COO-2245-69

COOLANT MIXING IN LMFBR ROD BUNDLES AND OUTLET PLENUM MIXING TRANSIENTS

Progress Report

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MASTER

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Reports and Papers Published Under MIT Coolant Mixing in LMFBR Rod Bundles Project

A. Quarterly Progress Reports

(Available from:
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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
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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

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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
(Jim Hawley)

1) Bundle Average Friction Factor

The goal of this work is to develop a bundle average friction factor correlation which is valid over the ranges of interest of Reynolds number, H/D ratio and P/D ration. To this end, work has continued on the compilation and assessment of bundle average friction factor data for various geometries of homogeneous, wire-wrapped rods in a hexagonal can. Multi-straight line best fits were made to all of the available friction factor data curves over the entire Reynolds number range of each curve. Qualitative similarities between the various data sets are: that at high Re ($\gtrsim$ 10,000 - 25,000) the data can be fit by a Re^{-n} straight line, where n is a function of the H/D ratio but not the P/D ratio; and that as Re decreases, there is a broad range of Re over which f_B smoothly varies to its laminar behavior of $f_B Re$ = constant. In the latter instance it should be pointed out that generally one line fits this transition region data satisfactorily but no correlation between the exponents of this line for the various data sets has been determined. The purpose of making these fits is to provide data to calibrate the correlation against. The writing of a program to produce the bundle average friction factor correlation has recently begun and will be the major emphasis in this area for the next quarter.

2) Subchannel Friction Factor

An immediate consequence of the bundle average friction factor correlation is that friction factors for the edge and interior subchannels will be derivable via the relation:

$$f_i = f_b \left(\frac{D_{ei}}{D_{eb}}\right)\left(\frac{1}{X_i}\right)^2$$

Thus, correlations for f_1 and f_2 will be derived which will have validity for the entire Reynolds number range of interest, as well as for the P/D ratio and H/D ratio ranges of interest.

IB.1 61-Pin Fuel Bundle

(Paul Symolon)

During this quarter, flow split measurements were completed on the 61-pin fuel assembly with a 6-inch lead length. This data, along with the data for the 12-inch lead assembly is presented in Figures 1 and 2. The flow splits, x_1 and x_2, become constant for fully turbulent flow. However, the data does not agree with the existing correlation[1] (see Table I). The discrepancy is due to surface roughness on the aluminum sides of the bundle caused by corrosion. Since the constants in the correlation (in particular c_{f2}/c_{f1}) were calibrated for a bundle with smooth (stainless steel or Plexiglas) walls, a new value for c_{f2}/c_{f1} had to be calibrated to account for the larger skin friction coefficient in the edge subchannel. For $c_{f2}/c_{f1} = 1.69$, the agreement between the data and the modified correlation is quite good. (See Table I.)

The data for the mixing test on the 6-inch lead fuel bundle was reduced to determine the dimensionless parameters ε_1^* and c_1 presented in Figures 3 and 4, respectively. These parameters, like the flow split, reach a constant value for high Reynolds numbers. The results vary with injection depth. For the case of ε_1^*, the variation is slight (see Figure 3) and both values are in good agreement with the existing correlation[2]. For the case of c_1, however, the results for the 12" injection are considerably higher than the predicted value. These values were reduced utilizing the entire salt distribution map. Efforts are underway to reduce c_1 based only on salt concentrations in the edge subchannels, where the effect of c_1 is important. This technique may improve the results. The mixing data for the 12" lead bundle is still being reduced. Some preliminary results indicate that the same variation with injection depth will be found.

In addition to completing the analysis of the 61-pin fuel bundle, work is underway preparing the 217-pin bundle for test, which should begin in early April.

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TABLE I

DATA	EXISTING CORRELATION[2]		MODIFIED CORRELATION	
	$c_{f2}/c_{f1} = 1.2$	% Error	$c_{f2}/c_{f1} = 1.69$	% Error
6" lead $x_1 = 1.09$	$x_1 = .99$	10	1.09	0
$x_2 = .81$	$x_2 = 1.03$	21	.84	4
12" lead $x_3 = 1.07$	$x_1 = .99$	8	1.09	2
$x_4 = .88$	$x_2 = 1.03$	15	.84	2

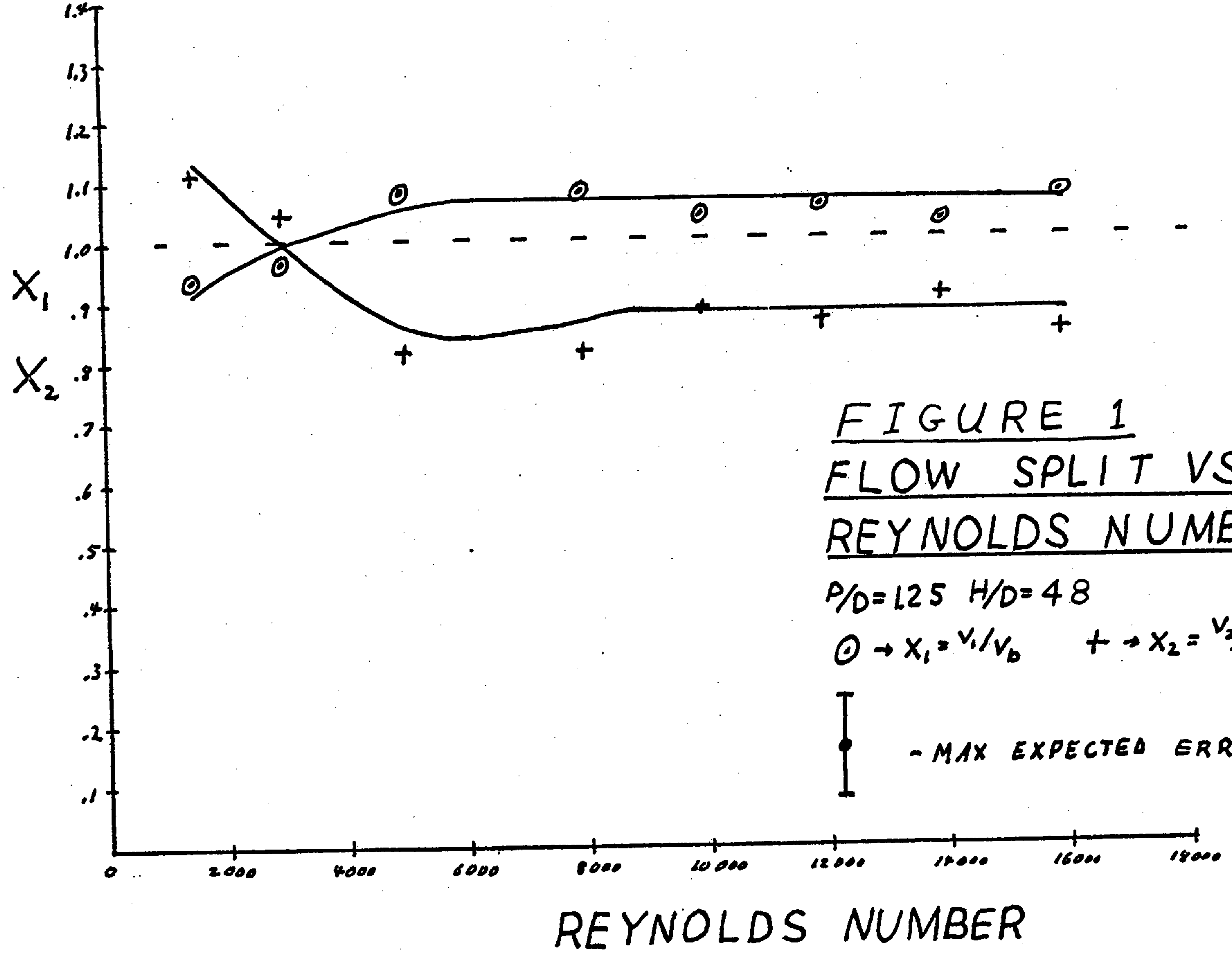

FIGURE 1
FLOW SPLIT VS
REYNOLDS NUMBER

P/D = 1.25 H/D = 48

⊙ → $X_1 = V_1/V_b$ + → $X_2 = V_2/V_b$

– MAX EXPECTED ERROR

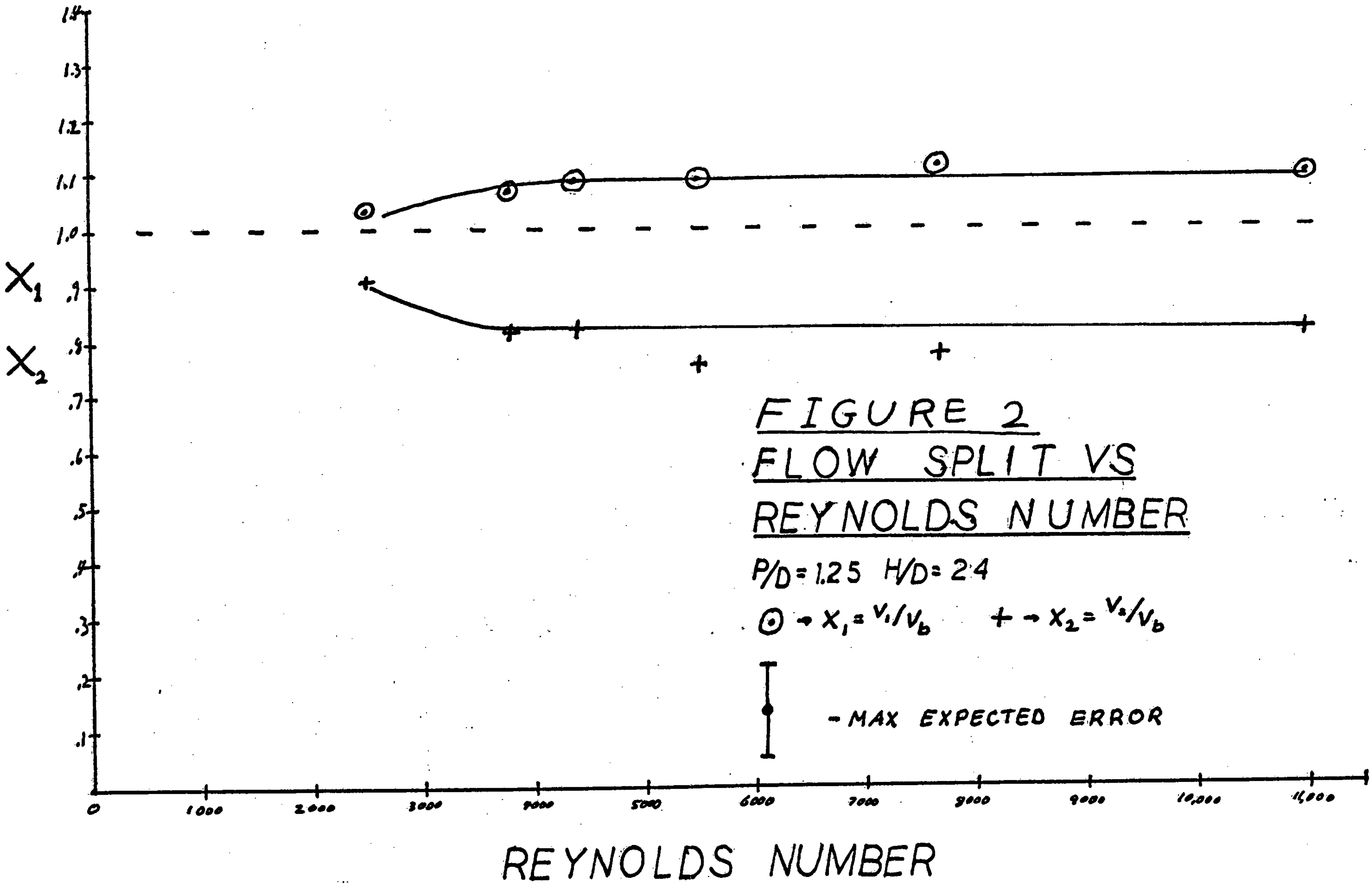

FIGURE 2
FLOW SPLIT VS
REYNOLDS NUMBER

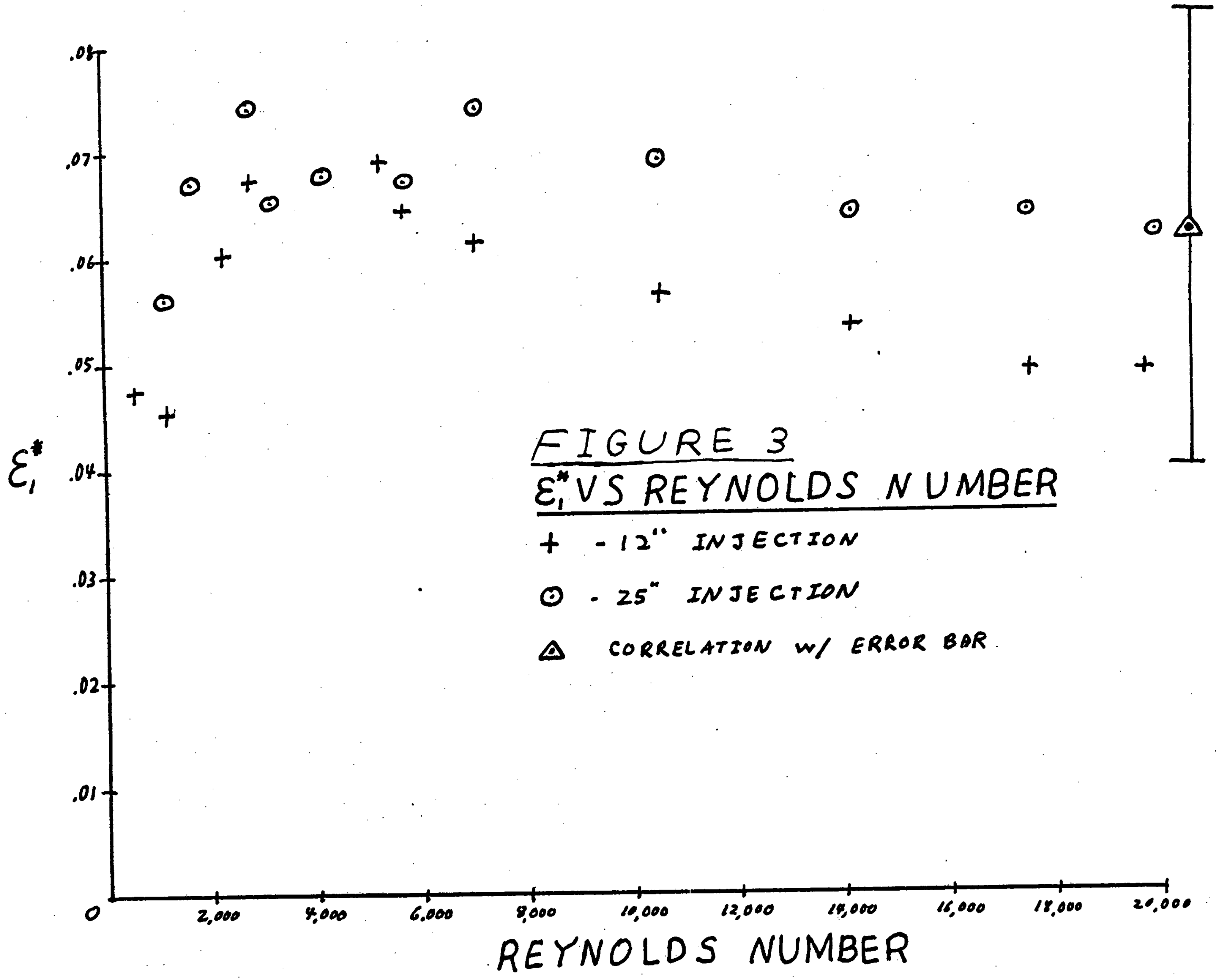

FIGURE 3

ε_1^* VS REYNOLDS NUMBER

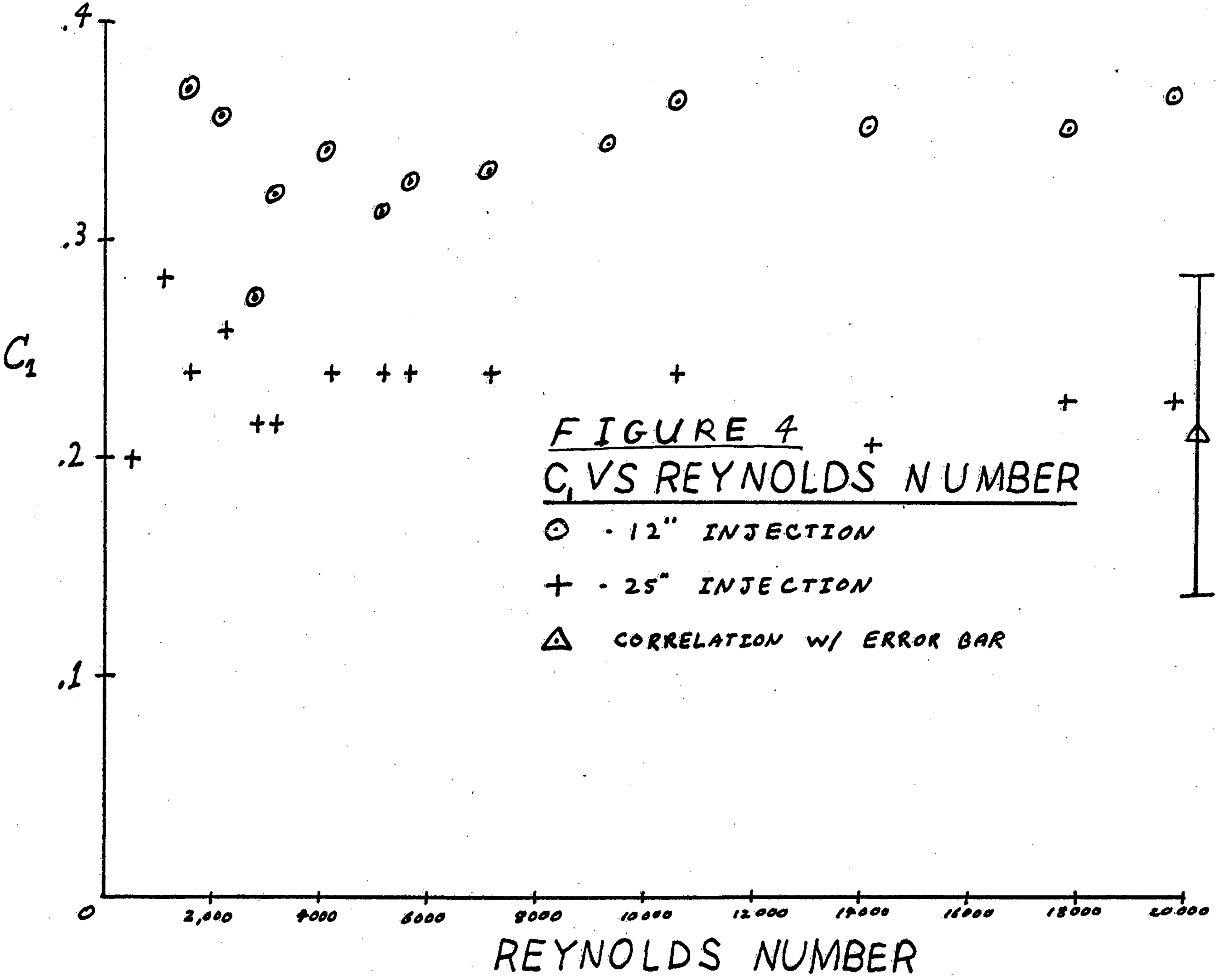

FIGURE 4
C_1 VS REYNOLDS NUMBER

IB.6 37-PIN BUNDLE

(Tom Chiu)

Work is being done of fabrication of a 37-pin blanket bundle with geometric characteristics of P/D = 1.15 and H/D = 20.88. These numbers are chosen to fill a gap in published experimental data which are also characteristic of Phenix geometry.

The bundle was fabricated and set up at the beginning of February. The mixing experiment was about underway. Calibration on the conductivity probes was done. However, the mixing experiment could not be carried out due to two reasons. One reason was the breakdown of flow meters which measure the salt solution injection flow rate. The second reason was that the modification of the Joint Computer Facility made the mixing data conversion procedure temporarily inoperable. Therefore, the original plan was changed. The pressure drop experiment was to be done first. Unfortunately, due to an accident, a lot of large plastic particles got into the bundle area and blocked some of the subchannels. To remedy this situation, the bundle had to be taken down and disassembled; filters were installed in the flow loop. After two weeks' work, the bundle is now ready again. However, due to the continued non-availability of data conversion system, the sequence of the experiment will be: pressure drop, mixing and flow split including "history effect".

I.B.7. Experimental Method for Flow Split

(Jim Hawley)

Work continued on a report on the experimental method used in determining the flow split parameters x_1, x_2, and x_3. The suggested methodology to be used in the case of an arbitrary upper plenum geometry was altered from two data points to three data points needed to deduce the isokinetic flow rate in a single subchannel. This alteration of method is now being reviewed by Dr. C. Chiu of Combustion Engineering. Also, an experiment has been proposed which will check the validity of the assumptions which underlies the flow split experimental methodology; this assumption is that the pressure taps on the isokinetic sampler measure the undisturbed pressure of the subchannel and this requires that the disturbance of the sampler is small and that the boundary layer covering the tap is laminar.

ID. ANALYTICAL MODEL DEVELOPMENT

Multi-Assembly Transient Analysis

(Tom Greene)

The modification of TRANSENERGY-S to permit multi-assembly analysis has been completed. A description of the modifications made and the motivation for developing the multi-assembly version were included in the last progress report. To date, sample problems run with the code have not been satisfactory. The energy balance, which serves as an accuracy check on the code, has been in error by as much as 10% in some cases. Work is continuing to correct this problem.

A study was made to determine the applicability of a forced convection model to the analysis of typical postulated LMFBR transients. Three representative transients were considered: a reactor trip, an uncontrolled rod withdrawal from 100% power, and a loss of offsite electrical power with coastdown to natural circulation. A prototypical 61-pin LMFBR radial blanket assembly was used in the analysis. The design operating conditions of the assembly are summarized in Table 1. The Modified Grashoff Criteria[1] was used to predict the inception of mixed convection in the bundle.

Table 2 summarizes the characteristics of the transients analyzed and the results of the analysis. It was found that, for the reactor trip and uncontrolled rod withdrawal transients, the flow remained within the forced convection regime. The emergency coolant pumps were assumed to maintain core flow at 10% of full flow. In the loss of offsite electrical power transient, the emergency pumps were postulated to fail, allowing the core flow to coast down to natural circulation conditions (~3.5% full flow).

For this case, inception of mixed convection was predicted to occur at 7% full flow. This corresponded to a Reynolds Number of 2456, based on the bundle average velocity and the interior subchannel hydraulic diameter. These results suggest that a substantial fraction of the postulated transients for LMFBR's may be analyzed, in whole or in part, using a forced convection flow model.

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Linear Power (KW/M)	12.12
Flow Rate (KG/SEC)	7.428
Heated Length (M)	1.626
Power Skew (PEAK/AVG)	1.71

TABLE 1. DESIGN OPERATING CONDITIONS FOR A PROTOTYPICAL 61-PIN LMFBR RADIAL BLANKET ASSEMBLY

TRANSIENT	ESTIMATED DURATION (sec)	POWER CHARACTERISTICS	FLOW CHARACTERISTICS sec/% core flow	INCEPTION OF MIXED CONVECTION
Reactor Trip	60	Trip at t= .02 sec	0.5/100% 30/10% Final=10%	Transient remains in forced convection regime
Uncontrolled Rod Withdrawal from 100% Power	360	Step increase to 115% power at t = 0 sec trip at t = 300 sec	0.0/100% 300/100% 330/10% Final=10%	Transient remains in forced convection regime
Loss of Offsite Electrical Power	120	trip at t = .5 sec	0.0/100% 30/10% Final=3.5%	Reynolds No.=2456 Flow=7% Full Flow

TABLE 2. TRANSIENT CHARACTERISTICS AND PREDICTION OF INCEPTION OF MIXED CONVECTION

ID.2 Mixed Convection in Sodium-cooled Reactors with Transients

(Song-Feng Wang)

TASK OBJECTIVE

The objective of this work is to develop computational methods for analyzing transient fluid flow and heat transfer processes in sodium-cooled fast reactors under mixed convection conditions. Current emphasis is on developing a realistic pressure drop model, from phenomenological considerations, for use in the more sophisticated computer programs.

MODEL DEVELOPMENT

The velocity and temperature, (V, T), fields in a reactor core are determined by pressure boundary conditions as well as the rod bundle power distributions. In sodium-cooled reactors, the effect of the power distributions on (V, T) fields is enhanced by the buoyancy effects and becomes a controlling factor under low flow situations. The velocity and temperature fields interact and, as a result, local flow recirculation within subchannels and rod assemblies may occur. Under extreme conditions, flow reversal may occur. Conditions of significant buoyant effects and possibly flow reversal can occur:

a) within subchannels with buoyant effects influencing the relative flows between subchannel regions
b) within a bundle with buoyant effects influencing the relative flows between subchannels or regions in the bundle
c) within a core with buoyant effects influencing the relative flows of assemblies

Our model development has been started on a subchannel basis (i.e, stage a) above). It was assumed that the subchannel problem could be divided into three essentially independent parts:

1) pressure drop behavior within a bare rod subchannel due to buoyant effects
2) pressure drop behavior within a wire-wrapped rod subchannel under isothermal conditions
3) transient effects on pressure drop behavior

The resultant effect is simply a superposition of these thess effects.

In Part (1), a symmetric section of a subchannel, called a cell, was analyzed using a multi-region analytical method. The onset of flow recirculation within this subchannel can be predicted from the local velocity distribution. The criteria for the onset of flow recirculation determines the limit on using a lumped parameter approach to model the subchannel. Any analysis beyond that limit should be done in a distributed parameter way, i.e., distributed parameter analysis. The reason is because in lumped parameter analysis, only one velocity and one temperature value is assigned in each subchannel, which makes it unable to handle flow recirculations. A buoyancy multiplier, ϕ_{sb}^{BY}, can be found as

$$\phi_{sb}^{BY} \equiv \phi_{sb}^{BY}\ (\mathrm{Gr},\ \mathrm{Re},\ \mathrm{Pr},\ \mathrm{Geometry})$$

where ϕ_{sb}^{BY} is defined as

$$\phi_{sb}^{BY} \equiv \frac{f_{sb}^{BY}}{f_{sb}^{ISO}} = \frac{\text{bare rod subchannel friction factor including the buoyancy effects}}{\text{bare rod subchannel friction factor for isothermal fluid}}$$

In Part (2), a wire-wrap multiplier, ϕ_{sw}^{ISO}, can be found as

$$\phi_{sw}^{ISO} \equiv \phi_{sw}^{ISO}\ (\mathrm{Re},\ \mathrm{Geometry})$$

where ϕ_{sw}^{ISO} is given as

$$\phi_{sw}^{ISO} \equiv \frac{f_{sw}^{ISO}}{f_{sb}^{ISO}} \equiv \left(\frac{\text{wire-wrapped rod subchannel friction factor}}{\text{bare rod subchannel friction factor}} \right)_{ISO}$$

Similarly, a transient multiplier, ϕ_{TR}, will be obtained from Part (3).

The resultant subchannel friction factor in wire-wrap rod bundle, f_{sw}^{BY}, is therefore approximated by

$$\left(f_{sw}^{BY}\right)_{ss} \equiv \phi_{sw}^{BY} f_{sw}^{ISO} \equiv \phi_{sw}^{BY} \left(\phi_{sw}^{ISO} f_{sb}^{ISO}\right)$$

$$\approx \phi_{sb}^{BY} \left(\phi_{sw}^{ISO} f_{sb}^{ISO}\right)$$

and

$$\left(f_{sw}^{BY}\right)_{TR} \equiv \phi_{TR} \left(f_{sw}^{BY}\right)_{ss}$$

$$\approx \phi_{TR}\, \phi_{sb}^{BY}\, \phi_{sw}^{ISO}\, f_{sb}^{ISO}$$

Both the wire-wrap multiplier and buoyancy multiplier are under calibration. The final results of ϕ_{sb}^{BY} and ϕ_{sw}^{ISO} and the criteria of onset of flow recirculation within subchannels will be reported in the future progress report. Work on transient effects, Part (3), will be initiated to find ϕ_{TR}.

TASK III: LMFBR OUTLET PLENUM MIXING

(Professor Michael G. Golay)

The consistent goals of this effort have been and remain validation and improvement of calculational methods for analysis of LMFBR outlet plenum flow transients. The method used is performance of flow-mapping measurements in simple geometries similar to those arising in the outlet plenum configurations. From comparison of the measurements and calculations it is possible to improve the choice of the free parameters appearing in the calculational models, to determine situations in which the models are fundamentally inadequate, to identify vital input data requirements for accurate calculations, and to guide improvements in the models.

Past work has been concerned with two-dimensional steady state isothermal and thermally-mixing flows. Current work is concerned with progressing to more complicated flow situations which are of greater direct relevance to designers. Each of the three current efforts is described in the following sections. They are concerned with the following flow situations.

1. Two-dimensional transient isothermal flows,
2. Two-dimensional transient non-isothermal flows, and
3. Three-dimensional steady isothermal flows.

The models being tested are the codes VARR-II (two-dimensional) and TEMPEST (three dimensional), which have been developed for designer use in the LMFBR programs.

III.1 Transient Two-Dimensional Isothermal Flows

(D. Boyle)

This effort is concerned with measurement and analysis of isothermal shutdown water flow transients in two-dimensional small scale outlet plenum flow cells. Work to date has mainly been concerned with improving the accuracy of existing experimental capabilities and with development of instrumentation and data-processing hardware for the transient measurements. That development is now completed, and the transient measurements and calculations have been initiated. These efforts are summarized in greater detail in the following sections.

III.1.1 Initial Measurements

A series of preliminary experimental measurements and computer test runs have been accomplished during the past quarter. The primary thrust of this early experimental work has been to characterize the flow at the inlet to the plenum accurately. This is important since it represents the only experimentally-derived information that the model uses for its predictions, and therefore should be known as precisely as possible. Further, since measurements and calculations are carried out in only half the cell, flow symmetry must be obtained initially and then maintained throughout the transient. A major concern has been to assure that symmetry is obtained in the measurements, and this goal has been accomplished.

Velocity measurements in the chimney entrance region of the outlet plenum test cell were performed early during the past quarter. It was determined that the single fine-mesh screen installed at the base of the chimney did not adequately flatten the inlet mean-velocity distribution. The screen was found to be subject to partial occlusion by the particles suspended in the water in order to scatter the laser light. A new entrance region section was constructed and installed. The new device (consisting of four parallel sheets of heavy-gauge stainless steel girds) is much more efficient in flattening the inlet velocity distribution and in eliminating the occlusion problem. Steady-state measurements at full flow and temperature conditions have been made for all five mean-turbulence parameters across the cell inlet. Figure 1 is included to illustrate the flatness of the velocity profile achieved, the degree of symmetry, and the effect of the transient upon the distribution.

A further advantage of the new inlet is the sharp reduction in size of the largest turbulent eddies entering the plenum, an attendant decrease in turbulence intensity, and an approach to true isotropy, at least at the inlet region. The impact of this factor on turbulence modeling is discussed in Section III.1.3.

III.1.2 Electronic Data Recording

A computer program to receive the unprocessed transient data, and to process it on the Nuclear Engineering Department's Tektronix mini-computer has been written and tested. The in-house effort to build a custom Analog-to-Digital Converter that interfaces with the computer-compatible tape cassette for processing the experimental data is nearing completion. All hardware components have been tested, all micro-processor sub-routines have been written and tested; system initialization and check-out of the five subsystems of the A-to-D converter remains to be finished.

III.1.3 Computer Work

The steady-state inlet data from the experiment has been used in the VARR II computer code to generate a steady-state flow field throughout the plenum which serves as the initial condition from which the coast-down transients can be started. The turbulence model used in VARR-II was heuristically derived based on the assumption of roughly isotropic turbulence, and has been shown to fail to predict experiments whenever significant anistropy is present. Indeed, an earlier steady state experiment with the same test cell but with highly anisotropic inlet conditions, showed that the VARR-II estimates of point-wise turbulence kinetic energy (TKE) were far lower than those measured. The new inlet region, described earlier, by imposing a high degree of turbulence isotropy on the inlet flow, better satisfies the turbulence model application criteria, and results in TKE predictions that appear to be much better than previously obtained.

In an effort to reduce the model running time, a coarser mesh has been tried and is still being evaluated for accuracy. If loss of accuracy is not significant, the coarse mesh will be used for sensitivity and parametric analyses. It has been found to reduce the run-time for a steady-state, FFTF calculation by a factor of approximately twenty.

III.2 Two-dimensional Non-Isothermal Transient Flows

(S. Chang)

Buoyant effects are of central importance in determining outlet plenum flow behavior during the shutdown transient. This effort is aimed toward understanding such effects and validating the buoyant flow treatment of models in current use. It should be noted that the VARR-II turbulence model was formulated without any explicit accounting of buoyant effects upon turbulence and validation of the model under buoyant flow conditions has not yet been done.

This work is in the stage of experimental design. The main problem to be resolved is that of whether the in-house Laser Doppler Anemometer (LDA) equipment can be used for such measurements. The difficulty which arises is that a mixing fluid of non-uniform density is also non-uniform optically--causing the LDA beams to be refracted. This can cause the beam crossing point--at which the velocity measurement is made--to move, imparting an error to the velocity measurement. This problem is being attacked in two ways: 1) Feasibility calculations and experiments involving the currently available LDA apparatus, and 2) Investigation of alternative LDA-based measurement methods. Nearly the entire effort to date has focussed upon the former direction. It is apparent that optical "jitter" would have a small effect upon mean-flow measurements; however, it could have an important effect upon fluctuating flow measurements. In order to evaluate this effect it is planned to perform short-term feasibility tests with injection of warm water into the cold outlet plenum.

In the proposed experimental work transients would be run in which the water flow rate would be held constant (i.e., steady flow), but the temperature of the incoming water would be reduced suddenly (by switching the inlet flow to a cold reservoir tank). A range of tests at different inlet densimetric Froude number values would be performed so that the effect of flow stratification upon buoyant turbulence could be examined. The experimental work is expected to begin after September, 1979.

III.3 Three-Dimensional Steady Isothermal Flows

(R. Sawdye)

A persistent requirement from LMFBR designers has been a three-dimensional flow analysis capability. The COMMIX code offers promise in this area, and the code TEMPEST has been developed at HEDL for this purpose. Neither code has--as far as we know--a turbulence model, and a key question is that of the appropriate level of modeling detail required to provide an accurate analysis.

In this work flows are planned to be examined in a simple three-dimensional geometry (not yet selected). Current work is concerned with experimental design. The main problem is that of how to use the currently available equipment (designed for one- and two-component velocity measurements) for three-dimensional velocity measurements. A variety of approaches are being examined, with the leading candidate being a marriage of the two currently available systems (for single component and for two-component measurements, using two separate lasers).

In addition the TEMPEST program has been requested from HEDL; with the goal of using it for experimental design calculations and possibly of addingthe TEACH-T (K,) turbulence model to it.

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

1. Wire-Wrapped Rod Bundle Heat Transfer Analysis

(Chung-Nin Wong)

In the past quarter of the year, work has been done on the development of the computer code to analyze the wire-wrapped rod bundle heat transfer in LMFBR. In the region of our interest (that is, the coolant region inside the reactor core), the spiral wire spacing induces swirl flow around the fuel pin and may possibly result in a radial cross-flow at the common boundary between two adjacent cells. Of course, the dominating flow is still the axial flow going up to the upper plenum. In order to pursue all these three velocities (Vr, Vθ and Vz), the set-up of this computer code should be able to analyze a 3-D non-linear flow problem. With this non-linear problem at hand, the Newton Iteration Method is suggested as the tool to solve it. However, for speeding up the convergence rate, the latest Newton Block Grauss Seidel Iteration Method will be adopted here. The resultant governing equations will be expressed in the form of the block matrices; then all three velocities (Vr, Va and Vz) within each unit mesh cell will be solved for simultaneously. In this way, one may obtain the solutions more efficiently because obviously, these three velocities are strongly coupled.

To solve the 3-D non-linear flow problem required a huge computer storage space and a substantial amount of iteration time. Therefore, it becomes quite expensive to run this program in the standard IBM 370/165 computer at MIT. For this economic reason, this program will be designed for the Multics System on Honeywell 6180. The Multics System costs much less and can provide an enormous storage space because it is a virtual system. A small portion of the time and effort have been spent to gain familiarity with this new system.

Recently, the testing of the code has been started. But, no good results have been obtained and analyzed. Probably in the next progress report, the result of the calculations will be reported and discussed.