated results show that for typical LMFBR core design, the effect of buoyancy force on subchannel friction factors is important only in blanket assemblies under both normal operation and natural circulation transients. Neglecting the thermal plume effect, the flow in fuel assemblies tends to become turbulent before any recirculation occurs, while in blanket assemblies the reverse is true. Furthermore, based on uniform radial power distribution assumption, present analysis indicates that the flow recirculation in typical fuel and blanket assemblies is unlikely to occur for most of the steady-state and transient conditions.

The detailed description of the calculational procedures along with the additional results, such as coolant temperature distribution, heat flux and shear stress distribution, average Nu number, and clad temperature distribution are being compiled into a topical report which will be issued next quarter.

To verify the analytical results based on isolated cell analysis, and to study the effect of radial power skew, a test section with heated rods arranged in square lattice is being designed. The geometric dimensions and operation conditions are listed in Table 1. A full description of the test section design will be given in the next progress report.

TABLE 1. TEST SECTION DESIGN

Rod Arrangement	4 × 4
Rod Diameter	0.5 in.
Pitch-to-Diameter Ratio	1.237
Heated Length	36 in.
Total Length	49.25 in.
Maximum Rod Power	2 kw/rod
Operating Pressure	1 atm.
Operating Temperature	<212°F
Bundle Re	200~1500
Bundle Gr	3.0~5.5×10 ⁵

I.D.4.2 Models for Mixed Convection - Assembly
(Paul Symolon)

Results of this work were reported earlier in progress report COO-2245-72 September 1, 1979 - November 30, 1979. Work is continuing in this area and additional results will be presented in the near future.

I.D.4.3 Models for Mixed Convection - Core
(Paul Symolon)

Results of this work were reported earlier in progress report COO-2245-72 dated September 1, 1979 - November 30, 1979. Work is continuing in this area and additional results will be presented in the near future.

I.D.5 Shape Factors for Transverse Conduction in Rod Bundles
(T. Greene)

Work this quarter has involved determining sensitivity of the temperature fields within LMFBR assemblies to variations in the value of the shape factor. The objective is to identify the range of operating conditions for which knowledge of the conduction shape factor is important to the prediction of the temperature field. As a criterion for establishing the importance of the shape factor, the maximum change in the temperature field resulting from the inclusion of a shape factor has been selected (ΔT_{sfmax}). This is illustrated qualitatively in Figure 1. The numerical value of this criteria $\Delta T_{sf max}$ was assumed, somewhat arbitrarily, to be 3°F.

Definition of the region of importance can be done in several ways. The most obvious way is to outline a region on an assembly power vs mass flowrate plot. In the work at hand however, the calculations will be made in bundles with geometry identical to prototype bundles, except for the number of pins. This is done because of the large number of cases which must be considered. By reducing the number of pins, the calculational effort (and cost) is significantly reduced. As will be shown later, the reduction in pins has a very small effect on the results of the calculations. It would be most convenient if the plots could be constructed

in a manner which eliminates the bundle size effect in the ordinates of the plots. The appropriate set of ordinates is Bundle Power/Wetted Perimeter and Bundle Reynolds Number. The reasoning for this choice is explained as follows. Consider two bundles with identical geometry except for the number of pins. The condition which must be met is that the bundle mean temperature rise be the same at the same Reynolds number.

$$\frac{P_1}{\dot{m}_1} = \frac{P_2}{\dot{m}_2} \quad \text{Rey}_1 = \text{Rey}_2 \quad \text{Rey} \equiv \frac{4\dot{m}}{\mu P_w}$$

where P is the assembly power

$\dot{m}$ is the assembly flow rate

P_w is the assembly wetted perimeter

Solving for $\dot{m}$ in terms of Rey ,

$$\dot{m} = \frac{\text{Rey} \mu \cdot P_w}{4}$$

Combining

$$\frac{P_1 \cdot 4}{\text{Rey}_1 \mu P_{w1}} = \frac{P_2 \cdot 4}{\text{Rey}_2 \cdot \mu \cdot P_{w1}}$$

or
$$\frac{(P_1/P_{w1})}{\text{Rey}_1} = \frac{(P_2/P_{w2})}{\text{Rey}_2}$$

noting that $\text{Rey}_1 = \text{Rey}_2$, then $(P/P_w)_1 = (P/P_w)_2$

Therefore, the ratio of assembly power to assembly wetted perimeter and the bundle Reynolds number form a set of bundle-size independent ordinates.

Calculations have been made for a 37-pin blanket geometry assembly over a range of operating conditions considered representative of a large-LMFBR blanket assembly. A nominal mean inlet temperature of 750°F was assumed. The powers and flowrates were chosen to give mean outlet temperatures in the range 900°F to 1050°F (i.e. bundle ΔT s of 150°F to 300°F). The radial power distribution was taken as 1.26/1.00 peak-to-average as a first case.

The calculational procedure is outlined in the flowchart of Figure 2. As is noted there, the calculation can be said to be composed of an inner iteration and an outer iteration. The results of the inner iterations are individual pieces of the total solution generated by the outer iterations. Figure 3 is an example of the results of inner loop calculations for two different shape factors. The results for the shape factor of 1.2 are notable in that the value of $\Delta T_{sf \text{ max}}$ never reached the assumed criterion and, at low Reynolds Numbers, actually decreased. This was interpreted to mean that at low Reynolds Numbers, some other transverse mechanism of energy transfer was beginning to overshadow the conduction effects. The calculations for the shape factor equal to 2.0 were extended to low Reynolds number to see if the $\Delta T_{sf \text{ max}}$ vs Reynolds number curve intersect defines the point at which the effect of shape factor becomes important. This point is the final result of the inner loop calculations.

The outer calculational loop produces a series of points where the effect of shape factor becomes important for a fixed value of the shape factor but for different power to flow ratios. These points are the final results which will be used to define the region of importance for the shape factor. These values are plotted on a graph of (P/P_w) vs Reynolds number. This type of plot was discussed earlier and is illustrated in Figure 4. The region of importance is defined as the closed region bounded by the extremes of expected operating conditions and the locus of operating points resulting in a $\Delta T_{sf \max}$ of 3°F . The particular case illustrated in Figure 4 is for a shape factor of 2.0. The connection between Figure 3 and 4 is that the intersection of the criterion and the curve for shape factor of 2.0 in Figure 3 is transformed to the point defined by the intersection of the $\Delta T_{sf \max} = 3.0$ curve and the operating line corresponding to a mean outlet temperature of 1050°F in Figure 4. Note that no curve corresponding to shape factor = 1.2 appears on Figure 4. This is because the $\Delta T_{sf \max}$ never exceeded the criterion of $\Delta T_{sf \max} = 3.0^\circ\text{F}$.

As was discussed earlier, the ordinates of plots such as Figure 4 are bundle-size independent. What remains to be shown is that the information plotted is also insensitive to bundle size. To show this, a number of runs were made with a 61 pin model which was identical to the 37-pin model except for the number of pins. The runs were made so

that $Re_{y37} = Re_{y61}$ and $P_{37}/P_{w37} = P_{61}/P_{w61}$.

Table 1 below summarizes the results of these comparisons. Note that in all cases the $\Delta T_{sf \max}$ from the 37-pin case is very close to the actual 61-pin case and conservative (i.e. overpredicts $\Delta T_{sf \max}$)

P/P_w (kw/ft)	Rey	$\Delta T_{sf \max} (^{\circ}F)$	
		61-Pin	37-Pin
40.12	10000	3.0	3.2
12.03	6000	2.8	2.9

NOTES (i) in both cases Power Skew = 1:1 radially
(ii) SF = 2.0 in both cases

TABLE 1. BUNDLE SIZE DEPENDENCE OF $\Delta T_{sf \max}$

Figure 1 Illustration of the Shape Factor importance Criteria.

Figure 2. Flowchart of calculational procedure for operating region of importance for conduction shape factor.

Figure 4. Typical Results For an Outer loop.
 Result is The operating Region of Importance

Figure 3 Typical Results for an Inner ^{Structure} Loop for Two Values of Shape Factor.

II. SUBCHANNEL GEOMETRY (BARE RODS)

Work in this area was completed with the reports of J. Kelly (COO-2245-45TR) and J. Bartzis (COO-2245-48TR) which are listed in the front of this report.

III.1 Three-Dimensional Steady Isothermal Flows

(Robert W. Sawdye)

The necessary optical and electronic equipment has been acquired for three-dimensional laser doppler anemometer operation. Test cell design has been established and its construction is now underway.

Optics and Electronics

A new feature has been added since the last progress report which will isolate the He-Ne laser measurements from those of the Ar-ion laser system to help eliminate cross-talk due to the scattering of light from one laser system to the photodetector of the other. This improvement was achieved using narrow band pass filters which allow only light of wavelengths close to the laser wavelengths to pass through to the photodetector, which should improve the signal quality of the photodetector outputs. Therefore, each photodetector has been fitted with a filter which has a center wavelength which corresponds to that of the appropriate laser. These filters have a bandwidth of $100\text{\AA}$ and a transmittance of about 50%. Two filters with center wavelength of $5145\text{\AA}$ (Ar-ion green) have been mounted on the two photomultiplier tubes to measure the vertical and one horizontal velocity components. Another filter with a center wavelength of $6328\text{\AA}$ has been mounted on the photodiode that will measure the horizontal velocity component perpendicular to the axis of the He-Ne laser.

It is planned that the photomultiplier tubes will be operated in the reference beam mode, while the photodiode and associated optics will be operated in a forward scatter dual beam or reference beam mode, depending on signal quality. The electronic equipment has been checked, and the turbulence processor unit (for Reynolds stress correlations) is presently being repaired. The repair appears to involve only a single transistor, so that the unit should be available soon.

Hydraulics

The test cell consists essentially of a 20 cm. cube with a 6 cm. square duct passing through it along a vertical axis. The duct flow should entrain a three-dimensional recirculating flow within the cube by viscous and turbulent momentum exchange. The effect of turbulent momentum exchange from the confined jet to the fluid within the rest of the test cell should be very important in establishing the velocities and turbulence intensity throughout the recirculating region. This should therefore provide a good test for a three-dimensional turbulence model in an hydraulic computer code, such as TEMPEST.

The 6 cm. square inlet is preceded by a long duct (L/D is about 10) to allow the flow to develop to a uniform velocity profile across the duct. Screens will be used to eliminate the effect of the jet at the lower pipe fitting. The 6 cm. square outlet is followed by a 6 cm. long duct that

leads to the upper pipe fitting which completes the connection of the test cell to the hydraulic loop. The tubing leading to and from the test cell will be attached to the beam from which the test cell is suspended in the water bath. Therefore, the tubing will translate along with the test cell, which should assure that a steady and reproducible flow field can be maintained during the measurement process.

The hydraulic loop is capable of providing upwards of 50 gpm of water at up to 110°F, which implies a maximum duct Reynolds number of about 70,000. The external dimensions of the test cell, the internal dimensions of the water bath, and the basic description of the assembly of these components can be found in Figure III.1.

vertical and horizontal components
photomultiplier tubes - Ar filters

test cell design

horizontal component
photodiode - He-Ne filter

figure III.1. Test Cell Assembly Description

scale: 1 cm = 10 cm

test cell dimensions are external
dimensions - subtract 4 cm for two
wall thicknesses:

cube region: 20X20X20 cm

square inlet and outlet: 6X6 cm

max. inlet velocity: 80 cm/s

max. Reynolds no.: 70,000

IV. THEORETICAL DETERMINATION OF LOCAL TEMPERATURE FIELDS IN LMFBR FUEL ROD BUNDLES

Wire-Wrapped Rod Bundle Heat Transfer Analysis

(Chung-Nin Channy Wong)

IV.A The objective of this task is to calculate the local velocity and temperature fields in LMFBR rod bundles. Better knowledge of the velocity and temperature fields will give a substantial improvement of the thermal margin. It also provides the required information for future multi-dimensional structural analysis of the fuel rod claddings and the hexagonal bundle walls.

IV.B Formulation of the Problem

In order to calculate the local velocity and temperature fields in the wire-wrapped rod bundles, the author intends to solve the complete three dimensional Navier-Stokes equations without neglecting any physical transport in any direction. The only assumptions made in this analysis are as follows:

- single phase
- incompressible
- no heat generation in the coolant
- no heat transport by radiation
- constant material properties

Our analysis is set up to be able to handle any transient or steady state problem. It is possible to include the effect in our model by using Boussinesq Approximation. To model the wire around the fuel pin, the first crude approximation is to treat it as an imaginary discrete rotating flow blockage. By modeling the wire as a discrete rotating blockage, it is easier to specify the boundary condition and to compute because the boundary has a regular shape. This implies that the mesh cells in this analysis are either totally fluid cells or totally structural cells. Later on the author will refine this crude model by

initiating a special partial fluid and structural cell to specify the location of the wire.

The governing equations in our analysis are written as followings:

(A) For the coolant

Continuity Equation

$$\underline{\nabla} \cdot \underline{v} = 0$$

Momentum Equations

$$\frac{\partial \underline{v}}{\partial t} + \underline{\nabla} \cdot (\underline{v} \underline{v}) = - \frac{1}{\rho} \underline{\nabla} P + \underline{v} \underline{\nabla} \cdot \underline{\underline{\tau}}$$

Energy Equation

$$\frac{\partial T}{\partial t} + \underline{\nabla} \cdot (\underline{v} T) = \frac{1}{\rho c_p} \underline{\nabla} \cdot (k \underline{\nabla} T)$$

(B) For the fuel , clad and wire

Heat Conduction Equation

$$\underline{\nabla} \cdot (k \underline{\nabla} T) + s = 0$$

where $s = 0$ for clad and wire.

IV.C Numerical Method

Because of the complexity of the problem, all the governing equations are formulated into a system of finite difference equations. Throughout this analysis, since the author is not interested in the mixed convection cases, he can easily decouple the momentum and the energy equations, and deal with each equation one at a time. In this report, the author intends to discuss only the process of solving the governing equations of motion with primitive variables (that is, radial velocity, azimuthal velocity, axial velocity and the pressure).

The solution technique employed in our analysis is quite similar to ICE technique [1] or MAC method [2]. For the temporal differencing part of the equations, the nonlinear convection term is treated explicitly while the pressure propagation is treated implicitly. The molecular diffusion term can be specified either explicitly or implicitly. It depends upon the flow rate of the problem. If the Reynolds number is high, the diffusion term can be treated explicitly because of the simplicity. But if the Reynolds number is too low (i.e. $Re < 10$), it is better to treat the diffusion term implicitly because with the explicit diffusion term in the equation, the time step has to be extremely small to maintain stability. For the spatial differencing part of the equation, interpolated donor cell method is used to operate on the convection term while the 3-point differencing is used for the diffusion term.

If substituting the velocities at the new time level in the momentum equations into the continuity equation, an elliptical pressure equation in discrete form will be obtained. This set of finite difference equations behave as a system of linear equations with only pressure variables as the unknowns. LU-decomposition which is a direct method, is employed to solve the system of linear equations. To improve the accuracy of the solution, an iterative refinement scheme is used. Obviously,

there will be problem to invert the coefficient matrix using the direct method if the size of the system gets too large. In order to resolve this difficulty, the author intends to use the latest dissection ordering scheme [3], which will cut down both the computing time and storage space substantially.

A computer code Flow3DT has been written to perform the numerical calculations as discussed in this section.

IV.D Results

Test problems had been run and the results had been examined in order to verify the code and to explore its capability. They will be discussed in this section.

1. Simple Circular Duct Flow with Uniform Inlet Axial Velocity

This is the simplest case to test the computer code and is also a good way to verify the code. The problem was run in a complete three dimensional geometry. The geometry of the pipe and the flow condition are expressed following:

Diameter of the Pipe = 0.042 ft.

Length of the Pipe = 0.168 ft. or 0.48 ft.

Reynolds Number = 20 or 200

Density of the Fluid = 62.3 lbm/ft. sec.

Viscosity of the Fluid = 2.3194×10^{-4} lbm/ft.sec.

The results show a very good agreement with the analysis solution [4] and other numerical solutions [5, 10]. The total number of grids used in these calculations is $8 \times 3 \times 18$ and the total time to achieve equilibrium state is less than 70 seconds.

2. Study of the Laminar Swirling Pipe Flow

This test case is intended to check the code in handling the swirling flow problem. A swirling flow is initiated at the inlet, together with an uniform inlet axial velocity. Hence, the inlet

boundary condition becomes:

$$\begin{aligned} v_{\theta} &= Kr \\ v_z &= 1 \end{aligned} \quad \text{at } z = 0 \text{ and for all } t$$

where $K = \Omega r_o / U_o$

with K is the swirling ratio

Ω is the angular velocity

U_o is the average inlet axial velocity

r_o is the radius of the pipe

v_{θ} , v_z are the normalized azimuthal and axial velocities respectively

The magnitude of this swirling flow at the inlet has a great impact on the axial velocity profile. If the swirling flow is too high, it is possible to induce reversed flow at the center-line downstream from the inlet. This phenomenon has been known for a while and had been studied thoroughly [6,7,8,9,10]. Fig. 3,4,5 show the azimuthal and the axial velocity profiles at different axial levels with $K=1,2,7.92$ respectively. In reference 10, it was reported that its solution technique failed when K is approaching 2. Flow reversal has never occurred in his calculations. However, our numerical method is always stable and well-predicts the flow reversal. Fig. 6 shows the development of the center-line axial velocity. Fig. 7 states the effect of the swirling flow on the pressure drop. This effect is strong especially near the inlet.

IV.E Summary and Discussion

The present numerical method for transient three-dimensional

flow problem has been examined and proved to be very attractive. Our next goal is to analyze the fluid flow problem in the wire-wrapped rod bundle.

A brief outline of the on-going and the future works are listed as followings:

A. Test Problems

1. Laminar / Turbulent Flow in a Circular Tube with a Twisted Tape.
2. Laminar / Turbulent Flow over an Infinite Triangular Array of the Bare Rod Bundle.

B. Wire Wrapped Rod Bundle Flow Problems

1. Isolated Interior Cell
2. True Boundary Condition
3. Coupled Cell Analysis

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Fig. 1 Axial Velocity Profiles for 3D Circular Pipe Flow Uniform Entry, $Re=200$ at $t=70$ sec.

Fig. 2 Axial Velocity Profile for 3D Circular Pipe Flow Uniform Entry, $Re=20$

Fig. 3 Distributions of Axial and Tangential Velocity Components for $K=1.0$, $Re=20$

Fig. 4 Distributions of Axial and Tangential Velocity Components for $K=2.0$, $Re=20$

Fig. 5 Distributions of Axial and Tangential Velocity Components for $K=7.92$, $Re=20$

Fig. 6 Comparison of Axial Velocity Component at the Centerline for $K=0, 2, 7.92$ respectively, $Re=20$

Fig. 7 Axial Distribution fo the Mean Total Pressure with Different K (Dimentionless Pressure, $P^*=P/\rho U_o^2$)