COOLANT MIXING IN LMFBR ROD BUNDLES AND

OUTLET PLENUM MIXING TRANSIENTS

Progress Report

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ABSTRACT

MEASUREMENT OF HEAT AND MOMENTUM EDDY DIFFUSIVITIES

IN RECIRCULATING LMFBR OUTLET PLENUM FLOWS

by

Vincent P. Manno

and

Michael W. Golay

An optical technique has been developed for the measure-
ment of the eddy diffusivity of heat in a transparent flowing
medium. The method uses a combination of two established
measurement tools: a Mach-Zehnder interferometer for the
monitoring of turbulently fluctuating temperature and a Laser
Doppler Anemometer (LDA) for the measurement of turbulent
velocity fluctuations. The technique is applied to the investi-
gation of flow fields characteristic of the LMFBR outlet plenum.
The study is accomplished using air as the working fluid in a
small scale Plexiglas test section. Flows are introduced
into both the 1/15 scale FFTF outlet plenum and the 3/80
scale CRBR geometry plenum at inlet Reynolds numbers of
22,000.

Measurements of the eddy diffusivity of heat and the
eddy diffusivity of momentum are performed at a total of 11
measurement stations. Significant differences of the
turbulence parameters are found between the two geometries,
and the higher chimney structure of the CRBR case is found to
be the major cause of the distinction. Spectral intensity
studies of the fluctuating electronic analog signals of
velocity and temperature are also performed. Error analysis
of the overall technique indicates an experimental error of
10% in the determination of the eddy diffusivity of heat
and 6% in the evaluation of turbulent momentum viscosity.
In general, it is seen that the turbulence in the cases
observed is not isotropic, and use of isotropic turbulent heat
and momentum diffusivities in transport modelling would not be
a valid procedure.

Reports Issued Under This Contract

B.   Topical Reports (Available from National Technical
                          Information Service, U.S. Depart-
                          ment of Commerce, Springfield,
                          VA 22151)

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,
September 1973.

E. Khan, W. Rohsenow, A. Sonin and N. Todreas, "A
Simplified Approach for Predicting Temperature Distri-
bution 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 Assem-
blies", 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,
September 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 an
LMFBR", COO-2245-16TR, MIT, June 1975.

E. Khan, W. M. Rohsenow, A. Sonin, N. Todreas, "Input
Parameters to the ENERGY Code (To be used with the
ENERGY Codes 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.

E. Khan, W. Rohsenow, A. Sonin, N. Todreas, "Manual for
ENERGY Codes I, II, III Computer Programs", COO-2245-18TR,
Revision I, MIT, July 1976.

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

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

B.   <u>Topical Reports (Continued)</u>

B. Chen and N. Todreas, "Prediction of Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer", COO-2245-20TR, Rivision I, MIT, December 1976.

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

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 Buncles and Outlet Plenum Mixing Transients, COO-2245-24TR, MIT, August 1975.

B. Bosy, "Fabrication Details for Wire Wrapped Fuel Assembly Components", COO-2245-27TR, MIT, November 1975.

Ralph G. Bennett and Michael W. Golay, "Interferometric Investigation of Turbulently Fluctuating Temperature in an LMFBR Outlet Plenum Geometry", COO-2245-29TR, MIT, June 1976.

N. E. Todreas, "Thermal Analysis Methods for LMFBR Wire Wrapped Bundles", COO-2245-32TR, MIT, November 1976.

K. L. Basehore and N. E. Todreas, "Development of Stability Criteria and an Interassembly Conduction Model for the Thermal-Hydraulics Code SUPERENERGY", COO-2245-33TR, MIT, December 1976.

Robert Masterson and Neil E. Todreas, "Analysis of the Feasibility of Implementing an Implicit Temporal Differencing Scheme in the SUPERENERGY Code", COO-2245-35TR, MIT, February 1977.

S. Glazer, C. Chiu and N. Todreas, "Collection and Evaluation of Salt Mixing Data with the Real Time Data Acquisition System", COO-2245-36TR, MIT, April 1977.

B. Mikic, E. U. Khan and N. E. Todreas, "An Approximate Method for Predicting Temperature Distribution in Wire Wrapped Fuel Assemblies of an LMFBR", COO-2245-37TR, MIT, April 1977.

C. Chiu and N. Todreas, "Development of a Technique for Subchannel Flow Rate Measurements in LMFBR Wire Wrapped Assemblies", COO-2245-39TR, July 1977.

B.   <u>Topical Reports (Continued)</u>

C. Chiu and N. Todreas, "WARD Blanket Assembly Pre-Test Predictions by SUPERENERGY", COO-2245-40TR, MIT, May 1977.

C. Chiu, N. Todreas, W. M. Rohsenow, "Flow Split Measurements in LMFBR Blanket Assemblies", COO-2245-41TR, MIT, April 1978.

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, "Mising Experiments in LMFBR Wire Wrapped Blanket Assemblies", COO-2245-43TR, April 1978.

Yi Ben Chen and Michael W. Golay, "Coolant Mixing in the LMFBR Outlet Plenum", COO-2245-44TR, June 1977.

J. Kelly and N. Todreas, "Turbulent Interchange in Triangular Array Bare Rod Bundles", COO-2245-45TR, July 1977.

K. L. Basehore and N. E. Todreas, "Assessment of the Need to Incorporate a Variable Swirl Flow Model into the ENERGY Code", COO-2245-46TR, July 1977.

K. L. Basehore and N. Todreas, "Analysis of the Thermal-Hydraulic Behavior in the CRBR Secondary Control Assembly, Including Interassembly Heat Transfer Effects", COO-2245-47TR, July 1977.

J. G. Bartzis and N. E. Todreas, "Hydrodynamic Behavior of a Bare Rod Bundle", COO-2245-48TR, MIT, June 1977.

M. R. Fakori-Monazah and N. E. Todreas, "Measurement and Analysis of Flow Wall Shear Stress in an Interior Subchannel of Triangular Array Rods", COO-2245-49TR, MIT, August 1977.

A. S. Hanson and N. E. Todreas, "Fluid Mixing Studies in an Hexagonal 61-Pin, Wire-Wrapped Rod Bundle", Coo-2245-51TR, MIT, August 1977.

S. Glaser, N. Todreas, W. Rohsenow, and A. Sonin, "TRANSENERGY S,M - Computer Codes for Coolant Temperature Prediction in LMFBR Cores During Transient Events", To be issued as COO-2245-52TR, MIT.

C. Chiu, W. M. Rohsenow, and N. E. Todreas, "Mixing Experiments in an Alternating Wire Wrapped Assembly", COO-2245-54TR, MIT, December 1977.

B. <u>Topical Reports (Continued)</u>

C. Chiu, W. M. Rohsenow and N. E. Todreas, "Turbulent Sweeping Flow Mixing Model for Wire Wrapped LMFBR Assemblies", COO-2245-55TR, MIT, April 1978.

C. Chiu, W. M. Rohsenow and N. E. Todreas, "Flow Split Model for LMFBR Wire Wrapped Assemblies", COO-2245-56TR, MIT, April 1978.

K. Basehore and N. E. Todreas, "SUPERENERGY: Multiassembly Thermal-Hydraulic LMFBR Code", To be issued as Topical Report COO-2245-57TR, Department of Nuclear Engineering, MIT.

C-N. Wong and L. Wolf, "A 3-D Slug Flow Heat Transfer Analysis of Coupled Coolant Cells in Finite LMFBR Bundles", COO-2245-58TR, MIT, February 1978.

Roohollah Karimi and L. Wolf, "Two Dimensional Structural Analysis of Reactor Fuel Element Claddings Due to Local Effects", COO-2245-59TR, MIT, April 1978.

Vincent Manno and Michael Golay, "Measurement of Heat and Momentum Eddy Diffusivities in Recirculating LMFBR Outlet Plenum Flows", COO-2245-61TR, MIT, June 1978.

Hafeez Khan, Chong Chiu and Neil Todreas, "Laboratory Manual for Salt Mixing Test in Rod Bundles", To be issued as Topical Report Coo-2245-62TR, Department of Nuclear Engineering, MIT.

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 Subchannel of a Bare Rod Bundle," J. of Heat Transfer, Vol. 98, No. 2, May 1976, pp. 262-268 (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.

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 Fluctuation in Turbulent Flows," American Nuclear Society Transactions, Vol. 22, 1975, p. 581.

B. Chen and N. Todreas, "Prediction of the Coolant Temperature Field in a Breeder Reactor Including Interassembly Heat Transfer," Nuclear Engineering and Design 35, (1975) 423-440 (Included as Appendix to Quarterly Progress Report, COO-2245-23).

R. Bennett and M.W. Golay, "Interferometric Investigation of Turbulently Fluctuating Temperature in an LMFBR Outlet Plenum Geometry," Accepted for the ASME Winter Annual Meeting, Dec., 1976, (Included as Appendix in Quarterly Progress Report, COO-2245-30).

B.B. Mikic, E.U. Khan, N.E. Todreas, "An Approximate Method for Predicting Temperature Distribution in Wire Wrapped Fuel Assemblies of a Liquid Metal Fast Breeder Reactor," Mech. Res. Comm., Vol. 3, 353-360 (1976).

C. Papers and Summaries (Continued)

L. Wolf, R. Karimi, J.Y. Kim, C.N. Wong, M.K. Yeung "2-D
Thermoelastic Analysis of LMFBR Fuel Rod Claddings,"
Paper C4/d, 4th International Conf. Structural Mechanics
in Reactor Technology, San Francisco, August 1977.

M. Yeung, L. Wolf, "Effective Conduction Mixing Lengths
for Subchannel Analysis of Finite Hexagonal LMFBR Bundles,"
ANS Meeting, New York, June 1977.

C. Chiu and N. Todreas, "Flow Split Measurements In An LMFBR
Radial Blanket Assembly," ANS Meeting, New York, June 1977.

J.K. Kim and L. Wolf, "Laminar Mixed Convection Heat Transfer
in Finite Hexagonal Bundles," ANL Winter Meeting, San
Francisco, Nov. 27 - Dec. 2, 1977.

Kelly, J.M., Todreas, N.E., "Turbulent Interchange in Tri-
angular Array Bare Rod Bundles," Presented at 6th Inter-
national Heat Transfer Conference, Toronto, August, 1978.

Chiu, C., Todreas, N.E., Rohsenow, W.M., "Turbulent Flow
Split Experiment and Model for Wire-Wrapped Assemblies,"
Transactions of the American Nuclear Society, June, 1978,
Vol. 28, TANSAO 28, (1978), pp. 536-537, ISSN: 0003-018X.

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)

TASK IB.2:   Experimental Bundle Water Mixing Experiments
             (Michael Pate and Hafeez Khan)

During the period of this report, most of the time
was spent on the training of Michael Pate, a newcomer to
the Project. He was given full training in the fabri-
cation and platinization of the probes, as well as their
locations in the flow separator housing. Considerable
time was also spent familiarizing him with the Computer
Operating System. During this period, another complete
set of mixing data was obtained for the 12" lead bundle
to check out the previous data, and also to confirm the
validity of the present arrangement for locating the
probes. Data was also taken for the pressure drop in
the bundle. This data was not for the overall bundle
pressure drop, but was for individual subchannels, i.e.
central, edge, and corner.

The 6" lead rods were also prepared by wire wrapping
them.

TASK IB.5: Shaved-Wire 61-Pin Blanket Bundle Experiment
            (Song-Feng Wang and King-Wo Chiu)

Progress in shaved-wire 61-pin blanket bundle experiment has been made in this quarter. The flow split measurements for interior, edge, and corner subchannels have been done both in laminar and turbulent flow regimes. Due to the lack of the existing data in laminar regime, most of the effort has been concentrated in this area.

The test section was made up by shaving the wire wrap spacers adjacent to hexagonal duct wall to half of their original diameter. Each face of the duct wall is then squeezed a little toward the center of the assembly so that the flow area in the peripheral subchannels is reduced while the flow areas in the interior subchannels remain the same as that for full-wire blanket bundle. The purpose of this design is to force the coolant flow toward the central region of the blanket bundle and hence, eliminate the local cladding hot spots and overall thermal gradients across the whole assembly.

Figure 1 shows the flow split parameter x_1 for interior subchannels as function of bundle average Reynolds number. In the laminar regime, as the flow increases, the higher pressure drop in the central region than that in the peripheral region tends to divert the coolant to the peripheral subchannels. However, this tendency gradually saturates as bundle flow becomes highly turbulent. In this region (highly turbulent), the average gain of coolant flow in the central region is about 3% over the full wire design. Detailed comparison on flow split behavior between half-wire and full-wire designs is under way.

The flow split parameter x_2 for edge subchannels is shown in Figure 2. As the flow increases, x_2 increases, as we might have expected from the conservation law, in the laminar region and finally reaches a constant value when the coolant flow is highly turbulent. The behavior of this flow split parameter in the transition (Re~5000) region is not clear and more data is going to be taken in this specific area.

The flow split data for corner subchannels is similar to that for edge subchannels. Figure 3 shows the flow split parameter x_3 for corner subchannels. It increases gradually from laminar to turbulent flow and comes up to a constant value approximately equal to 1.0. This result confirms the assumption that we made previously: the flow velocity in the corner subchannels is roughly equal to the bundle average coolant velocity. But, notice that this assumption is only good for turbulent flow.

The "closed loop test" has been postponed because low coolant temperature is favorable for the present experiment which is concentrated in the laminar region. The test run will be conducted when it is necessary.
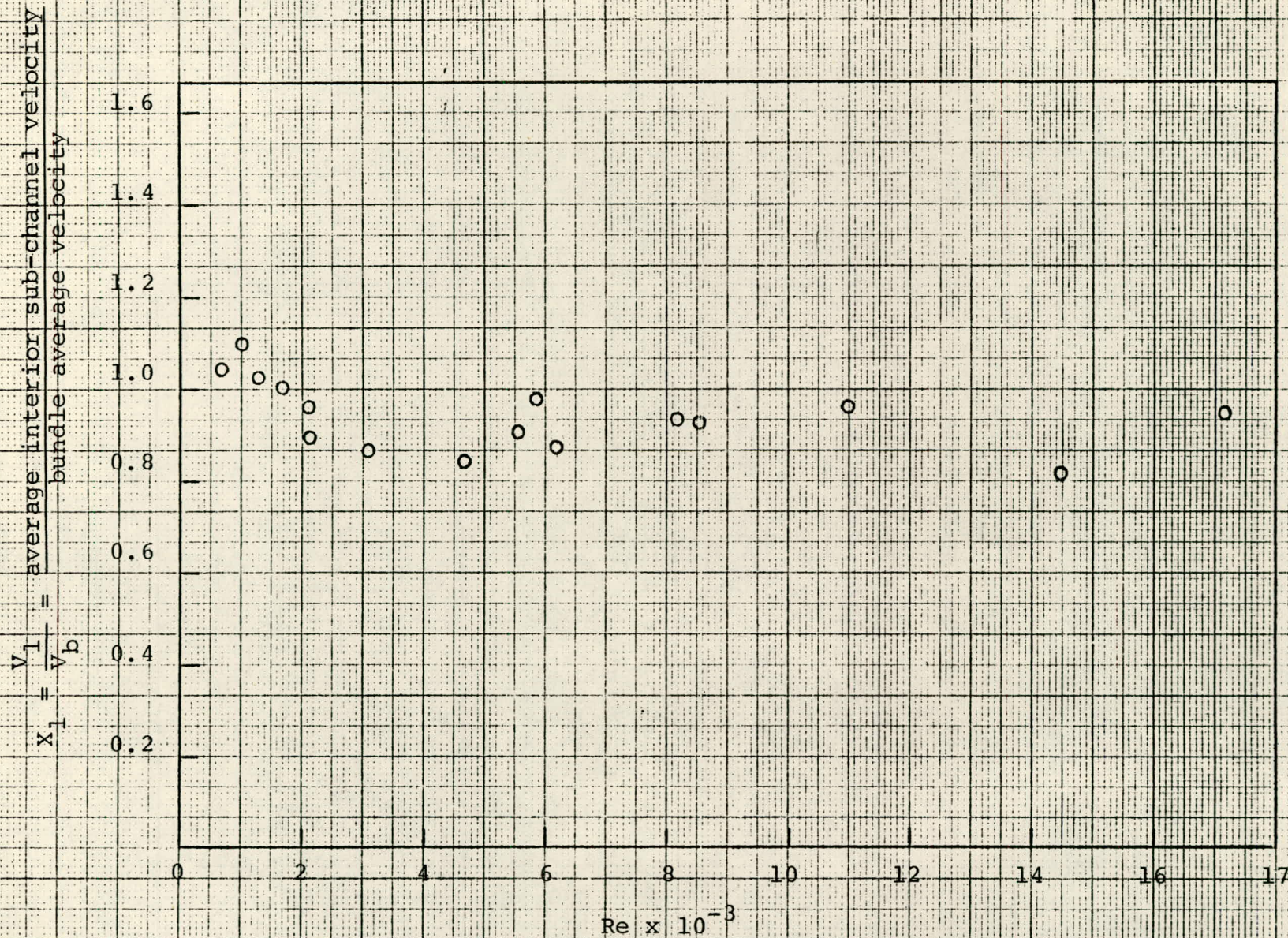
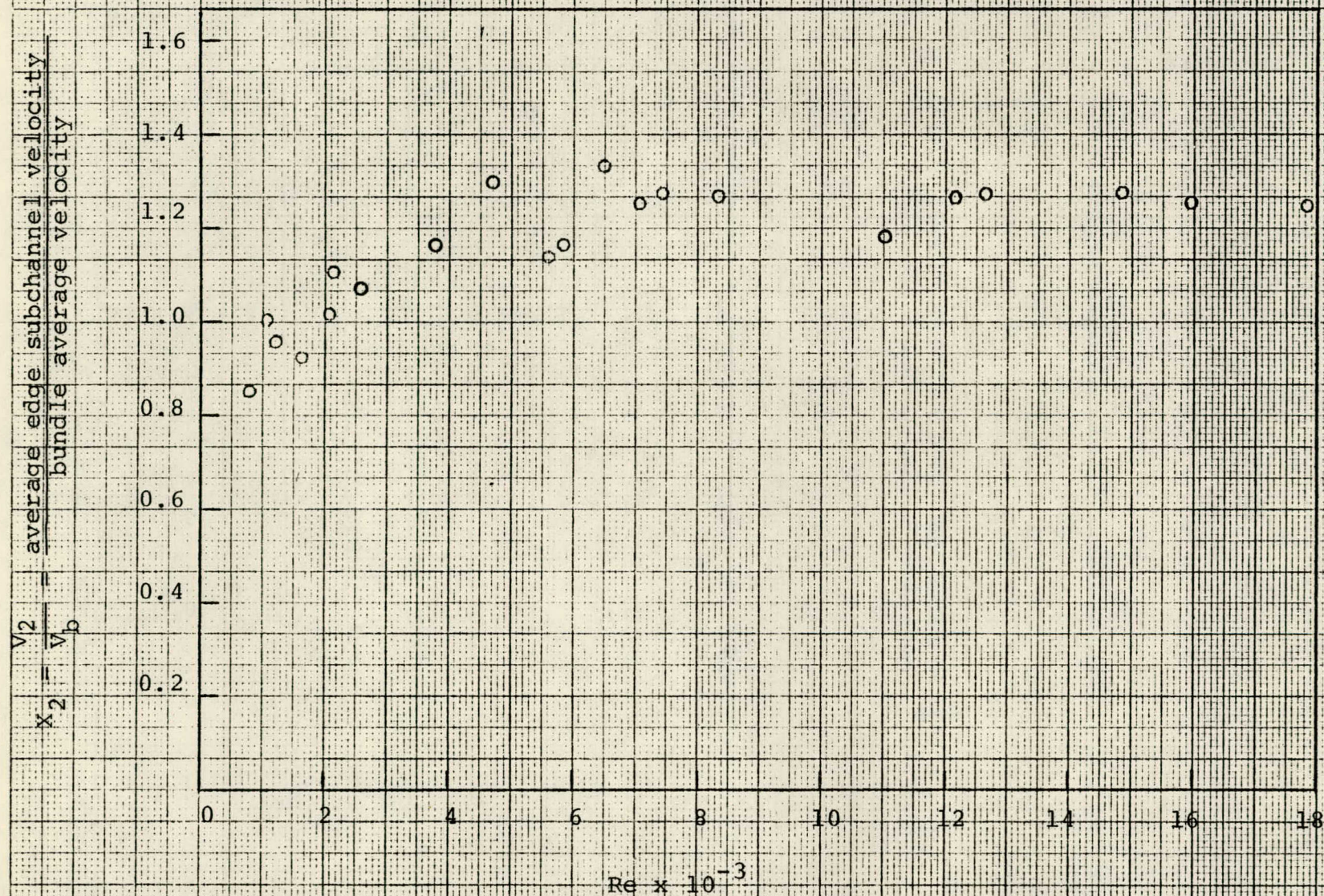Figure 1.   Interior Subchannel Flow Split Parameter X_1 versus Bundle Average Re

Figure 2. Edge Subchannel Flow Split Parameter X_2 versus Bundle Average Re
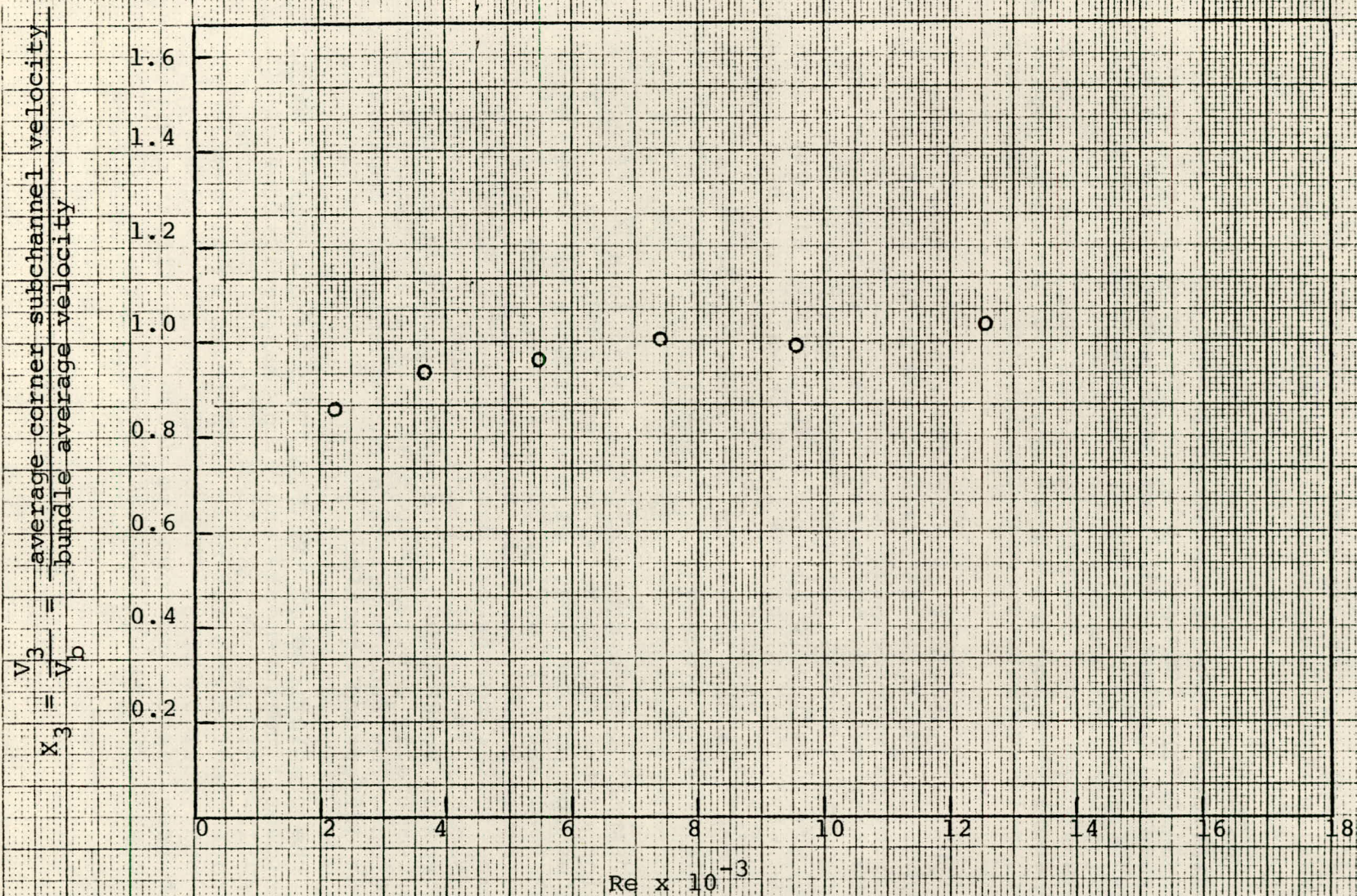
Figure 3. Corner Subchannel Flow Split Parameter X_3 versus Bundle Average Re

TASK 1D.2: Transient Code Development
            (Stuart Glaser)

        Our work on transient code development has progressed
to the point of completion of the code TRANSENERGY-S. This
discussion summarizes our entire effort to date in this
area.

        Techniques of predicting LMFBR coolant temperatures
were investigated with the objective of developing a
production-type computer code for use in transient safety
analyses and design studies of LMFBR cores. Existing
computer codes in the COBRA family are able to predict
transient coolant temperatures. However, their complex
models require long computation times and large amounts of
core storage making them undesirable for use as production
codes until accurate schemes for lumping regions are devel-
oped.

        The extreme simplicity of the steady-state ENERGY
model indicated that, if its approach could be extended to
transient cases, then the resulting codes would be
faster than existing codes and would be suitable for use
as production codes. It was found that if the ENERGY
model was modified to include heat capacity effects asso-
ciated with the coolant and the duct wall, and if a transient
model of the fuel pins could be developed, then a transient
model could be developed for hexagonal wire-wrapped
assemblies in which natural circulation effects are negli-
gible.

        TRANSERGY-S, a computer code based on a modified
version of the ENERGY model, was developed. The code cal-
culates coolant temperatures for a single wire-wrapped
LMFBR fuel assembly during coolant flow, power and inlet
temperature transients. It is based on a computational
scheme similar to the one used in the SUPERENERGY code.
The assembly is nodalized using the subchannel concept
employed in SUPERENERGY. The energy equation for the coolant
is a temporally implicit, spatially explicit finite difference
equation. The fuel model is a one-dimensional implicit
finite difference equation.

        The predictions of TRANSENERGY-S were compared with
experimental measurements and with the predictions of
COBRA-III-C/MIT and COBRA-III-M. TRANSENERGY-S made
accurate predictions for most transients in wire-wrapped
hexagonal fuel bundles. Changes in geometry and very
rapid transients were found to cause significant deviations
in the predictions by TRANSENERGY-S.

The computation time and core storage required to extend TRANSENERGY-S to analysis of more than 19 assemblies make it unsuitable as a production code. A second code, TRANSENERGY, TRANSENERGY-M, has been proposed. It calculates coolant temperatures in from one to 41 coupled fuel assemblies. The computational requirements are reduced by lumping the assembly into six interior nodes, six edge nodes, six nodes in the duct wall and six nodes in the interassembly gap. The coarse nodalization of the assemblies makes TRANSENERGY-M useful for complete assemblies only. The coolant temperature predictions within the assemblies by TRANSENERGY-M are not as accurate as the detailed predictions made by TRANSENERGY-S for single assemblies. However, they are accurate enough to identify the hottest assemblies relative to the other assemblies.

This suggests a technique which may be useful for many transient analyses. Detailed core analyses may be made using a cascade approach. TRANSENERGY-M is used to determine the heat flux on each face of the fuel assemblies as a function of time. These heat fluxes are input to TRANSENERGY-S as boundary conditions for the sub-channel-level analysis of the hottest fuel assemblies indicated in the TRANSENERGY-M analysis.

Future work is expected to include indepth testing of TRANSENERGY-S in order to determine its accuracy and its limitations. Development of the proposed TRANSENERGY-M computer code is pending awaiting an assessment of ongoing other national efforts.

TASK III.   LMFBR OUTLET PLENUM FLOW MIXING

TASK IIIA.   MEASUREMENTS OF THE RATIO OF THERMAL TO MOMENTUM
              DIFFUSIVITIES IN OUTLET PLENUM FLOWS

              (V.P. Manno)

In work recently completed the eddy diffusivities of heat and momen-
tum in small scale LMFBR outlet plenum flows have been measured.
Each diffusivity has been measured separately in air flows,
and the dimensionless ratio of these diffusivities has been
computed. The purpose of these measurements is to investigate
the degree to which common assumptions in the formulation of
these quantities in turbulence modelling are valid.

In particular, it is commonly assumed (e.g. in the VARR-II
analyses of LMFBR Outlet Plenum Flows) that the ratio of
$\varepsilon_H/\varepsilon_M$, where ε_H and ε_M are the eddy diffusivities of heat and
momentum, respectively, is constant in time and space throughout
a flow transient. It is usually also assumed that the turbu-
lence is isotropic. Our work shows that these are poor approxi-
mations for outlet plenum flows.

The experiments were performed in two-dimensional steady non-
isothermal air flows. In these flows co-flowing streams of hot
and cold air were introduced symmetrically at the plenum inlet,
and their turbulent mixing was observed at selected stations in
the flow field (see Fig. III-1). The turbulent velocity and
temperature fields were measured using a laser doppler anemometer
and a Mach-Zehnder interferometer, respectively. These measure-
ments add to the relatively small literature in existence
regarding turbulent heat transport, and are of special import-
ance in outlet plenum flow modelling. Power spectral density
data at a representative FFTF measurement station for velocity
and temperature are shown in Figs. 2 and 3. It is seen that
velocity fluctuations remain strong in the range up to 16 KHz,
while significant temperature fluctuations in the range above 4KHz
are not observed. The resulting measured diffusivity values
are shown in Figs. 4 through 8. It is seen that overall turbu-
lence levels decay monotnically as the inlet jet follows mean
streamlines to the plenum exit, and as the flow becomes well-
mixed the magnitude of the effective eddy heat diffusivity
becomes progressively damped. It is also seen that the turbu-
lence is generally anisotropic, especially down stream of the
inlet chimneys.

These data provide the basis for formulation of an improved
turbulence model for heat transport. However, our research
has indicated the existence of basic problems in models for
turbulent momentum transport. This latter class of problems
must be resolved before it would make sense to formulate an

eddy heat transport model--based upon the momentum transport
model.

This work is described in detail in Ref. 1, which has been
distributed separately. The abstract of Ref. 1 is appended
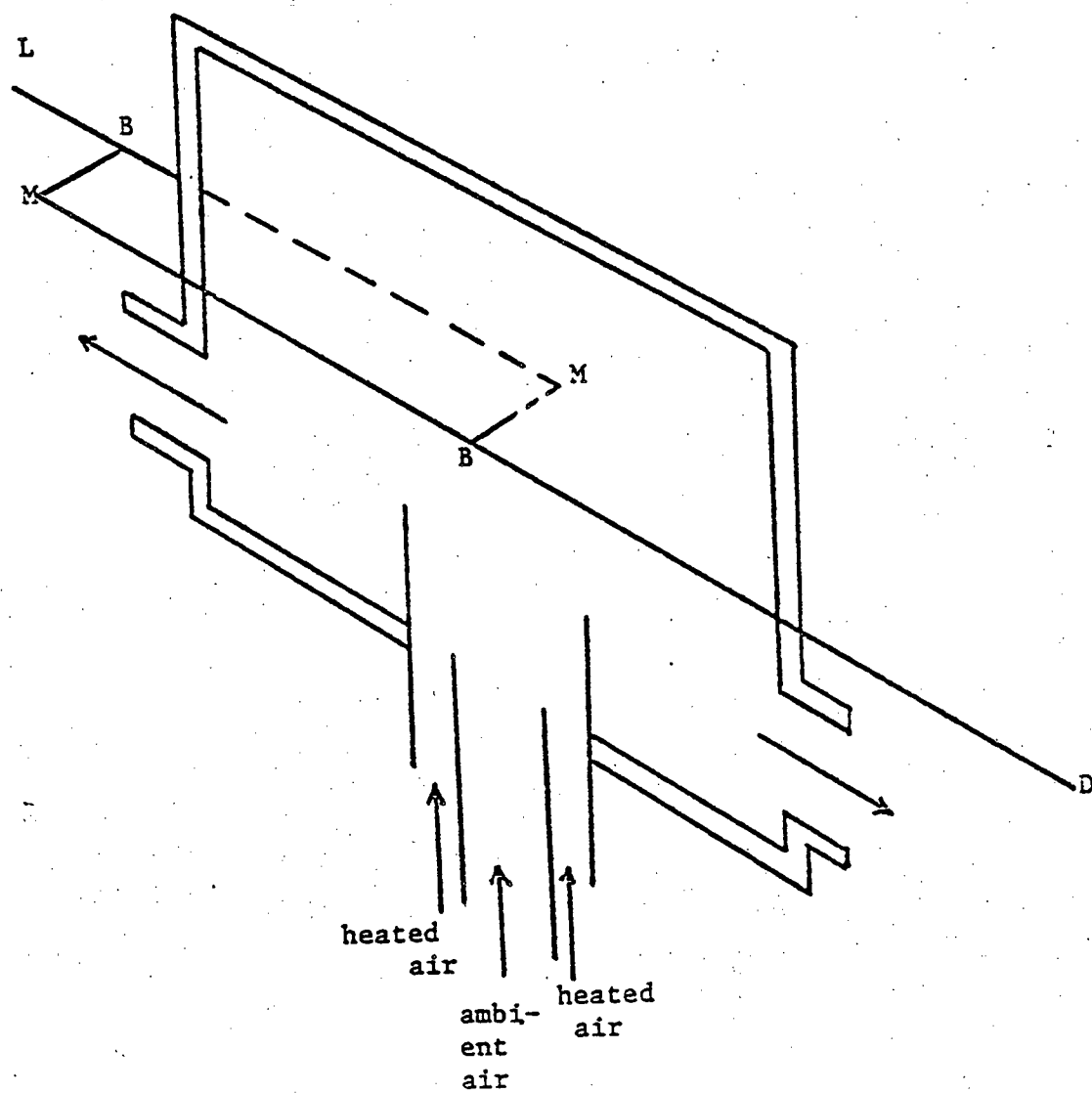to this text.

L   B   M   M   B   D

heated
air

ambi-
ent
air

heated
air

FIGURE 1:   ISOMETRIC VIEW OF MACH-ZEHNDER INTERFEROMETER

L — Laser, B — Beamsplitter, M — Mirror, D — Detector

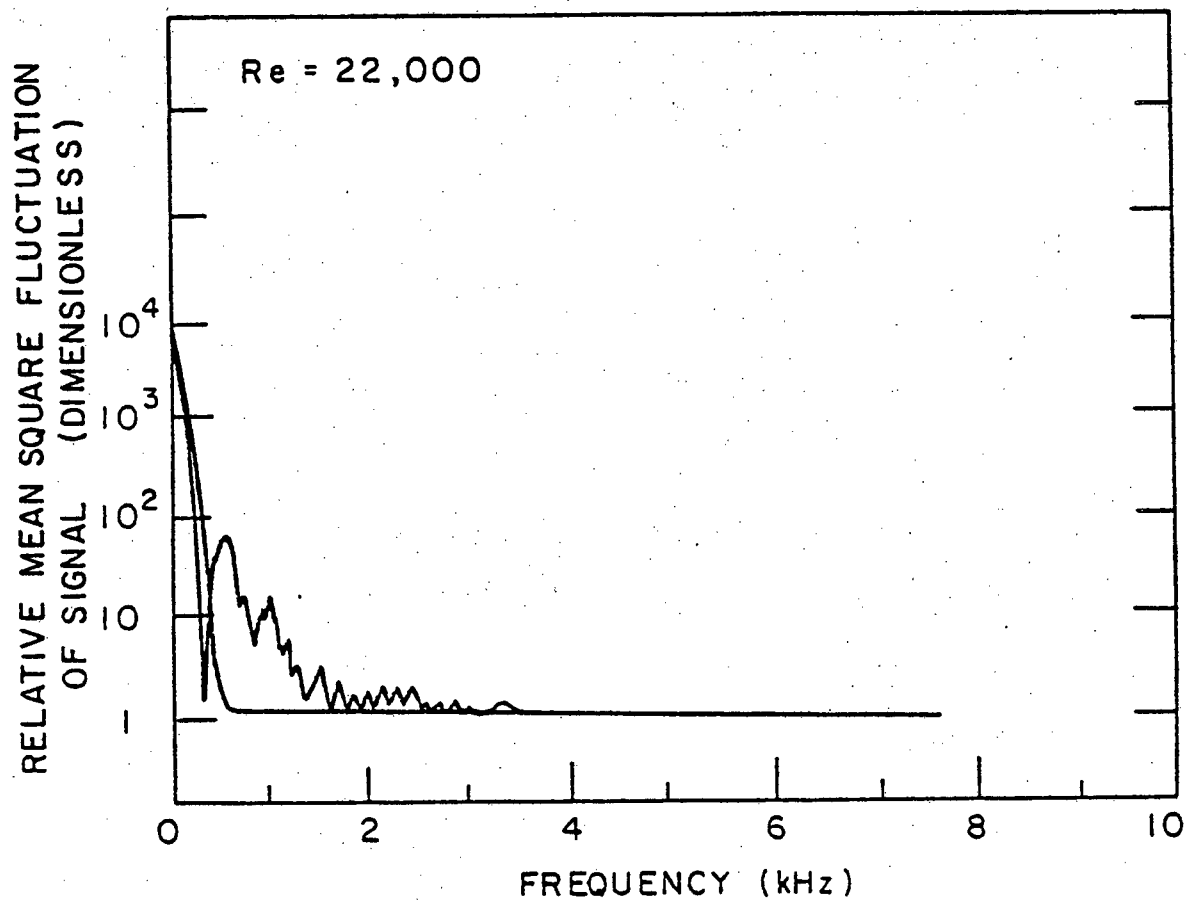FIGURE 2: T' FREQUENCY SPECTRUM AT STATION B
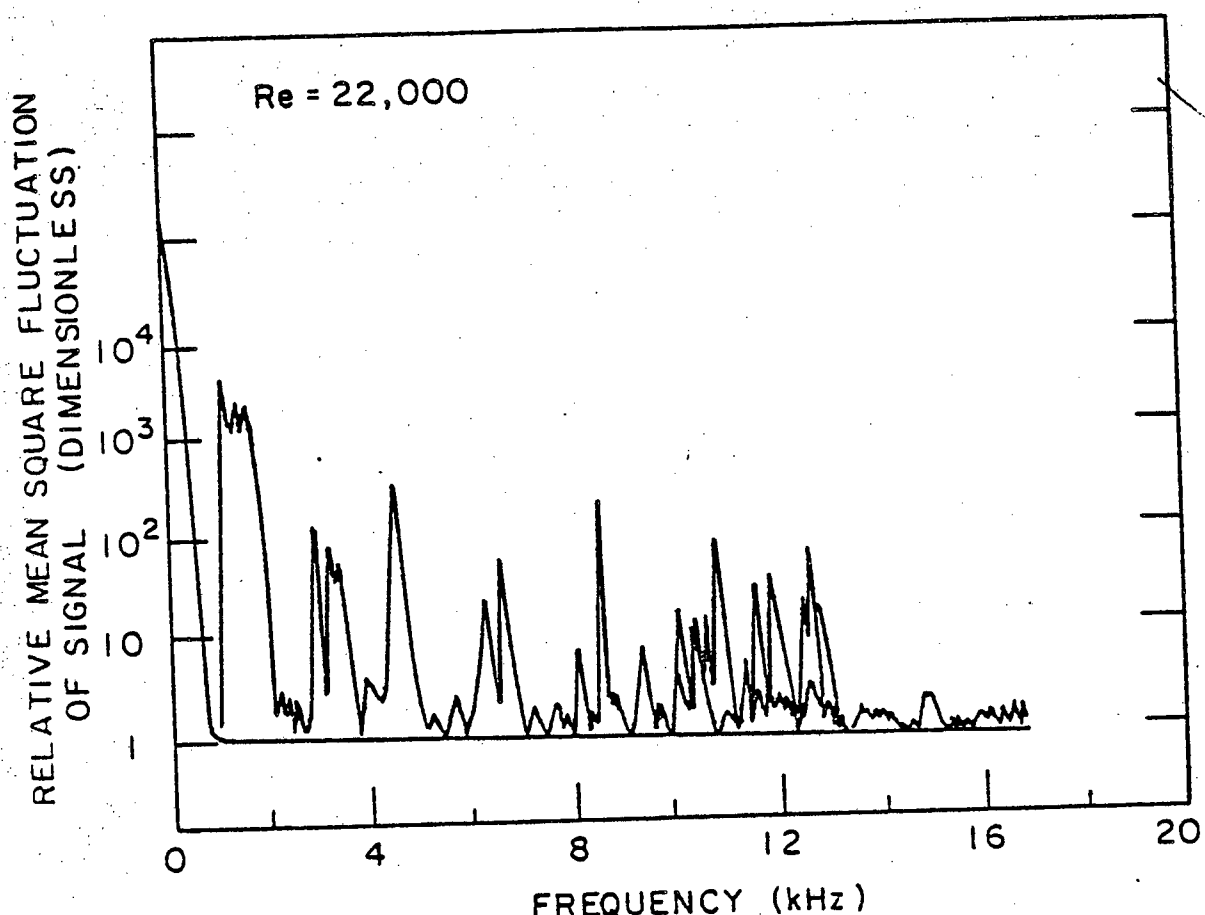IN FFTF GEOMETRY

FIGURE 3: u' FREQUENCY SPECTRUM AT STATION B
IN FFTF GEOMETRY

FIGURE 4:   EDDY DIFFUSIVITY OF HEAT IN FFTF GEOMETRY (X-COMPONENT) (m^2/sec)

FIGURE 5: EDDY DIFFUSIVITY OF HEAT IN FFTF GEOMETRY (Y-COMPONENT)
(m^2/sec)

D
•
0.0840

E   C
•   •
0.0012   0.1333

F   B
•   •
0.0009   0.2569

HEATED   AMBIENT

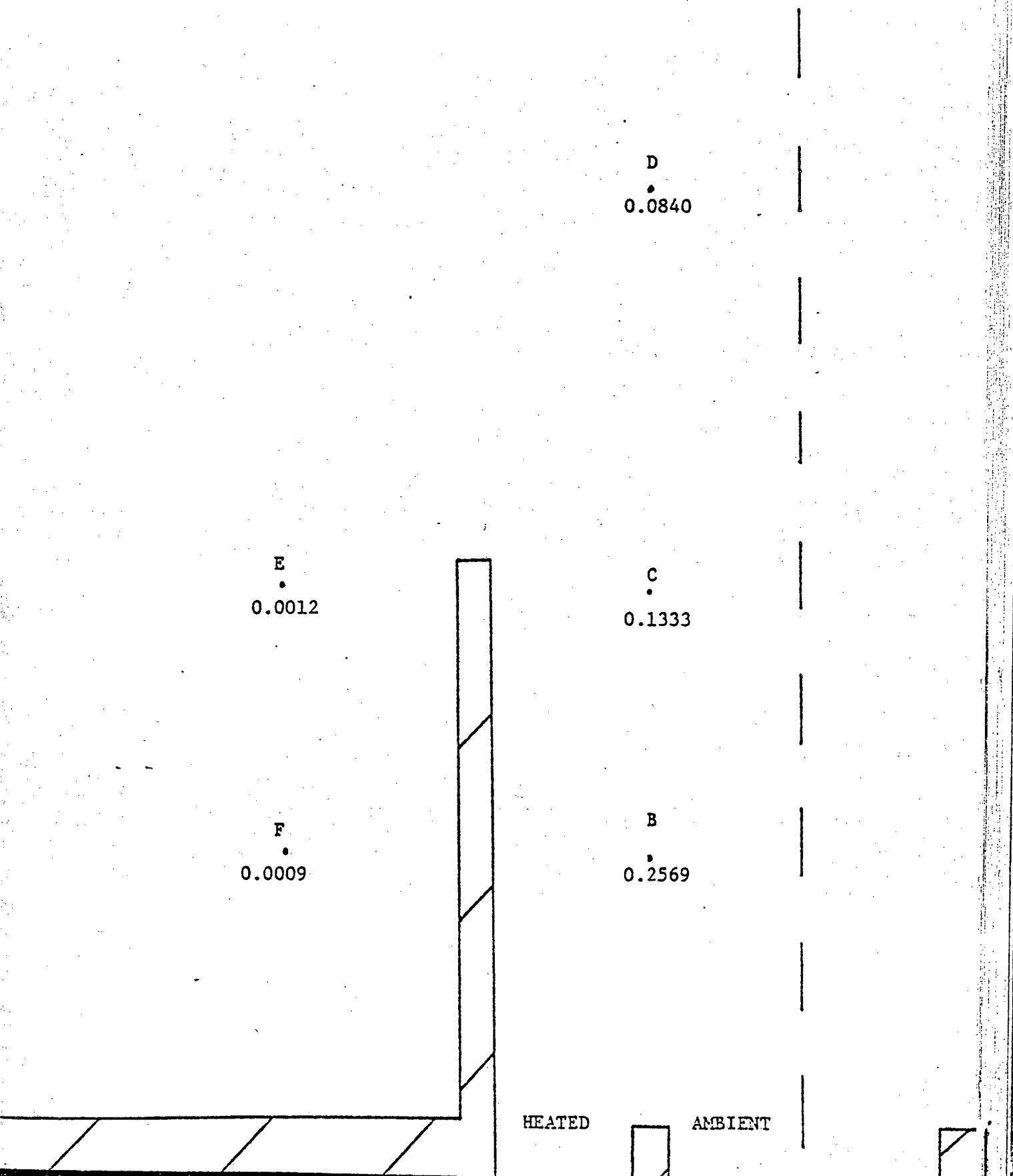FIGURE 6: EDDY DIFFUSIVITY OF MOMENTUM IN FFTF GEOMETRY (X-COMPONENT) (m^2/sec)

FIGURE 7: EDDY DIFFUSIVITY OF MOMENTUM IN FFTF GEOMETRY (Y-COMPONENT)

(m^2/sec)

D
•
0.0482

E
•
0.0868

C
•
0.0434

F
•
0.0229

B
•
0.0964

HEATED   AMBIENT

TABLE 1: $(\varepsilon_H/\varepsilon_M)x$ In the FFTF Geometry

Position	$(\varepsilon_H/\varepsilon_M)x$
B	.119
C	.065
D	.211
E	.227
F	.055

TABLE 2: $(\varepsilon_H/\varepsilon_M)y$ In the FFTF Geometry

Position	$(\varepsilon_H/\varepsilon_M)y$
B	2.665
C	3.071
D	1.743
E	.014
F	.039

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

TASK IV.A: Coupling of Lumped and Distributed Parameter Codes (Man-Kit Yeung)

In the previous report, a computational scheme of coupling the distributed and lumped parameter solution methods was proposed. The general flow chart of this scheme is shown in Figure 1. It has been reported that the results for the 7-rod bundle calculation were quite encouraging. More detailed results of this 7-rod bundle calculation can be found in the forthcoming topical report by Yeung and Wolf [1].

During the last quarter, a 19-rod bundle calculation has been performed and compared with the measurement of Möller and Tschöke's experiment [2] in order to demonstrate the capability of this analysis. The geometric configuration and the subchannel layout of the bundle is shown in Figure 2. The mixing parameters used for the COBRA-IIIC calculation are those presented in [3]. As shown in Figure 2, by the shaded region, a 7-rod section has been cut out from the 19-rod bundle. In order to obtain a reasonable estimate for the clad temperature of the corner rod, it is necessary to have some knowledge of the coolant temperatures of the two shaded areas. Unfortunately, these are not directly available from the COBRA-IIIC calculations. Approximations have to be made to obtain these values. In this case, it has been assumed that the average temperature of the shaded area which consists of $<A_3>_3$ and half of $<A_2>_3$ is equal to $\overline{T}_3$, the coolant temperature of subchannel 3. This approximation should be reasonably valid as long as a large power gradient does not exist across the bundle. On the other hand, it would be questionable to use $\overline{T}_4$ as the temperature of the shaded area $<A_4>_4$ because of the geometric irregularity of subchannel 4. One possible way to determine $<T_4>_4$ is to utilize the calculational results of the fully developed temperature field of the 19-rod bundle. In addition, the axial correction $F(Z)$ is also used to account for the thermal etnrance effect. Thus, the relation between $<T_4>_4$ and $\overline{T}_4$ is given by the following:

$$\frac{<T_4>_4 - \overline{T}_4}{\overline{q}''' a^2/2kc} = \frac{<A_3>_4}{<A_3>_4 + <A_4>_4} \{2 Y_{0142} + F(Z) [<\theta_4>_4 - <\theta_3>_3]\}$$

Having established the values of the coolant temperatures necessary for the analysis for the 7-rod section, the coupled distributed-lumped parameter technique is applied at the axial position of $Z = 25.94"$ and the result of calculation is shown

in Fig. 3 in which the clad temperature distribution of the corner cell is plotted vs. the angular position ϕ. For comparison, the clad temperature distribution of the corner cell measured by Möller and Tschöke is also presented. It can be seen that the shape of the predicted curve compares fairly well with the experiment. The clad temperature distribution predicted by the coupled analysis matches the experimental data in the near-wall region fairly well but tends to over-estimate the temperature in the away-from-wall region. In addition, the predicted clad temperature distribution has a maximum (minimum) circumferential variation of approximately 50°F which is about 16°F higher than the measurement. The discrepancy between the calculated and the measured clad temperature distribution may be the combined effect of the following uncertainties and derivations between experiment and calculation:

(1)   Uncertainty in the geometric and thermal parameters of the experimental apparatus.

(2)   The rounded corner of the bundle shroud in the experimental apparatus.

(3)   Underestimation of the mixing parameter.

Among these three possibilities, it is felt that the mixing parameter probably has the greatest impact on the result of the calculation.

Therefore, it becomes apparent that the determination of a realistic clad temperature distribution relies on the validity of the subchannel calculation which cannot be achieved without the proper knowledge of the various mixing parameters. As a result, the present analysis is only a first step effort to link the distributed and lumped parameter analysis and improvements in many areas will be made to extend and upgrade the analysis.
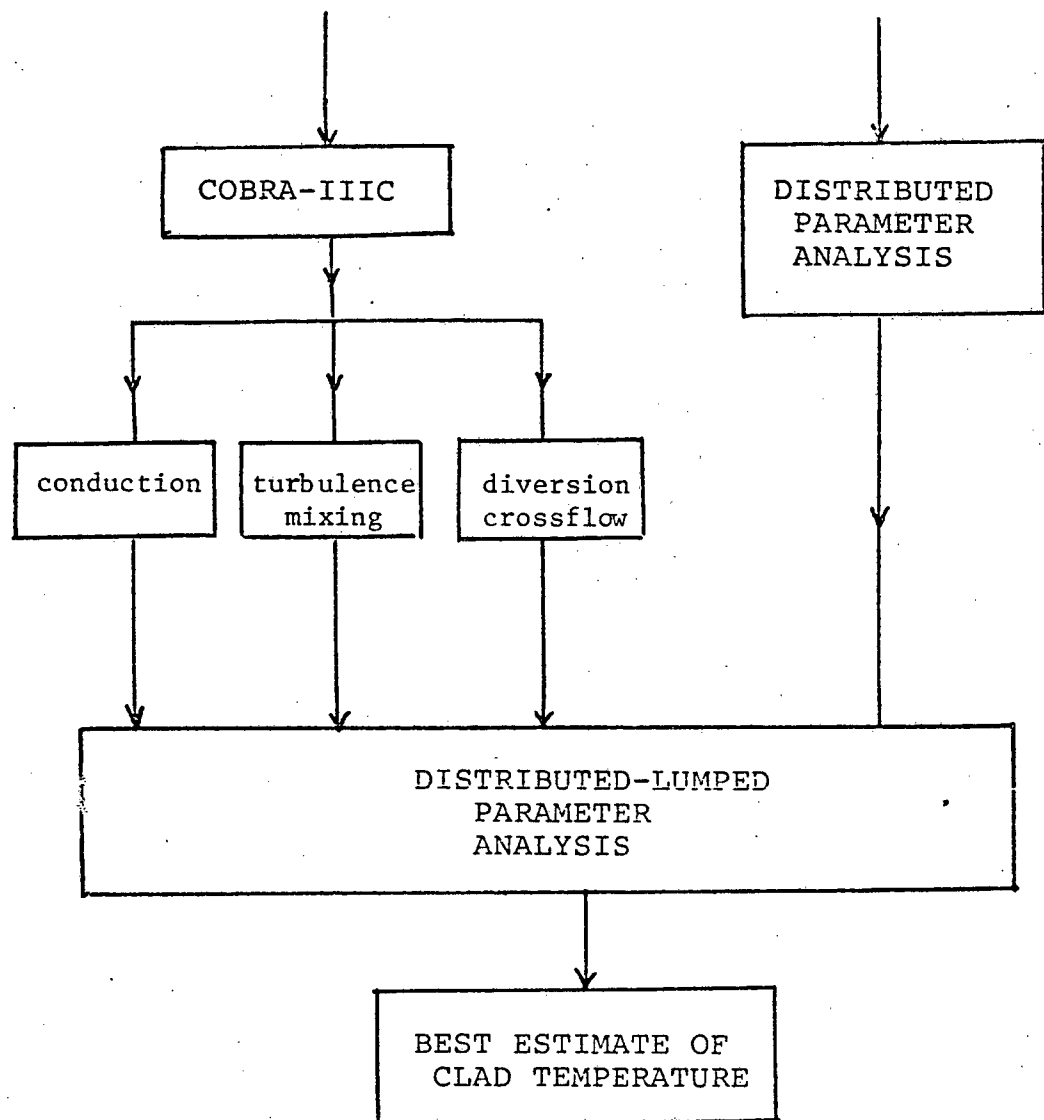
Fig. 1. General Procedure of the Coupled Distributed-Lumped

Parameter Analysis

SUBCHANNEL BOUNDARY

$<A_1>_1$ $<A_2>_1$ $<A_3>_2$ $<A_2>_2$ $<A_3>_3$ $<A_3>_4$ $<A_4>_4$ $<A_2>_3$ $<A_3>_3$ ϕ
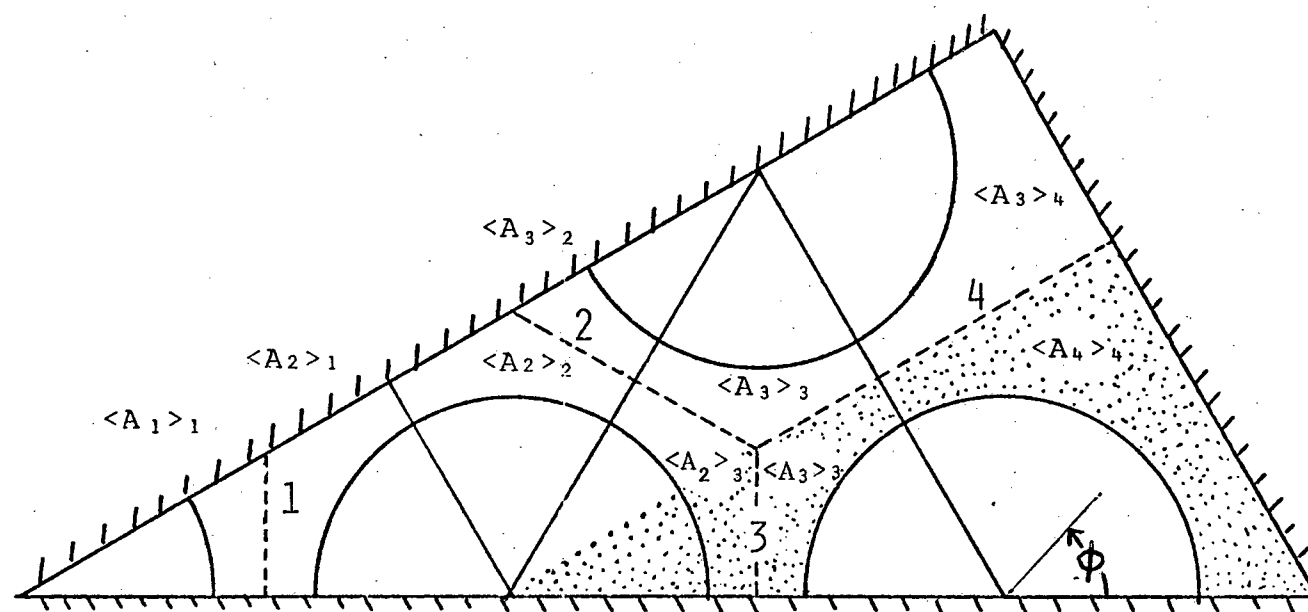
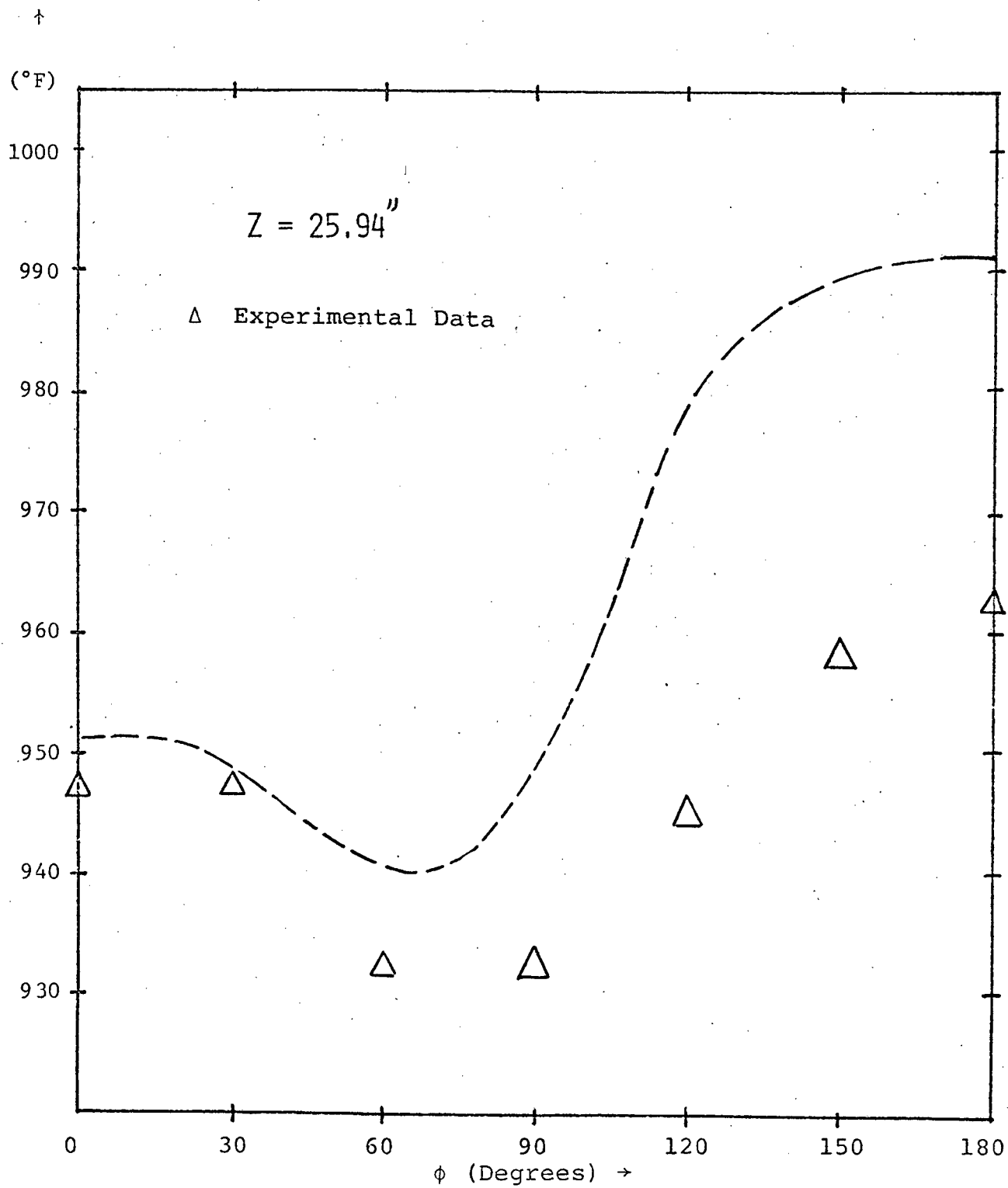Fig. 2. Subchannel Layout of the 19-Rod Bundle

Fig. 3   Clad Temperature Distribution of the Corner Rod for
           the Experimental 19-Rod Bundle

TASK IV.B: 3-D Multi-Region Single Cell Turbulent Flow Analysis
             (Chung-Nin Wong)

        The work on the turbulent heat transfer analysis of hexa-
gonal rod bundles in LMFBRs has been underway throughout this
quarter. The computer code RODBUN by Ramm [4] has been made
operational and employed for various analyses. Thus far, the
principal work has been the set-up of the code and an attempt
to initiate the code to run in an efficient way.

        The code RODBUN uses the finite differencing scheme to
solve the conservation equations of momentum and energy for an
incompressible, steady-state, hydrodynamically fully developed
turbulent flow for an equilaterial triangular rod array. A
phenomenological turbulent model, based on the principal ideas
of Buleev's theoretical model of turbulent transfer in a three
dimensional fluid flow [5], is used in the code. Morever, the
code can handle any anisotropic turbulent diffusivity and also
the effect of secondary flow.

        Substantial time and effort have been spent to fix up
the code and have it run well because quite a number of errors
have been detected in the original version of the code due to
various reasons. First, an initiation for the arrays in the
common blocks and many of the unknown variables has been imple-
mented. Second, several statements have been changed because
they read variables from a scrap tape that is not needed at
M.I.T.. Third, a minor re-adjustment of the iteration loop
is performed, thus making sure that there won't be any needless
iterations. Furthermore, a graphic display of the velocity fields
has been added to the code.

        By solving the momentum equation, the velocity field of
the internal cell can be obtained and plotted in a three-dimen-
sional way as shown in Fig. 4 and Fig. 5. Since the underlying
basic principle assumes that the flow is hydrodynamically fully
developed, the velocity profile stays the same at any of the
axial levels. Obviously, with the addition of the secondary
flow, the azimuthal gradient of the axial velocity becomes
comparatively smaller. Finally, the typical time to run the
code in order to obtain the velocity profile requires less than
30sCPU time totally in an IBM370-168 machine, which is amazingly
good. Next, with the result of this velocity distribution,
the temperature field of the internal cell will be calculated
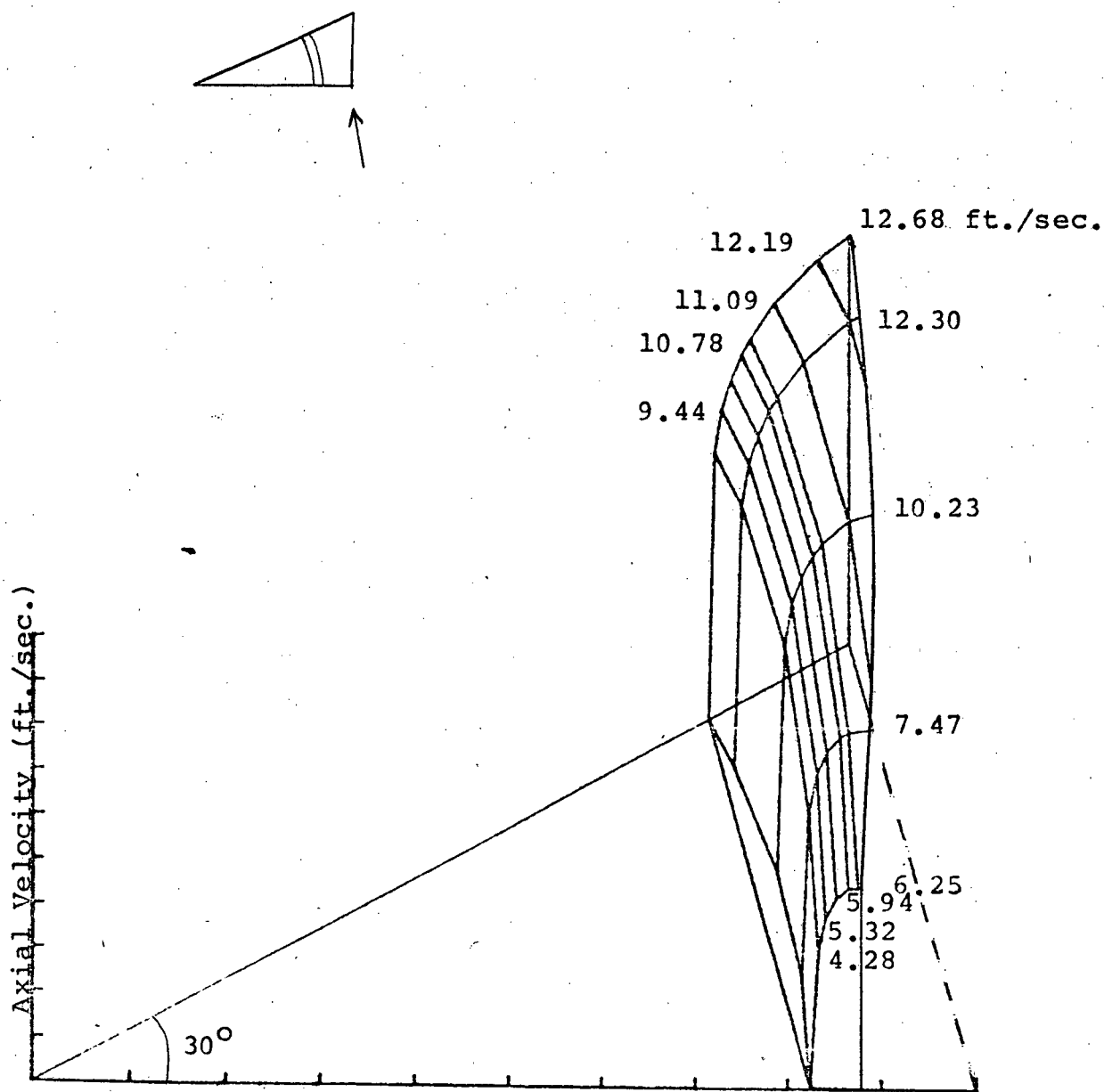and shown in the next quarter report.

Fig. 4   Velocity Profile of the Internal Cell with
          Anisotropic Turbulent Model and No Secondary
          Flow

          (Boundary Condition: P/D = 1.05, Dia. = 0.622 in.,

          Re = 3.40 x 10^4, Hydrodynamically Fully Developed,

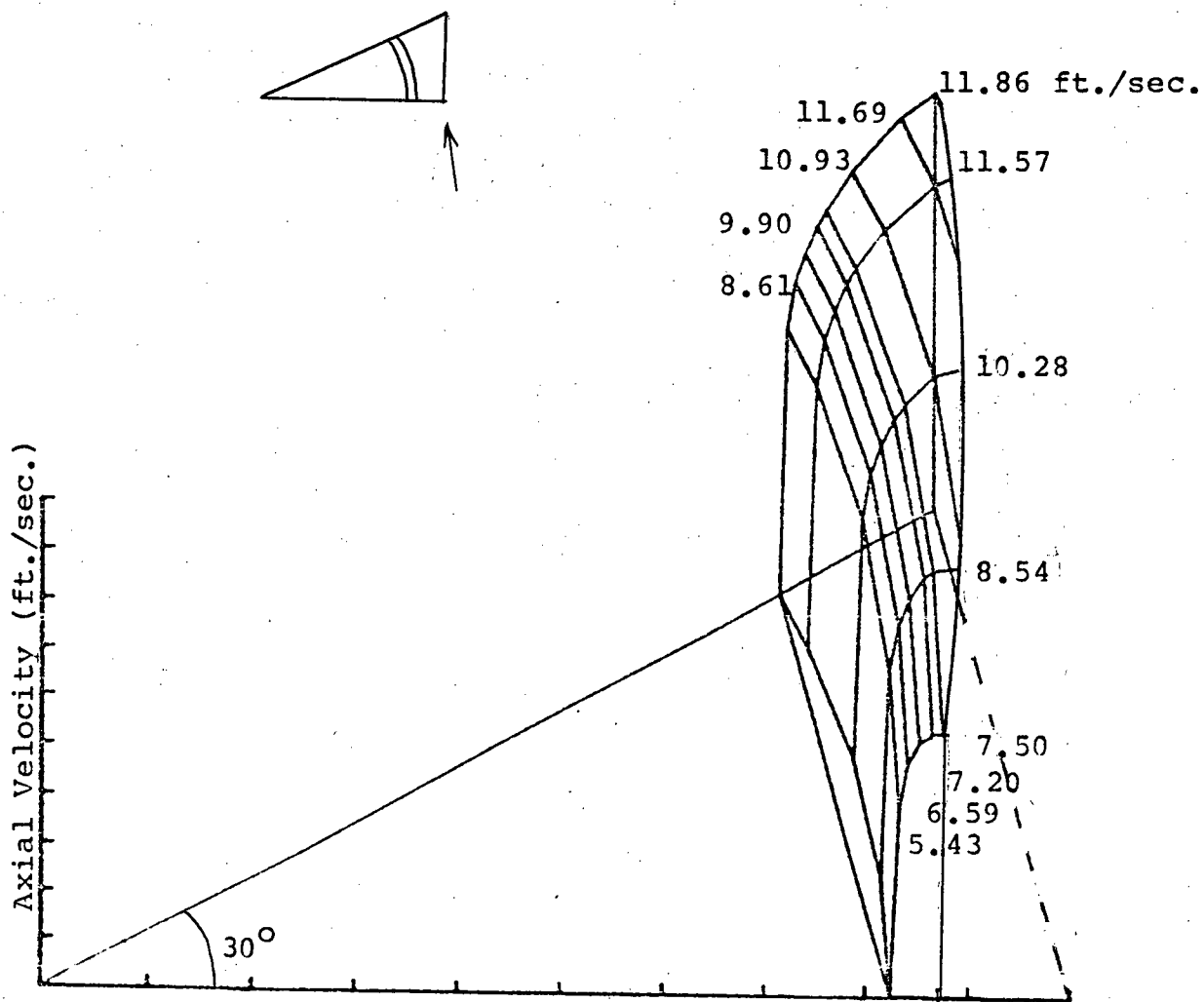 $V_{avg.}$ = 10.3 ft/sec.)

Fig. 5   Velocity Profile of the Internal Cell with
          Anisotropic Turbulent Model and Secondary
          Flow

          (Boundary Condition: P/D = 1.05, Dia. = 0.622 in.,

          Re = 3.39 x 10^4, Hydrodynamically Fully Developed,

          $V_{avg.}$ = 10.14 ft/sec.)

REFERENCES

(1) M.K. Yeung, L. Wolf: "A Multi-Cell Slug Flow Heat
     Transfer Analysis for Finite LMFBR Bundles," M.I.T.
     Report, to be published.

(2) Möller, H. Tschöke. "Experimental Determination of
     Temperature Fields in Sodium-Cooled Pin Bundles"
     (In German)., Nuc. Conf., Dusseldorf, Germany, 1976.

(3) M.K. Yeung, L. Wolf, "Effective Conduction Mixing Lengths
     for Subchannel Analysis of Finite Hexagonal LMFBR
     Bundles" ANS Meeting, New York, June 1977.

(4) H. Ramm, K. Johannsen, "A Phenomenological Turbulence
     Model and its Application to Heat Transfer in Infinite
     Rod Arrays with Axial Turbulent Flow" J. of Heat Transfer,
     August 1975.

(5) N.I. Buleev, "Theoretical Model for Turbulent Transfer
     in Three-Dimensional Fluid Flow," Paper No. 329 presented
     at the 3rd UN Intern. Conf. on Peaceful Uses of Atomic
     Energy, Geneva, 1964.