COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Progress Report

Principal Investigators

Neil E. Todreas

Michael W. Golay

Massachusetts Institute of Technology
Department of Nuclear Engineering
Cambridge, Massachusetts 02139

September 1, 1975 - November 30, 1975

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Prepared for the U.S. Energy Research and Development
Administration under Contract No. AT(11-1)-2245

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

leg

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

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
COO-2245-13 Period June 1, 1974 - August 31, 1974
COO-2245-14 Period September 1, 1974 - November 31, 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

Reports Issued Under This Contract

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-2245-4TR, MIT, Sept. 1973.

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

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

Y. B. Chen, K. Ip, N. E. Todreas, "Velocity Measurements in Edge Subchannels of Wire Wrapped LMFBR Fuel Assemblies," COO-2245-11TR, MIT, September 1974.

E. Khan, N. Todreas, W. Rohsenow, A. A. Sonin, "Analysis of Mixing Data Relevant to Wire-Wrapped Fuel Assembly Thermal-Hydraulic Design," COO-2245-12TR, MIT, Sept. 1974.

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distributions in Wire Wrapped Fuel and Blanket Assemblies of a LMFBR," COO-2245-16TR, MIT, March 1975.

E. Khan, W. M. Rohsenow, A. Sonin, N. Todreas, "Input Parameters to the ENERGY Code (To be used with the ENERGY Code Manual) COO-2245-17TR, MIT, May 1975.

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "Manual for ENERGY Codes I, II, III," COO-2245-18TR, MIT, May 1975.

P. Carajilescov and N. Todreas, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Subchannel of a Bare Rod Bundle," COO-2245-19TR.

B. Chen and N. Todreas, "Prediction of Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer," COO-2245-20TR, MIT, May 1975.

F. Carre and N. Todreas, "Development of Input Data to Energy Code for Analysis of Reactor Fuel Bundles," COO-2245-21TR, MIT, May, 1975.

Reports Issued Under This Contract

B. Topical Reports, Continued

H. Ninokata and N. E. Todreas, "Turbulent Momentum Exchange Coefficients for Reactor Fuel Bundle Analysis," COO-2245-22TR, MIT, June 1975.

R. Anoba and N. Todreas, "Coolant Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients," COO-2245-24TR, MIT, August, 1975.

Reports Issued Under This Contract

C. Papers and Summaries

Yi Bin Chen, Ka-Lam Ip, Neil E. Todreas, "Velocity Measurements in Edge Channels of Wire-Wrapped LMFBR Fuel Assemblies," American Nuclear Society Transactions. Vol. 19, 1974, pp. 323-324.

P. Carajilescov, N. Todreas, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Sub-Channel of a Bare Rod Bundle," accepted for the ASME Winter Annual Meeting, Nov. 1975 (Included as Appendix to Quarterly Progress Report COO-2245-15).

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Fuel Rod Assemblies," Nuclear Engineering and Design, 35 (1975) 1-12.

B. Chen and N. Todreas, "Prediction of Coolant Temperature Field in a Breeder Reactor Including Inter-assembly Heat Transfer," Submitted to Nuclear Engineering and Design (included as Appendix to Quarterly Progress Report COO-2245-23).

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "A Porous Body Model for Predicting Temperature Distribution in Wire-Wrapped Rod Assemblies Operating in Combined Forced and Free Convection," Nuclear Engineering and Design, 35 (1975) 199-211.

Ralph G. Bennett and Michael W. Golay, "Development of an Optical Method for Measurement of Temperature Fluctuations in Turbulent Flows," American Nuclear Society Transactions. Vol. 22, 1975, p. 581.

COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Contract AT(11-1)-2245

Quarterly Progress Report

September 1, 1975 - November 30, 1975

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

Figures, Tables and References are grouped for each of the three tasks at the end of the writeup of each task.

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

TASK IA: Assessment of Available Data

No work was performed this quarter.

TASK IB: Experimental Bundle Water Mixing Investigation

1a) 61-Pin Fuel Experiments (Alan Hanson)

During this quarter, work continued on the reduction and analysis of mixing data from the experiments finished in the preceeding quarter. In order to efficiently reduce the data obtained from the experiments in which bundle flowrate was varied for a fixed axial injection location, it was necessary to substantially modify the reduction code written previously for axial injection location variation at a constant bundle flowrate. The former code has been designated SALT-AXIAL and the new code is called SALT-FLOW. The principal differences between these two versions are in the input and output handling and in the plotting routines.

Figure 1 illustrates a typical result of the mass balance check on a flowrate variation experiment. This particular experiment was run on the 12-inch wire-wrap lead bundle with salt injection into an interior type subchannel that was adjacent to an edge type subchannel. Similar curves were obtained from all other experiments with both 6-inch and 12-inch leads and with various injection locations. At low flowrates which are well within the laminar flow regime (Reynolds numbers much less than 2000), the mass balance is generally poor. This poor balance is believed to be due to at least two effects. The first effect is the physical phenomenon of striping which occurs when injected tracer follows flow streamlines and is not dispersed by turbulence. The second effect is an experimental problem -- at very low flows it is difficult to maintain a constant and accurate injection flowrate with the experimental injection system, and consequently injection fluctuations approach the magnitude of the total injection flow. This second effect would result in underprediction of salt concentrations since some of the probes would be expected to record signals during the low point of the injection fluctuations. As the bundle bulk flow is increased the injection effect is diminished and the mass balance improves. Finally as the flowrate passes through the transition to turbulent flow (Reynolds number of 2300 at a flow of around 13.5 GPM), both effects are reduced and the quantity of salt observed approaches asymptotically 100% of that injected. The apparent dip in the curve beyond 40 GPM in Figure 1 has no obvious physical reason

and may be due to a change in flowmeters made there to accomodate higher flowrates. Since the planar salt distributions do not change significantly in the turbulent regime as the flowrate is increased, it appears that there is at most a minimal effect of Reynolds number on mixing.

An examination of the edge subchannel injection data was made to obtain a rough estimate of the average swirl velocities. The data for a long injection-to-instrumentation distance of 24 inches was used to get a good average over more than one axial pitch. An estimate of the distance that the salt tracer had traveled circumferentially around the bundle periphery was obtained by finding the furthest edge channel to show a significant quantity of salt from the injection channel at the instrument plane. The ratio of this circumferential distance to the fixed 24-inch axial distance is an approximation of the ratio of the circumferential (or swirl) velocity to the edge subchannel axial velocity. The results of this calculation are shown in the fourth column of Table 1. In order to calculate the ratio of the swirl velocity to the bundle-average velocity, it is necessary to know the subchannel flow splits; the fifth column of Table 1 contains this velocity ratio based on an assumed flow split using Sangster's method. Finally the last column of Table 1 lists the ratio of the circumferential velocity to the axial velocity which would be expected if the fluid were to follow the wire-wrap exactly. This term can be referred to as the wire-wrap velocity ratio. These data compare favorably to the analysis of report COO-2245-12TR from which Figure 2 is taken. Table 1 reveals several interesting conclusions:

- 1) In the turbulent flow regime, the ratio of swirl velocity to both the edge channel and the bundle-average velocities is greater than the wire-wrap velocity ratio. This means that on the average the swirl velocity vector is at a steeper angle to the vertical than is the wire wrap.
- 2) In the laminar flow regime, the wire-wrap velocity ratio lies between the two swirl flow velocity ratios. This indicates that the swirl flow closely follows the wire wrap in laminar flow.
- 3) If the swirl flow were to follow the wire wrap exactly, then a decrease in wire-wrap lead by a factor of two would produce an increase in swirl velocity by a factor of two as shown by the wire-wrap velocity ratio. In fact, however, such a decrease in lead produced an increase by only a factor of 1.68 in turbulent flow and 1.81 in laminar flow. Thus as the lead is reduced, the fluid tendency to slip over the wire axially rather than to be deflected by it laterally must be increasing.

It should be possible to obtain a better estimate of the swirl flow from a more sophisticated model of rod bundle hydraulics than that used above. To get such an estimate as well as to obtain information on the mixing process in the bundle interiors, it is planned to use the ENERGY code developed at MIT to analyze the experimental data. An intermediate version of this code which had previously been used to look at other salt data was acquired from its author. In order to make the code operational many changes were necessary. Extraneous coding was removed from the program where it was found to be unnecessary. Output was reformatted to produce a more legible listing of results. Logic errors in the handling of edge and corner channels were corrected. Although these changes helped to make the program functional, it remains clumsy to deal with the output because the code requires a completely different channel numbering scheme than that used in the experiments. Thus more programming is necessary to translate ENERGY output into a form directly comparable to tracer experimental data. This additional programming will be completed next quarter and will probably include some graphical display of results.

A manual describing the details of design and operation of the electronic data acquisition system used in collecting the salt tracer data was written during the quarter.

1b) 61 Pin Fuel Experiments (Stuart Glazer)

As reported earlier by A. Hanson, extremely poor mass balances resulted during mixing tests run in the 61 pin bundle in laminar flow. The causes are speculated to be striping, which causes the injected saline solution to remain essentially within the boundary layer on the fuel pin, and imprecise injection solution flowrate control. To test the effectiveness of the flow separation approach, described in section 2, mixing in the 61 pin bundle will be extensively studied in the laminar and transition regions using a flow separator designed for the 61 pin bundle. During the current quarter, design was completed for this flow separator. Fabrication has already been initiated, and will be completed shortly. Mixing tests will be run early in the next quarter. Alternative injection schemes are being considered to eliminate inaccuracies in flowrate control such as utilizing a positive displacement pump. Design and fabrication of the flow separator for the 217 pin bundle is conditional pending the successful performance of the device in the 61 pin laminar test series. If the reliability of the laminar and transition mixing data from the 61 pin test is considered acceptable, it will be used in the calibration of the ENERGY computer codes.

2) 217 Pin Fuel Experiments (Stuart Glazer)

At the beginning of the current quarter, MIT took receipt of the 217 pin fuel assembly mockup used in the HEDL mixing experiments. After replacement of the phenol dummy fuel pins with stainless steel elements, and fabrication of the instrumentation and data recording system, this bundle will become the test article for the MIT 217 pin single phase hydrodynamic and mixing experiments.

Currently identified goals of the 217 pin assembly test series include the determination of pressure, flow split, velocity, and mixing data at the subchannel level in the turbulent, transition, and laminar flow regimes. It is also desired to maintain the option to perform a series of transient flow tests to verify mixing predictions by a transient version of the code SUPERENERGY.

An analysis was initiated to determine the type of tracer to be used in the 217 pin mixing tests; salt, heated water, or electrically heated pins. Advantages of the salt tracer include: 1) high signal to noise ratio attainable due to high salt concentration in the injection fluid, 2) low mass diffusivity of salt in water which prevents false interpretation of salt mass diffusion as bulk fluid mixing, 3) extremely rapid response of electrical conductivity sensors to transient changes in salt concentration, enabling the possible future study of mixing during flow transients, and 4) extensive previous experience at MIT and at other research laboratories with salt tracers in water flow through wire wrapped pin assemblies. The primary disadvantages of salt tracers are: 1) inaccuracies in signal measurement due to nonuniform salt concentration in the immediate neighborhood of the sensor, 2) faulty interpretation of sensor output as subchannel average concentration because of concentration gradients within subchannels, and 3) unavailability of commercial conductivity sensors of the necessary size consistent with current project funding levels. The latter shortcoming has in the past required custom in-house fabrication of large quantities of electrical conductivity sensors.

The major advantage of injecting hot water for use as a tracer is that extremely accurate and sensitive temperature sensing instrumentation is commercially available within current budget constraints. Disadvantages of hot water injection include: 1) relatively high thermal diffusivity, 2) significant changes of water viscosity with temperature which would interfere with the flow field, and 3) low signal to noise ratio attainable, requiring large volumes and flowrates of injected hot water relative to salt injection with subsequent disturbance of the flow field.

The use of electric heaters to simulate fuel pins was also considered. This represents a method of tracer addition which is

much closer to heat addition in an actual fuel bundle. As such, tracer strength increases with increasing axial distance down the assembly, and all perturbations to the flow field due to liquid tracer injection are eliminated. The detection instrumentation is the same commercially available equipment as required for hot water injection. The primary disadvantages of this method of tracer addition include: 1) limitations on the heat transfer rate from the heaters to the water so as not to cause local boiling on the sheaths of the heaters, 2) significant thermal diffusivity relative to heat transfer by fluid mixing, 3) inability to measure subchannel average temperatures at more than one axial level, and 4) disturbance to the flow field due to the temperature dependence of viscosity.

The use of electrically heated pins to provide heat as a tracer was eliminated because analysis indicated that only very small localized increases in temperature could be obtained at the exit plane while observing the heat transfer rate limitation. Injected hot water was eliminated due to the small temperature rise resulting from injection flowrates set at levels to eliminate significant flow perturbations. Injected salt was therefore chosen as the tracer for the 217 pin fuel bundle mixing tests.

To eliminate errors in salt concentration measurements due to incomplete mixing of the salt both in the immediate neighborhood of the sensors and throughout subchannels, a device which enhances fluid mixing was conceived. At the bundle exit plane, beginning immediately where the wire wrapped pins terminate, a series of impermeable baffles, called a flow separator, is to be placed. This device exactly separates the flow emerging from the exit plane into component subchannels. The flow from each subchannel is kept isolated until it has passed through the flow separator for a length sufficient to cause complete mixing by virtue of turbulent eddies within each subchannel. In addition, three dimensional partial flow blockages are placed in each subchannel in the flow separator to further enhance fluid mixing in the transition and laminar regimes. Electrical conductivity sensors are placed within the flow separator, near the exit of the device. The flow separator is shown schematically in Figure 3.

Concentration measurement using the flow separator is functionally similar to the isokinetic sampling technique, where the flow from an entire subchannel is withdrawn and mixed until the sample concentration is uniform throughout. The real time mixing of flow within the flow separator device makes its use particularly attractive during flow transient tests.

During the next quarter, design of the flow separator device, additional bundle modifications required for mounting, and the computerized data acquisition and recording system, will be initiated.

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

(R. Anoba and C. Chong)

No work was performed this quarter.

TASK ID: Analytical Methods Development

No work was performed this quarter.

FIGURE 1- MASS BALANCE VS. BUNDLE FLOWRATE

Figure 2.

FIGURE 3. FLOW SEPARATOR DEVICE

<u>Wire-Wrap Lead</u>	<u>Flow Regime</u>	<u>Circumferential Distance</u>	$\frac{V_{\text{SWIRL}}}{V_{\text{SUB}}}$	$\frac{V_{\text{SWIRL}}^*}{V_{\text{AVERAGE}}} = C_1$	<u>Wire-Wrap Velocity Ratio**</u>
6"	Turbulent	4.43"	0.185	0.202	.165
6"	Laminar	3.27"	0.136	0.170	.165
12"	Turbulent	2.64"	0.110	0.120	.083
12"	Laminar	1.79"	0.075	0.094	.083

* Based on $\frac{V_{\text{SUB}}}{V_{\text{AVERAGE}}}$ of 1.09 and 1.25 for turbulent and laminar flow regimes, respectively where V_{SUB} is the edge channel. Recall that if the flow split of 1.00 is utilized for turbulent flow as suggested by analyses of A. Bishop, then column 4 also equals C_1 .

** Wire-Wrap Velocity Ratio $\equiv \pi \times \text{ROD PITCH} / \text{WIRE-WRAP LEAD}$

TABLE 1

Apparent Experimental Swirl Velocities

TASK II: SUBCHANNEL GEOMETRY (BARE RODS)

TASK IIA: Assessment of Available Data

No new data was published in the literature which could be assessed this quarter.

TASK IIB: Experimental Investigation (Joseph M. Kelly)

After a search for very accurate pressure transducers and an attempt to use incline manometers we ordered the Datametrics "Electric Manometer" at the beginning of December. Delivery was originally planned for mid-January, however, a delay on the part of the supplier of the diaphragms will postpone it to mid-February.

While waiting for this instrument, the sampling loop for point concentration measurements was built and will be tested during January in order to trouble-shoot the procedure. Actual point data cannot be taken without the pressure system but the rest of the setup can be operated in order to find the potential problem areas as soon as possible.

The computer program for our data reduction has been written and debugged. In the program, the diversion crossflow is assumed to be independent of axial position for each of the two mixing sections and is calculated for each of these sections along with the natural mixing. Since axial independence is not a reality, the computed results will have an unknown accuracy. One possible method of checking this would be to check the dye concentrations at many axial locations instead of just two. Due to a lack of time it is impractical for me to attempt this, however, it is a possibility for future work.

Upon arrival of the pressure transducer, data acquisition should begin. It will last about 6 weeks followed by the analysis and write-up which should be completed in May.

TASK IIC. Experimental Subchannel Local Parameter Measurements (Laser Doppler Anemometer)

TASK IID. Analytic Model Development - Subchannel (John Bartzis)

Previous work in this area by Pedro Carajilescov (summary in ASME paper included as Appendix to Quarterly Progress Report COO-2245-15) initiated experimental and analytic studies of the flow field in a simulated interior subchannel. Measurements were taken with an LDA and a one equation turbulence model was formulated. During this report period the desirable extensions to Carajilescov's work were assessed in detail and a definitive statement of the scope of future work was prepared. Additionally efforts were initiated to prepare the experimental apparatus and develop the desired numerical code to solve the momentum and energy equations in the geometry of interest. These efforts are described in detail in the following paragraphs.

1.0 Introduction

Heat transfer within the rod bundle of a nuclear reactor is of major importance in nuclear reactor design. The temperature field affects the mechanical and physical behavior of the reactor materials such as fuel and clad. Thus, the temperature directly or indirectly imposes a limit on the thermal power produced by the fuel element. Especially in the LMFBR, the clad temperature is one of the significant design limits. Thus a detailed knowledge of the temperature within the fuel element and especially in the clad region is very important. However this knowledge can only be obtained by determining the detailed hydrodynamic behavior of the coolant which is the most difficult part of the problem due to the complexity of the turbulence phenomena.

1.1 Assessment of Existing Methods for Rod Bundle Analysis

The methods which yield the detailed knowledge of the hydrodynamic (and/or thermal) behavior of the rod bundle are called Distributed Parameter (DP) Techniques. The DP techniques with respect to flow, as presently formulated, are restricted to fully developed flow and bare rod bundles which correspond to special cases in a reactor such as nearly incompressible flow in an interior subchannel far away from disturbances.

The advantages of such a simplified case are evident, i.e.

1. Low computer time, since the problem becomes 2-dimensional and the solution is limited to a characteristic triangle (Figure 1).
- 2) Easier modeling of turbulent quantities. For example, the eddy diffusivity and near wall velocity, as we will see later.

In addition such a simplified case is a powerful tool for understanding phenomena such as shear stress distribution and heat transfer coefficient along the periphery of the rod, secondary flow effects and thermal exchange coefficients between subchannels. Such information can be used for improving the solution from Lumped Parameter Techniques (LP) in which the properties are lumped over a characteristic region of the core (subchannel, bundle, etc.). Parenthetically it is noticed here that the LP techniques are the only practical tool for obtaining energy and flow information for the whole reactor core.

It is evident that any attempt to use a DP technique for analysis of a rod bundle or a reactor will have to cope with the following problems:

1. Modeling of the turbulent flow in 3-dimensions.
2. Very long computer time (which is the most severe difficulty).

The modeling of the turbulent flow in 3-dimensions can be done by using the turbulent equation models which recently have been used for a quite large variety of flow problems. However the requirement for very long computer time will be a persistent difficulty. Because of this constraint a 3-D DP technique can be most beneficially useful in design when it is applied "locally" at regions where one is interested in detailed information (e.g. hot spot, blockage) with boundary conditions supplied by an LP technique.

Of course we do not underestimate the difficulty of transforming LP boundary conditions into DP ones but it can be done at least approximately. Such an approximation becomes less restrictive as the local region becomes bigger. The reason is that the further from the boundary, the less the influence of the boundary and consequently the less significant are errors in the boundary conditions.

So it is evident from the above discussion that there is a need for developing to 3-D DP techniques which can be applied in a local region of interest. One of the simplest cases that does not require an LP solution is the study of the entrance region of a channel of an infinite triangular array of a bare rod bundle. Beside the engineering interest of such a case, this work will also help us to understand some of the problems related to the 3-D DP techniques.

However, it is better before going to a turbulent analysis of the developing region of the channel, to fully understand the 2-D fully developed flow case. With respect to the latter, a large amount of work has appeared in recent years in the open literature.

As a result of this work one can claim that quantities such as velocity and mean shear stress can be predicted with a good accuracy from an engineering point of view. However, values for quantities such as Reynolds stresses, eddy viscosity, circumferential shear stress distribution and especially secondary flow are much more uncertain. Such uncertainties are related of course with the difficulty of obtaining accurate enough experimental results. Especially in the case of secondary flow, satisfactory experimental results do not exist. It is noticed here that a better understanding of above quantities is closely associated with the turbulent structure of the flow so that the turbulent equation models are the most appropriate ways for studying those quantities. It is worthwhile recalling here that among the existing methods of turbulence, only the turbulence equation models can predict secondary flow.

From the above discussion one can draw the following conclusions:

1. The 3-D DP techniques can be used for obtaining a detailed solution in a local region of interest in the reactor core. The most appropriate methods with respect to modeling turbulence appear to be the turbulent equation models.
2. Such models can predict quantities closely related to the turbulence such as Reynolds stresses, eddy viscosity and secondary flow more easily and correctly compared with the other existing methods.
3. A useful first step towards the utilization of 3-D DP techniques can be their application to the developing region of a channel of an infinite triangular array of a bare rod bundle, a problem of a great interest from an engineering point of view.
4. This problem will be considered in this work. However, before going into the developing region, an accurate knowledge of the fully developed flow predicted by turbulent equation models is necessary.

So our problem can be defined in 2 stages:

1st stage: Obtain, through experimental and analytical work, a good prediction of the hydrodynamic behavior of the channel through a turbulence equation model in fully developed flow.

2nd stage: Use the above information and extend into the developing region.

The detailed problem related to this work is defined below.

1.2 Problem Definition

1.2.1 Experimental Work

Recently P. Carajilescov [1] has used a 1-equation model to predict the hydrodynamic properties of the infinite rod bundle in fully developed flow. The model is based on his experimental results performed in a duct whose cross-section is shown in Fig. 2 with pitch ratio (P/D) equal to 1.123, Reynolds number $Re=27,000$, and distance from the entrance $L=77$ times the hydraulic diameter, D_H (i.e. $L/D_H=77$). For his measurements, a Laser Doppler Anemometer (LDA) has been used with water as the working fluid. His test section as is shown in Figure 3 is composed of three sections, one of which is provided with windows through which the laser beam penetrates the flow. The test section at the window is shown in Figure 4. The interchange of the three sections permits measurements to be performed at positions $\frac{L}{D_H} = 15, 46$ and 77 .

A closer look at the above experimental work leads to the following observations:

1. The measurement of the Reynolds stresses were performed by measuring one velocity component at a time rather than performing simultaneous measurements for both velocity components. As a result, relatively large errors were introduced. Therefore, the simultaneous measurements of the two velocity components for the Reynolds stresses seem necessary.

2. Application of his theoretical model which will be discussed later, to both his data and Kjellstrom's experiments data [2] for which $P/D=1.217$ and $Re=1.49 \times 10^5$ show that the constants introduced to the model should be a function of the Reynolds number and possibly P/D . On the other hand the $Re=27,000$ was too low to permit measurement of the secondary flow with the available LDA equipment. Therefore, experimental data for at least one Reynolds number much higher than 27,000 is necessary as well as experiments in other P/D geometries.

3. At the position $\frac{L}{D_H} = 77$ where the measurements have been performed, there is suspicion that the flow may not be fully developed. So an increase of L/D_H seems necessary together with taking measures to reduce as much as possible the length of the developing region. Such a measure can be the entrance region configuration.

4. The analytical model to be developed is to be valid for the whole channel. So complete measurements are necessary for the

developing region as well.

From the above discussion, it is clear that the following experimental work should be performed:

1. Improve the test section used for P. Carajilescov's work [1] by extending it and by improving the entrance region so that the fully developed flow will be achieved.
2. Perform simultaneous measurements of the two velocity components for the Reynolds stresses.
3. Obtain experimental data for the developing region as well.
4. Repeat all above experiments for a higher Reynolds number and seek detection of secondary flow at this higher Reynolds number. A Reynolds number of 100,000 has been selected after taking into consideration our desire to make it the highest possible while maintaining a reasonable size of water pump and reasonable loop expenses.
5. Measure the wall shear distribution along the periphery of the rod in the fully developed and the developing region. However due to the large amount of work such an experiment will not be performed by the present author. It will rather be a topic for an MS thesis.
6. Repeat all measurements in another P/D geometry. Hopefully other experimentors will do this in parallel tests. Our work will utilize only one P/D for the near future. Future efforts will be applied to edge and corner channel geometries rather than another interior subchannel P/D.

Table 1 shows in more detail, the quantities to be measured in this work.

1.2.2 Analytical Work

1.2.2.1 Turbulence Model

In [1] the 1-equation model (i.e. transport equation for turbulent kinetic energy) is used. The eddy viscosity is taken isotropic for both radial and tangential direction given by the relations

$$\nu_{rz}^T = \nu_{\theta z}^T = c_\nu k^{1/2} l \quad (1.1)$$

where ν^T is the eddy viscosity

k the turbulent kinetic energy

and l a length scale given by an empirical relation based on experimental data of Ref. 1.

From the analytical work related to the turbulent model approach, the following observations can be made:

1. Comparison between the theoretical and experimental results show that the analytical model tends to overestimate the Turbulent Kinetic Energy (TKE) and the axial velocity in the central regions for small angles and overestimate the TKE near the wall. Such a behavior might lead to the following conclusions:

a. The introduced constants are spatially dependent. A higher equation model (e.g. 2-equation) could decrease such a dependence.

b. A better representation of the wall region might be necessary.

c. Since the model we are going to use has to be extended to the developing region, a 2-equation model at least seems preferable rather than inventing a 3-D empirical relation for length scale for this case.

2. The eddy viscosity has been taken as isotropic. Experiments, however, have shown that eddy viscosity in the tangential direction is on the average 2-3 times higher than the eddy viscosity in the radial direction [3,12].

Under these circumstances our analytical work with respect to the turbulence modelling will be:

1. Use 2-equation model as well as the 1-equation model and try to fit the present experimental data. Examine the effect of the Reynolds number.

2. In the literature [4] empirical expressions based on experimental data are given for turbulent kinetic energy in closed channels in the fully developed flow. Taking into consideration the simplicity of such a model, it will be interesting to compare this model (we will call it 0-equation model) with the models and data from 1. above.

3. To be consistent with the experimental observations a model taking into consideration the non-isotropic nature of the eddy viscosity has to be used.

4. If the time permits, initiate work on the developing region.

5. Include the energy equation into above turbulent models and make a one or multi region heat transfer calculation which will enable prediction of the clad temperature and clad coolant heat transfer coefficient.

These thermal predictions will be compared to existing experimental and analytical data.

1.2.2.2 Numerical Work

The solution of the problem of fully developed flow in the infinite array of a bare rod bundle in Ref. 1 is obtained in terms of axial velocity v_z , turbulent kinetic energy k , whereas the secondary flow is obtained through its vorticity ω and stream function ψ . The vorticity is the "natural" parameter of studying the secondary flow since the existence of secondary flow is attributed to the vorticity source.

The numerical procedure is based on that proposed by Gosman et al [5] which consists of solving a set of non-linear difference equations with non-negative coefficients by the method of successive displacements [6].

The author's experience with such a computer code and the ψ, ω model in general [10] using the Gosman et al procedure is as follows:

1. The non-linear boundary conditions and the sharp gradients for the vorticity at the walls are the main sources for numerical instability and slow rates of convergence which makes the use of the code more difficult.

The strong dependence of the rate of convergence and instability on the Reynolds number and P/D increases the difficulties of obtaining good solutions. It is worth noticing here that D. Naot et al [8] working on the secondary flow of the square duct, could not succeed in obtaining convergence for $Re > 200,000$ and the reason for that was attributed to a group of parameters including vorticity. Therefore the use of the vorticity as an unknown in the difference equation should be abandoned. This can be done by using v_r , v_θ , and pressure p as unknowns in which the boundary conditions for v_r and v_θ at the wall are linear and are expected to have better behavior with respect to instability.

2. The computer time increases rapidly with the number of grid points. This fact, plus the nonlinearity is associated with the nature of the difference equations and the method of successive displacements.

The difference equations are usually of the form

$$\phi_{i,j} = c_1 \phi_{i-1,j} + c_2 \phi_{i+1,j} + c_3 \phi_{i,j-1} + c_4 \phi_{i,j+1} \quad (1.2)$$

where

$$\begin{aligned} \sum_{n=1}^4 c_n &= 1 \quad \text{for interior points} \\ \sum_{n=1}^4 c_n &\leq 1 \quad \text{for boundary points} \end{aligned} \tag{1.3}$$

c_n 's are positive numbers and usually change from iteration to iteration.

Let us assume for a moment that the c_n 's are constants, so the equations (1.2) are linear. The iteration matrix for the successive displacement method, because it is a positive matrix [6], has its largest eigenvalue real which determines the rate of convergence.

If eq. (1.3) would hold for all points, then the largest eigenvalue is equal to 1 (ref. 6, p. 123). The convergence of the linear equations (1.2) is obtained due to existence of the boundaries where the sum of c_n 's is less than unity (i.e. convergence).

However, as we increase the mesh points we increase the size of the iteration matrix by introducing elements obeying the first equation of (1.3). So the "importance" of the boundary conditions relative to establishing the value of the largest eigenvalue is reduced and this eigenvalue becomes closer to one, i.e. the rate of convergence is reduced.

If one takes into consideration that in the Laplace equation eq. 1.2 and 1.3 hold, it is reasonable to assume that the rate of convergence for a linear problem of the type (1.2) is expected to behave as in the case of Laplace equations, i.e. proportional to the inverse of the number of mesh points. The non-linearity of eq. (1.2) which is a source for instability is expected to decrease at an even lower rate. Therefore more efficient numerical techniques are needed. On the other hand, in order to reduce the number of the necessary grid points we have to increase the accuracy of the difference equations, i.e. to improve the truncation error.

Recently a new code TEACH [11] has been developed at Imperial College, treating the 2-equation model with transport equations for turbulent kinetic energy k and energy dissipation ϵ for 2-dimensional flow in a duct which is quite different from our case from a geometry point of view. However, it can be modified to our case.

In the numerical approach in [11] the successive displacement has been performed only in the one direction whereas in the other

direction matrix factorization technique is used [Ref. 7, p.55-58].

So the numerical work can be summarized as follows:

1. Use the TEACH code and modify it to solve the problem of the fully developed flow in a triangular channel of an infinite bare rod bundle.

It is worth noting here that TEACH [11] code appears to have some drawbacks related to the convergence criteria and the accuracy of the finite difference equations which can be improved. Therefore improvements related with above problems and others which may appear in the future will be performed. Care will be taken also to improve the truncation error of the difference equations. Progress on the resolution of these problems will be reported in later progress reports.

2.0 Experimental Work

2.1 Test section

2.1.1 Test section characteristics

The test section to be used in the present work, as we mentioned before is basically the same used by P. Carajilescov [1]. The cross section shown in Figure 2 has the following characteristics.

Characteristic Triangle					Test-Section	
Pitch (in) $\underline{P}$	Rod Diam (in) $\underline{D}$	Pitch ratio $\underline{P/D}$	Hydraulic Diameter (in)	Area (in ²)	Hydraulic Diameter (in)	Area (in ²)
2.2617	2.014	1.123	0.787	0.1037	0.641	2.074

2.1.2 Improvements

Improvements to the test section have been designed and are listed below.

- 1) Extention of the test section so the parameter L/D_H will be increased. This is obtained by building a new section similar to

those shown in Figure 3. The length of the section is estimated to be 28" which means that the measurements will be able to be performed at $L/D_H=113$ instead of $L/D_H=77$ obtained in [1].

2) Addition of an entrance region as shown in Figure 5. The entrance region is necessary:

a) To suppress undesired turbulence coming from the piping system. Such turbulence, the decay of which is roughly proportional to the inverse of the square of the eddy size, increases the entrance length. Thus the entrance region, by killing the pipe turbulence reduces the entrance length.

b) To provide approximately uniform mean flow with negligible turbulent intensity. Such inlet conditions can be applied easily in an analytical model studying the developing region of the channel.

The entrance region as shown in Figure 5 includes a honeycomb. The purpose of the honeycomb is to transform inlet turbulent flow to a laminar field. Our honeycomb will consist of coffee stirrers (cell hydraulic diameter $D_F \approx 1.5$ mm)

The Reynolds number within the cell is given by the relation

$$Re_L = \frac{Q \cdot D_F}{\sigma A v} < 2.000; \quad \sigma = \frac{A'}{A} \quad (2.1)$$

where

A, A' :	areas shown in Figure 5
Q :	the flow rate
v :	the water kinematic viscosity
D_F :	hydraulic diameter of the cell
Re_L :	Reynolds Number within the cell (laminar)
	(Re_L has been estimated to be around 1800 for $Re=100,000$)

The test section extension and entrance configuration are being fabricated.

2.2 Hydraulic Loop

Hydraulic loop: An upgraded loop is designed based on the loop used in [1] to meet the additional requirements noted below:

1. Higher flow rate in order to obtain a Reynolds number of order 100,000. Such a requirement introduces changes in the pump power, pipe and flow meter size.

2. Removal of the heat which is generated due to friction losses within the loop necessitating the addition of a heat exchanger.

The loop design is shown in Figure 6. Materials for the loop construction have been ordered.

3.0 Analytical and Numerical Work

A new program based on TEACH [11] applicable to the geometry of Figure 1 is under development. The program will include the following options:

1. A turbulent model where the eddy diffusivity is given by semi-empirical expressions. The model of Eifler and Nijssing [14] which seems to be the most advanced among these models since it includes secondary flow effects has been selected.
2. 0-equation model.
3. 1-equation model.
4. 2-equation model.

All above models will be described in detail in later reports.

With respect to the eddy viscosity the program includes the option of isotropic and non-isotropic viscosity.

References

1. P. Carajilescov, "Experimental and Analytical Study of Axial Turbulent Flows in an Interior Subchannel of a bare rod bundle", MIT, Department of Nuclear Engineering, PhD Thesis, April 1975. Also COO-2245-19TR.
2. B. Kjellstrom, "Studies of Turbulent Flow Parallel to a Rod Bundle of Triangular Array", Report AE-RV-196, A B Atomenergi, Sweden, 1971.
3. R. Nijssing and N. Eifler, "Temperature Fields in Liquid-Metal-Cooled Rod Assemblies", Progress in Heat and Mass Transfer, Vol. 7, Pergamon Press, 1973.
4. V. P. Bobkov, M. Ch. Ibragimov and G. I. Sabelev, "Correlation of Experimental Data on the Pulsation velocity intensity for Turbulent Fluid Flow in Channels of Different Form", 12v. AN SSSR, Mekhanika Zhidkosti i Gaza, Vol. 3, pp. 162-165 (English Translation).
5. Gosman, A. D. et al., "Heat and Mass Transfer in Recirculating Flows", Academic Press (1969).
6. M. Clark and K. F. Hansen, "Numerical Methods in Reactor analysis", Academic Press, 1964.
7. E. Isaacson and H. B. Keller, "Analysis of Numerical Methods", John Wiley and Sons, 1966.
8. D. Naot, A. Shavit and M. Wolfshtein, "Numerical Calculation of Reynolds Stresses in a square duct with Secondary Flow", Warme-und Stoffubertragung 7 (1975), p. 151-161.
9. Brundrett, E. and Baines, W. D., "The Production and Diffusion of Vorticity in Duct Flow", J. Fluid Mechanics, Vol. 19 (1964), pp. 375-394.
10. J. G. Bartzis, "Partially Blocked Flow between Parallel Plates", Euratom Internal Report, Ispra, 1975.
11. A. D. Gosman, "Listing of the TEACH-T Computer Program and Sample output", The Pennsylvania State University, August 1975.
12. Elder, J. W., "The dispersion of worked fluid in Turbulent shear flow", J. Fluid Mech. 5, 544-61 (1959).
13. R. Nijssing, W. Eifler, B. Delfau, "Lateral Turbulent Diffusion for Longitudinal Flow in a Rectangular channel", Euratom Internal Report, Ispra, 1974.

References (continued)

14. R. Nijssing, "Heat Exchange and Heat Exchangers with Liquid metals", AGARD No. 57, 1972.

MEASUREMENTS		Re = 27,000				Re = 100,000			
		$L/D_H^{(1)}$				$L/D_H^{(1)}$			
		113	77	46	15	113	77	46	15
Axial Velocity	$\bar{v}_z$	x	x	x	x	x	x	x	x
Reynolds Shear Stresses	$\overline{v'_r v'_z}$	x	x	x	x	x	x	x	x
	$\overline{v'_\theta v'_z}$	x	x	x	x	x	x	x	x
Reynolds Normal Stresses	$\overline{v'^2_r}$	x	x	x	x	x	x	x	x
	$\overline{v'^2_\theta}$	x	x	x	x	x	x	x	x
	$\overline{v'^2_z}$	x	x	x	x	x	x	x	x
Turbulent Kinetic Energy	k	x	x	x	x	x	x	x	x
Wall shear stress distribution	$\tau_w(\theta)$	0	0	0	0	0	0	0	0

x Experiment performed or to be performed in the present work

0 Experiments to be performed by other investigator (as a M.S. thesis)

(1) Lengths based on 28" extension of the test section

Experiments to be repeated (i.e. experiments already performed by P. Carajilescov but with a single-component measurement for Reynolds stresses)

TABLE 1. Experimental Work to be Performed

Figure 1. Characteristic triangle for the study of fully developed flow in an infinite triangwave array of bare rods

Figure 2. Cross-Section of Test Section [1]

Figure 3. Test Section Used in [1]

Figure 4. Design of Test Section Windows

Figure 5. Entrance region

Figure 6. The hydraulic loop

TASK III: LMFBR OUTLET PLENUM FLOW MIXING

TASK IIIA: Analytical and Experimental Investigation of Velocity and Temperature Fields (Y.E. Chen, Ralph Bennett)

In this task, which is concerned with the development of design methods for use in characterizing the flow distribution in the LMFBR outlet plenum, there are parallel analytical and experimental efforts. The experimental work is concerned with measurements of the turbulent velocity and temperature fields in the outlet plenum geometry, and the analytical work with determination of the best turbulence model for use in design calculations.

III.1 Theoretical Work (Y.B. Chen)

Two turbulence model computer codes are being used in the project, TEACH-T1 and VARR-II². The former code has been made operational at MIT for approximately six months, and the latter for about one month.

A series of calculations using TEACH-T has been performed during the past quarter examining the results to be expected in the water velocity experiments over a range of inlet Reynold's numbers (5000 to 100,000) in the 1/15-scale FFTF outlet plenum model. It is observed that the spatial distributions of velocities, Reynold's stress, and eddy diffusivity are insensitive to the value of the Reynold's number. The distributions presented in the previous progress report are observed typically.

The code VARR-II has been run remotely on the ERDA-owned CDC 7600 computer via the DOD Advanced Research Projects Agency (ARPA) network at the University of California-Berkeley. This has been possible only with the generous cooperation of the computer staff of the Laboratory for Nuclear Studies at MIT, who worked for six months with project staff to establish this remote computing capability. The current status of this effort is that the VARR-II version stored on disc at Berkeley is retrievable from MIT, and has been compiled successfully. However, execution errors have arisen which are currently being resolved.

The goal in using both of these codes is to permit inter-comparison of their results and to permit evaluation of their

accuracy in predicting the results of the experiments.

Experimental Effort: In the experimental work two parallel developments - concerned with velocity field measurements and with temperature measurements - have been carried on. In both cases the experiments are performed in a two-dimensional geometry which matches the transverse dimensions of the ANL 1/15-scale FFTF outlet plenum test cell. The two-dimensional cartesian geometry was chosen because the optical velocity and temperature measurement techniques are difficult to use when the light beams must penetrate a curved boundary, or when a thick flow section is used (as with a cylindrical drum). Thus, the experiments are performed in a thin cartesian-geometry section as shown. This also avoids the problems of azimuthal asymmetry in the flow field, which would be expected in the cylindrical geometry due to the use of discrete (although symmetrical) outlet nozzles.

III.2 Velocity Field Measurements (Y.B. Chen)

In August, 1975 the project's MK I³ laser doppler anemometer system was replaced by a MK II⁴ system, purchased from DISA Electronics. This was done in order to have a single system which would be capable of performing two-velocity component measurements simultaneously, on both forward and back-scattered modes. Such a system is required if the same set of instrumentation is to be used for all of the tasks funded under this contract. The past quarter has been spent trying to get the new measurement system (see Fig. 1) operational for the outlet plenum test cell velocity measurements. With a lot of effort from the project staff and from vendor personnel this was accomplished at the end of the quarter. At about that time also the experimental test cell began leaking seriously, and a new cell is currently being fabricated (see Fig. 2). The new test cell is designed to permit variable cell geometries to be tested, by inserting plastic blocks to vary the geometric ratios of the cell dimensions.

III.3 Temperature Measurements (Ralph Bennett)

The ability to measure turbulent temperature fluctuations in two dimensional flows has been developed in work reported previously, using a Mach-Zehnder Interferometer (see Fig. 3). During the past quarter this capability was exercised in performance of power spectral density measurements of the flow temperature turbulence.

As has been indicated previously the need exists in turbulent temperature measurements for non-intrusive, fast response measurement methods. Recent development of fast response thermocouples for use in liquid metals⁵ also points to this need. The most recent measurements illustrate the capabilities of the optical method which has been developed.

The measurements were performed in the test cell shown in Fig. 4 in which co-flowing air streams at different temperatures enter the 1/15-scale FFTF outlet plenum model cell; and then mix in steady state. Some representative results of these measurements are shown in Figs. 5 and 7.

The data of Fig. 5 were taken at a point, shown in Fig. 4, 2 1/4 in. above the inlet flow divider. This measurement point is characterized by high shear and turbulence, as is evident in the data of Fig. 6 which shows typical temperature fluctuation data observed at that point. In Fig. 5a is shown the total temperature signal spectrum at the point of measurement, and in Fig. 5b is shown the flow-associated turbulence spectrum (obtained by subtracting the background signal). It is seen that the background is primarily a low frequency noise, and that the flow-associated turbulence has a median frequency of 1600 Hz, with a frequency bandwidth of approximately 2300 Hz. For this flow the inlet Reynolds number is 5000; however, the observed turbulence is due to the wake-effect in the flow downstream from the inlet flow divider, and -- more importantly -- to flow slip between the hot and cold inlet streams due to expansion of the warm fluid during heating.

The data shown in Figs. 7 and 8 were taken at a point displaced approximately 0.5 in. radially outward from the measurement point for the data of Figs. 5 and 6. It is seen from both the temperature signal output (Fig. 8) and the turbulence spectrum that the fluctuations observed in this case are much less intense, with a median frequency of 1400 Hz and a frequency bandwidth of 1500 Hz; both of which characterize the flow at this point as being much less turbulent than at the former point. This is due to moving the measurement point out of the wake, slip-flow region which characterizes the former data.

Finally it is observed in Figs. 7a and 9 that the naturally convective flow pattern in this plenum (obtained with the fan turned off, as the plenum cools-down) is characterized by low flowrates and very low frequency oscillations.

All of these results serve to demonstrate the power of this measurement tool, and to point in the directions in which it will be applied in the future -- in providing measurements of the statistical thermal parameters in the outlet plenum flow.

Administrative Item

The paper "Development of an Optical Method for Measurement of Temperature Fluctuations in Turbulent Flows" by Ralph Bennett and Michael W. Golay, arising from work in this project was presented at the meeting of the American Nuclear Society in San Francisco, California, November 16-20, 1975.

References

1. A. D. Gosman, Listing of the TEACH-T Computer Program and Sample Output, Penn. State Univ. (1975).
2. J. L. Cook and P. I. Nakayama, VARR-II Computer Program for Calculating Time Dependent Turbulent Fluid Flows with Slight Density Variation, WARD-D-0106, Westinghouse Electric Co. (1975).
3. Scientific Research Equipment Catalog, DISA Electronics, Franklin Lakes, N. J., 3 (1975).
4. Scientific Research Equipment Catalog, DISA Electronics, Franklin Lakes, N. J., 10 (1974).
5. H. Bunschi and W. Seifritz, A Fast-Response Thermocouple for Temperature Fluctuation Measurements in Sodium Coolants, Nuclear Technology, 27, 523 (1975).

Fig. 1. Mark II Laser Doppler Anemometer System
Set-up For Simultaneous Two-Component
Velocity Measurements

Fig. 2. Variable Geometry Outlet Plenum Test Cell

Figure 1.

Fig. 3. Mach-Zehnder Interferometer System
Set-up For Turbulent Temperature
Measurement

Fig. 5a. Uncorrected High Shear Region Turbulent Temperature Spectral Density at Various Temperature Upset Values

Fig. 5b. Corrected High Shear Region Turbulent Temperature Spectral Density at Various Temperature Upset Values, Background Signal Subtracted From Total Signal

Fig. 6. Typical High Shear Zone
Temperature Data, Re = 5000

Fig. 7a. Uncorrected Low Shear Region Turbulent
Temperature Spectral Density at Various
Temperature Upset Values

ENHANCEMENT OF SPECTRAL DENSITY

Fig. 7b. Corrected Low Shear Region Turbulent Temperature Spectral Density at Various Temperature Upset Values, Background Signal Subtracted From Total Signal

Fig. 8. Typical Low Shear Zone Temperature Data, $Re = 4400$

FLUCTUATING TEMPERATURE

(°F; arbitrary zero)

Fig. 9. Typical Natural Convective Flow Temperature Data, No Forced Convective Inlet Flow, Test Cell Cooling Down