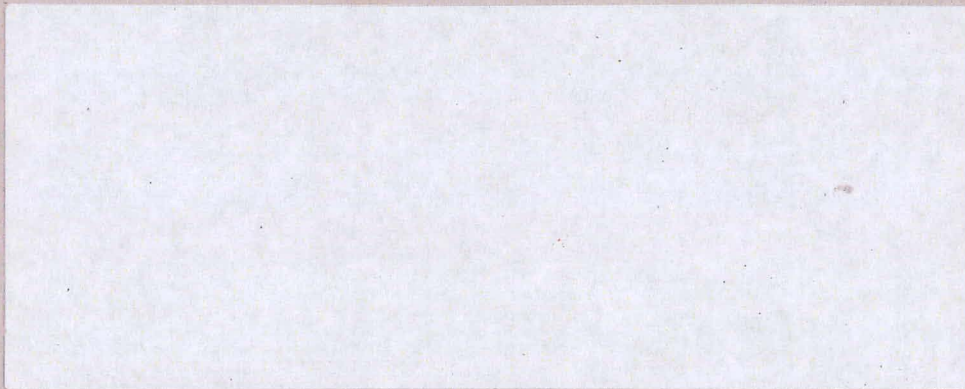


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COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

P.I.: Neil E. Todreas - Tasks I and II
Michael W. Golay - Task III
Lothar Wolf - Task IV

PROGRESS REPORT

Report No. DOE/ET/37240-85
February 1981

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MIT COOLANT MIXING IN LMFBR ROD BUNDLES PROJECT

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

COO-2245-1 Period June 1, 1972 - November 30, 1972
COO-2245-2 Period December 1, 1972 - February 28, 1973
COO-2245-3 Period March 1, 1973 - May 31, 1973
COO-2245-6 Period June 1, 1973 - August 31, 1973
COO-2245-7 Period September 1, 1973 - November 30, 1973
COO-2245-8 Period December 1, 1973 - February 28, 1974
COO-2245-10 Period March 1, 1974 - May 31, 1974
COO-2245-13 Period June 1, 1974 - August 31, 1974
COO-2245-14 Period September 1, 1974 - November 30, 1974
COO-2245-15 Period December 1, 1974 - February 28, 1975
COO-2245-23 Period March 1, 1975 - May 31, 1975
COO-2245-25 Period June 1, 1975 - August 31, 1975
COO-2245-26 Period September 1, 1975 - November 30, 1975
COO-2245-28 Period December 1, 1975 - February 29, 1976
COO-2245-30 Period March 1, 1976 - May 31, 1976
COO-2245-31 Period June 1, 1976 - August 31, 1976
COO-2245-34 Period September 1, 1976 - November 30, 1976
COO-2245-38 Period December 1, 1976 - February 28, 1977
COO-2245-50 Period March 1, 1977 - May 31, 1977
COO-2245-53 Period June 1, 1977 - August 31, 1977
COO-2245-60 Period September 1, 1977 - November 30, 1977
COO-2245-63 Period December 1, 1977 - February 28, 1978
COO-2245-64 Period March 1, 1978 - May 31, 1978
COO-2245-65 Period June 1, 1978 - August 31, 1978
COO-2245-66 Period September 1, 1978 - November 30, 1978

COO-2245-69 Period December 1, 1978 - February 28, 1979
COO-2245-70 Period March 1, 1979 - May 31, 1979
COO-2245-71 Period June 1, 1979 - August 31, 1979
COO-2245-72 Period September 1, 1979 - November 30, 1979
DOE/ET/37240-75 Period December 1, 1979 - February 29, 1980
DOE/ET-37240-76 Period March 1, 1980 - May 31, 1980
DOE/ET-37240-85 Period June 1, 1980 - August 31, 1980

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- * 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.
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- * 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" Issued as Topical Report COO-2245-57TR, August 1980.
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- Vincent Manno and Michael Golay, "Measurement of Heat and Momentum Eddy Diffusivities in Recirculating LMFBR Outlet Plenum Flows", COO-2245-61TR, MIT, June 1978.
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- J. Y. Kim and L. Wolf, "Fully-Developed Mixed Convection Heat Transfer and Pressure Drop in Characteristic Coolant Cells of Finite Hexagonal Bare Bundles", COO-2245-67TR, MIT, Dec. 1978.
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- P. D. Symolon, N. E. Todreas, "A Manual for Use with the Computer Code Superenergy-Data Reduction Version", COO-2245-74TR, MIT, February 1980.
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S. F. Wang, W. M. Rohsenow, and N. E. Todreas, "Flow Split, Pressure Drop, and Mixing Experiments in a 61 Pin Shaved-Wire Blanket Assembly, DOE/ET/37240-86TR, Feb. 1981.

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- ** P. D. Symolon and N. E. Todreas, "Fluid Mixing Studies in a Hexagonal 61 Pin Wire Wrapped Rod Bundle", COO-2245-51TR, (Revision I), February 1981.
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- ** Y. N. Chan and N. E. Todreas, "Turbulent Flow Split Model and Supporting Experiments for Wire Wrapped Core Assemblies", COO-2245-56TR, (Revision I), December 1980.

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COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Contract AT(11-1)-2245

QUARTERLY PROGRESS REPORT

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

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

TASK IA: Assessment of Available Data

TASK IB: Experimental Bundle Water Mixing
Investigation

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

TASK ID: Analytic Model Development - Bundles

TASK II: SUBCHANNEL GEOMETRY (BARE RODS)

TASK IIA: Assessment of Available Data

TASK IIB: Experimental Subchannel Water
Mixing Investigation

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

TASK IID: Analytic Model Development-Subchannels

TASK III: LMFBR OUTLET PLENUM FLOW MIXING

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

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

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TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

I.A Assessment of Available Data

I.B Experimental Bundle Water Investigations

- I.B.1 61 Pin Fuel Bundles - Turbulent Flow
- I.B.2 61 Pin Fuel Bundles - Laminar and Transition Flow
- I.B.3 217 Pin Fuel Bundle
- I.B.4 61 Pin Blanket Bundles
- I.B.5 Shaved Wire 61 Pin Blanket Bundle
- I.B.6 37 Pin (P/D=1.15) Bundle
- I.B.7 Experimental Method for Flow Split Determination
- I.B.8 Experimental Method for Pressure Drop Determination
- I.B.9 Experimental Method for Mixing Parameter Determination

I.C Experimental Bundle Peripheral Velocity Measurements (Laser Anemometer)

I.D Analytic Model Development - Bundles

- I.D.1 Steady State ENERGY/SUPERENERGY
- I.D.2 Transient TRANSENERGY
- I.D.3 Models for Forced Convection Analysis (Pressure Drop, Flow Split and Mixing)
- I.D.4 Models for Mixed Convection
 - I.D.4.1 Models for Mixed Convection - Subchannel
 - I.D.4.2 Models for Mixed Convection - Assembly
 - I.D.4.3 Models for Mixed Convection - Core
 - I.D.4.4 Predictors of Inception of Mixed Convection
- I.D.5 Determination of Shape Factors

TASK I. BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

I.A Assessment of Available Data

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

I.B EXPERIMENTAL BUNDLE WATER INVESTIGATIONS

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

(Paul Symolon)

Work on the 61 pin bundle in the turbulent flow regime has been completed. A report entitled "Fluid Mixing Studies in a Hexagonal 61 Pin Wire Wrapped Rod Bundle" Report No. COO-2245-51TR Revision 1, dated February 1981 will be issued shortly.

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

(Paul Symolon)

Work on the 61 pin bundle in the laminar and transition flow regime has been completed. A report entitled "Fluid Mixing Studies in a Hexagonal 61 Pin Wire Wrapped Rod Bundle" Report No. COO-2245-51TR Revision 1, dated February 1981 will be issued shortly.

I.B.3 217 Pin Fuel Bundle

(Paul Symolon)

Work on this task has been completed. A report entitled "Fluid Mixing Studies in a Hexagonal 217 Pin Wire Wrapped Rod Bundle" Report No. DOE/ET/37240-84TR will be issued shortly.

I.B.4 61 Pin Blanket Bundles

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

I.B.5 Shaved Wire 61-Pin Blanket Assembly

(Song-Feng Wang)

In this quarter, the analyses of the flow split, pressure drop, and mixing experimental data were completed. The results will be issued shortly as Report No. DOE/ET/37240-86TR.

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

(Yee-Ning Chan)

The previously obtained 37-pin wire-wrapped fuel rod data was not consistent because of non-uniformities in the housing dimensions which have occurred over time due to warpage. Since it is too expensive to build a new housing, it is planned to put together a new 37-pin assembly to fit the extruded, hexagonal housing originally used for the 217-pin assembly.

New stainless steel rods and matching wires have been procured such that the new assembly will have a P/D of about 1.15. The construction of the new assembly will commence in winter 1980/81.

I.B.7 Experimental Method for Flow Split Determination

(James T. Hawley)

The manual on the flow split method was completed and issued as Report No. DOE/ET/37240-80TR, August 1980.

I.B.8 Experimental Method for Pressure Drop Determination

(Kevin Burns)

This task was completed and issued as Report No. DOE/ET/37240-77TR, July 1980.

I.B.9 Experimental Method for Mixing Parameter Determination

(Yee Ning Chan)

This task has been completed and will be issued shortly.

I.C. EXPERIMENTAL BUNDLE PERIPHERAL VELOCITY MEASUREMENTS

(Laser Anemometer)

No work being done on this task at present.

I.D ANALYTIC MODEL DEVELOPMENT - BUNDLES

I.D.1 Steady-State ENERGY-III

(Tom Greene)

No work was performed on steady-state ENERGY-III during this period. The latest results on this task were reported in DOE/ET/37240-76.

I.D.2 Transient TRANSENERGY

(Tom Greene)

No work was performed in this area during the current period. Last Results were reported in Report No. COO-2245-71, August 1979.

I.D.3 Mixing Model for Forced Convection Analysis

(Kevin Burns)

During this quarter work was completed on this task and will be issued shortly as a report entitled "Laminar/Transition Sweeping Flow Mixing Model for Wire Wrapped LMFBR Assemblies" Report No. DOE/ET/37240-81TR.

I.D.4 MODELS FOR MIXED CONVECTION

(Paul Symolon)

1. Buoyancy Effects in Reactor Heat Transfer

Figure 1 indicates some of the important areas where buoyancy affects reactor heat transfer. The first area shown is the primary coolant loop. The core acts as a heat source, and the steam generator as a heat sink. This gives the situation shown in the schematic of a primary coolant loop in Figure 2. The difference in elevation head between the reactor (R) and steam generator (SG), along with the difference in densities between the hot and cold legs causes a pressure head which drives the flow in the direction shown. If the forced flow is not too large, this gravitational pressure head may be a significant or the dominant driving force for the loop. The latter case is termed "natural circulation".

Buoyancy forces also play an important role in the reactor core and the steam generator, though in a somewhat more localized sense. Localized buoyancy effects are usually termed "natural convection", or "mixed convection". In what follows, only the reactor core will be given further consideration.

Analysis of buoyancy effects in the reactor core can be divided into three categories, as shown in Figure 1. Inter-assembly heat transport analysis deals with the

interaction of assemblies with their neighbors, and their common upper and lower plena. The lumped parameter computer code COBRA-WC(1) seems to be the best analytical tool available for these cases.

Analysis of intra-assembly heat transport deals with fluid flow and heat transfer within a single assembly. COBRA-WC can also analyze these situations. The primary difference between the first two cases is the presence of barriers to flow in the inter-assembly case, but this is easily handled by COBRA-WC. In practice the difficulty comes in the noding scheme used. It is too costly to consider each subchannel a node for an entire reactor core, so a coarse noding scheme must be selected, which does not sacrifice accuracy too much.

The inter- and intra- assembly cases are similar in that buoyancy forces cause flow redistribution to occur through either a power skew (channels get different power) or differing channel areas. In both cases, the hotter channel (greater power input, or smaller area) gets more flow, so the effect of considering buoyancy in the analysis in each case is to reduce the maximum temperature which would occur without the consideration of buoyancy. This situation is shown in Figure 3 for moderate power skews. For more severe power skews, a gross flow reversal may occur. In an assembly for the inter-assembly case, or a flow recirculation may develop in the intra-assembly case.

In these cases, one cannot say that the effect of buoyancy will be a reduction of the maximum temperature.

Gross flow reversals due to buoyancy forces were observed experimentally, and predicted analytically by Chato (2) for flow in three-parallel vertical tubes. He also observed, and predicted analytically a metastable flow regime where two stable flows could exist.

Yahalom and Bein (15) developed a code which analyzed flow in parallel channels where boiling was allowed to occur, and applied it to flow reversal in a simulated four channel reactor core. A dimensionless channel preference number was derived which gave a criteria to determine the order in which flow reversal would occur among the four channels. KHATIB-Rahbal et al (3) analyzed flow reversal in homogeneous and heterogeneous core designs using the SSC-6 computer code.

Flow recirculation patterns were observed in the transient and steady state BNWL 2x6 tests of Bates (4) and Quigley (5), and were predicted by the COBRA-WC code. Flow recirculation was observed to occur under less severe conditions (smaller power skew, greater bundle flow) for a flow transient due to the effects of fluid inertia during the coastdown. Namekawa (7) observed recirculation under natural convection conditions, but only flow redistribution under mixed convection conditions. Flow recirculation can

be thought of as a limiting case of assembly flow redistribution, as indicated by the bundle flow diagrams of Figure 3. In either case the inlet flow to the assembly is prescribed. Similarly, flow reversal can be thought of as a limiting case of core flow redistribution (Figure 3), but in this case the assembly inlet flow is not prescribed, but is determined by an equal pressure drop requirement for each channel (since they have common upper and lower plena).

Computer analysis of subchannel heat transport required a sophisticated distributed parameter code such as BODYFIT which is capable of calculating the details of the flow field, though even BODYFIT is limited to laminar flows. A fundamental understanding of subchannel heat transport is needed to formulate physical models for friction factors, heat transfer coefficients, and turbulent interchange parameters under mixed convection conditions. These physical models are then input to subchannel computer codes such as COBRA-WC, to allow accurate predictions to be made of peak clad temperatures.

Subchannel heat transport can be divided into two situations: that of aiding flow (buoyant flow in direction of forced flow) and opposing flow. Unless a gross flow reversal occurs in an assembly, aiding flow is obtained in reactor applications. Both of these cases can be further divided into isolated subchannel analysis, or

interacting subchannels. Strong power skews cause subchannels to interact, resulting in transverse flows and heat fluxes.

The case of isolated subchannels has been investigated analytically by Wang et al (14). He performed a computer analysis of steady, laminar fully-developed mixed convection flows in bare rod bundles. Interior, edge, and corner subchannels were considered for both aiding and opposing flows. The results of the BNWL 2x6 test indicate that these results may be of little practical importance, as the flow was never observed to be fully developed, and even under low Reynolds number conditions was not laminar. Future research efforts should address the issues of laminar and turbulent developing mixed convection flows. Insight into the flow behavior can be obtained through the literature of vertical heated tubes.

2. A review of Vertical Mixed Convection Flows in a Circular Heated Tube

The behavior of an isolated subchannel where the flow is predominantly axial can be expected to exhibit similar hydraulic and thermal characteristics (aside from θ coordinate variations) as a flow in a vertical heated circular tube. Exceptions occur when strong power skews exist in the rod bundle, and transverse or recirculating flows develop, as observed in the BNWL 2 x 6 test. A review follows which summarizes heat transfer in aiding and opposing mixed convection

flows under laminar and turbulent conditions in a vertical heated tube.

Figure 4 shows qualitatively the velocity and shear stress distributions in a vertical tube for aiding and opposing flow, along with isothermal forced flow profiles. The distributions are different in detail for laminar and turbulent flows, but the manner in which they are affected by buoyance is similar. It is then surprising that for laminar aiding flow, buoyancy increases h , while for a turbulent aiding flow buoyancy decreases h (initially, at least). Both effects reverse for an opposing flow. This behavior can be explained qualitatively in the following manner.

The heat transfer coefficient in a convective system is in general determined by two factors: the distribution of the velocity, and the distribution of the diffusivity for heat in the fluid. For a laminar flow, the diffusivity for heat is a constant so the effect of buoyancy on heat transfer is determined by the velocity distribution. The higher the velocity close to the wall, the higher heat transfer coefficient is obtained. Figure 4 shows that for aiding flow, buoyancy will increase the velocity close to the wall, and increase h . For opposing flow the opposite will initially occur. For large buoyancy forces a point may be reached when the flow near the wall reverses direction, and increasing the buoyancy increases h ; but this type of profile is highly unstable, and the flow is not likely to remain laminar.

The same effect on the velocity profiles exist for turbulent flow, but in this case the change in turbulent diffusivity dominates. A turbulent pipe flow, turbulence kinetic energy is produced close to the wall and diffuses out to the core (turbulence energy production is equal to the product of the turbulent shear stress and the gradient of the mean velocity). The region of high turbulence production (given as $Y^+ = 10$ to 30 in Reference 8) is shown in Figure 4 with dotted lines close to the wall. It follows from these profiles that an opposing flow creates higher turbulence production and better heat transfer. The turbulence production in an aiding flow is reduced, lowering the heat transfer coefficient (initially).

The case of turbulent aiding flow merits closer study, as it is the flow obtained in reactor applications. The velocity and shear stress profiles of Figure 5, which represent profiles for increasing buoyancy effects, or increasing G_r/R_e^2 . If the buoyancy forces are sufficient to reduce the turbulence production to zero (see profile number 3) the flow will become laminar. This phenomena also occurs in turbulent boundary layers undergoing strong acceleration (9), or suction at the wall and has been termed laminarization. It was observed in buoyant flows of supercritical fluids (see the review artical by Hall (10)) in which the density is a strong function of temperature, and large buoyancy forces

are easily generated. It was later shown to occur in non critical fluids (11). Further increase in the buoyancy forces will cause the shear stress to reverse sign near the wall (see profile number 4) and the maximum velocity to shift from the channel centerline (This was cited a Type II flow by Connor (12), as opposed to a Type I flow where the maximum velocity is along the channel centerline). If this occurs the turbulence production increases, improving the heat transfer.

This lamination and subsequent transition to turbulence has been observed to cause a localized deterioration in heat transfer in developing aiding flow in vertical pipes, and peaks in wall temperature. Many examples of this phenomena are given by Jackson and Hall (13).

3. Reactor Applications

Figure 6 summarizes some of the findings of the transient BNWL 2 x 6 tests (5). They measured fluid temperatures and velocities under various transient flow and steady power skew conditions, and compared the results to COBRA-WC predictions. For the high Reynolds number flows, good agreement was obtained with the standard COBRA turbulent mixing model ($w' = BS\bar{G}$), and for lower flow rates satisfactory agreement was obtained with $w' = 0$ (no turbulence mixing). However, for $Re < 450$ turbulence was observed to be generated by interacting "thermal plumes", or zones of locally heated

fluid which rise more rapidly than the bulk fluid in the subchannel. For this case w^1 was correlated as:

$$w^1 = .01 \frac{G_r}{Re^2} \hat{Q}_p$$

where Q_p is the ratio of local to bundle average heat generation rate. Thus w^1 is not uniform throughout the bundle, and varies with transient time since Re is an imposed function of time. No buoyancy induced turbulence was observed in the steady state runs (4).

The observations of the transient tests can be explained in terms of the phenomena discussed in Section 2. As GR/Re^2 increases in the turbulent flow regime, laminarization occurs. Further increase in $\frac{G_r}{Re^2}$ causes a Type II profile to develop (called "thermal plume" in 5) and turbulence production increases. The fact that the runs were transient should not change the essence of the phenomena of turbulence production.

The observation that buoyancy induced turbulence existed in the transient but not steady state runs is reasonable on the following physical basis: The flow field of Figure 7a is broken up into an inertia-dominated region (core) and a viscous-dominated region (close to wall). If the flow transient of Figure 7b is imposed, a steady profile (1) will develop with the flow rate at Q_1 . When the flow coastdown occurs, the flow in the inertial region will decrease faster

than in the viscous region, and a Type II profile may develop (3), causing buoyancy induced turbulence. When the second steady flow (Q_2) is reached, the flow rate in the viscous layer (which has lagged behind the core flow coastdown) can reduce to another steady flow profile (4). Thus, a Type II profile (and buoyancy induced turbulence) is expected to occur at a lower $\frac{G_r}{Re^2}$ for a flow coastdown than for a steady flow.

The phenomena of laminarization and buoyancy induced turbulence seem to qualitatively explain some of the observations of the BNWL 2 x 6 test. Further verification that these are in fact the phenomena at work will aid in modeling of COBRA input parameters under mixed convection conditions. It is also important to determine if laminarization will occur locally, and cause peaking of wall temperatures, as has been observed for mixed convection in vertical tubes.

4. Development of a Version of COBRA-WC compatible with MULTICS FORTRAN

Efforts are underway to convert the COBRA-WC code from CDC compatible FORTRAN to MULTICS FORTRAN for use at MIT. Figure 8 shows the procedure used for producing a compilable COBRA-WC program tailored to the size of a given problem. In this way the code utilizes only the core storage required for the problem at hand.

First, the program SPECS is used to properly dimension the COMDECKS depending on the size of the problem at hand.

(A comdeck is a set of declarative statements: dimension, common, equivalence, etc.). One input file contains the case size data, and the other input file the dummy dimensioned comdecks. The code performs a character-by-character search of the input file for dummy dimension parameters. Each statement is written to an output file with the dummy parameters replaced by integers calculated by SPECSET or supplied in the input file of case size data.

Next, program CSPECS is used to insert the dimensioned comdecks produced by spec set into a dummy COBRA-WC code. This is done by searching the COBRA-WC dummy input for statements of the form*

```
* call specXX
```

and replacing them with the appropriate dimensioned comdeck, which is read in on unit 1. The output is a correctly sized compilable version of COBRA-WC, which is then compiled.

COBRA-WC produces three output files: an echo of the input data; a dump file if a later restart is required; and the actual results of the calculation. For bare rod bundles, the entire input file must be constructed by the user, but for wire-wrapped bundles, geometric input data can be calculated by the auxiliary program GEOM, as indicated in Figure 8.

Work will be continuing in the next quarter on the code conversion.

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Figure 1

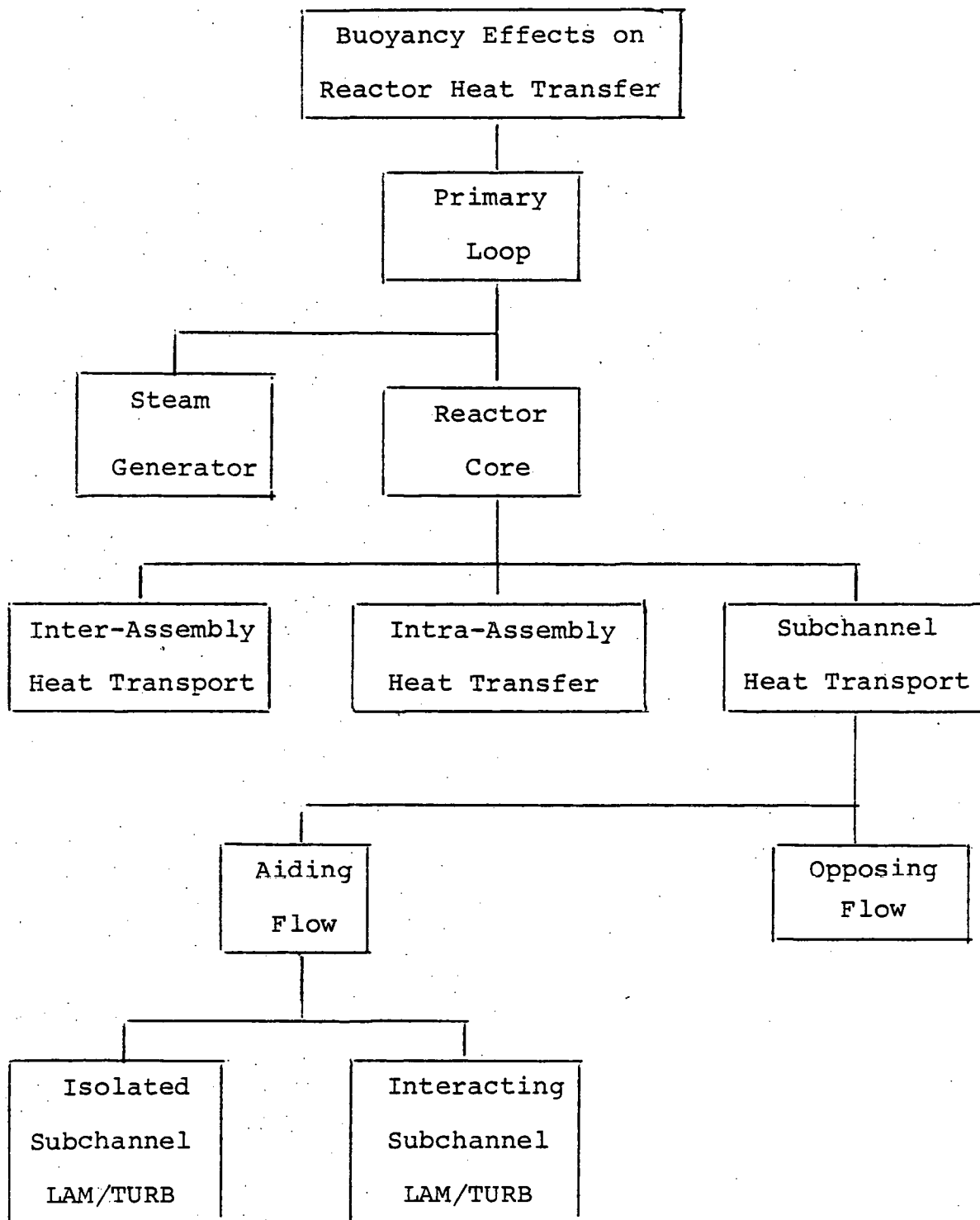


Figure 2

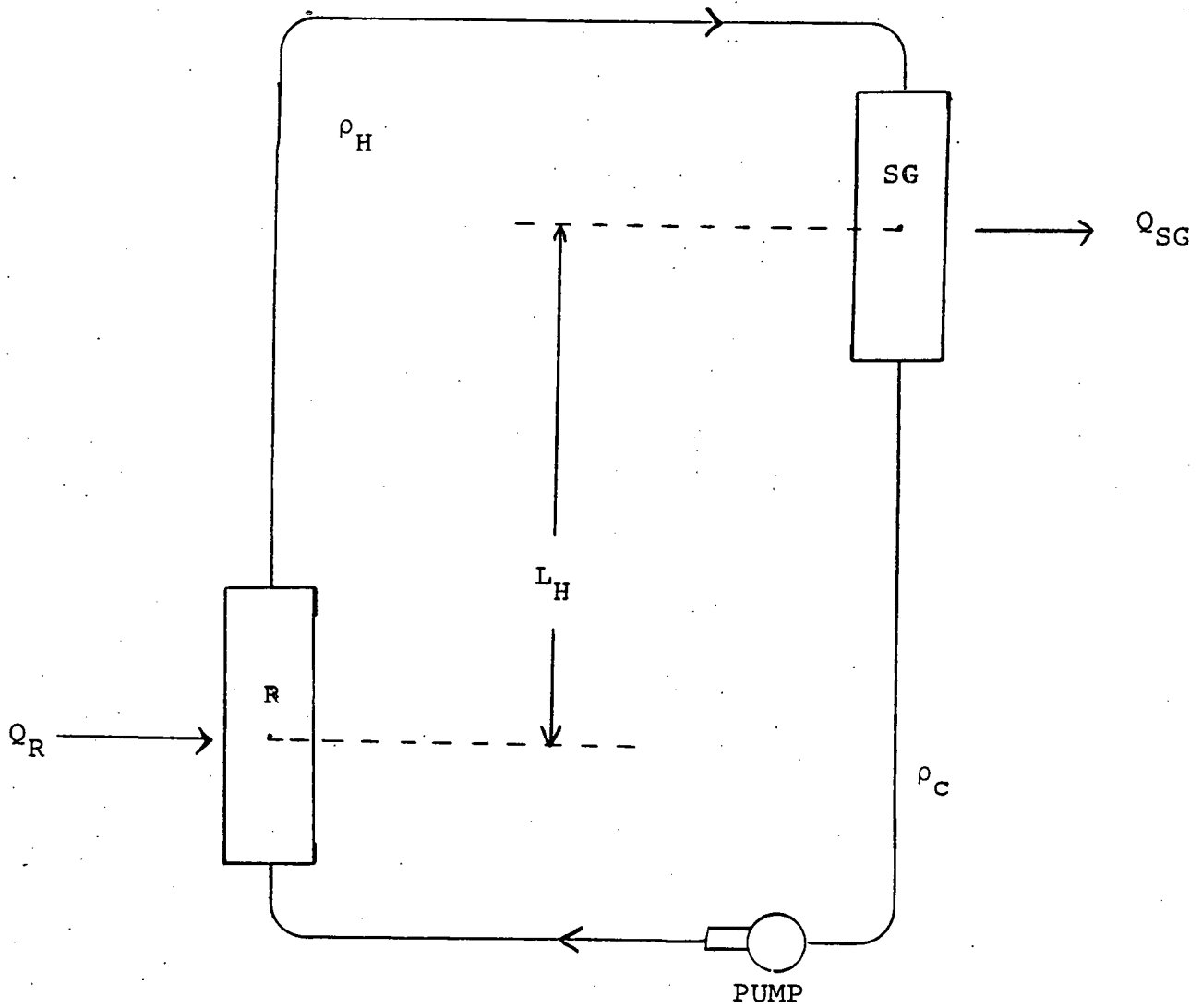
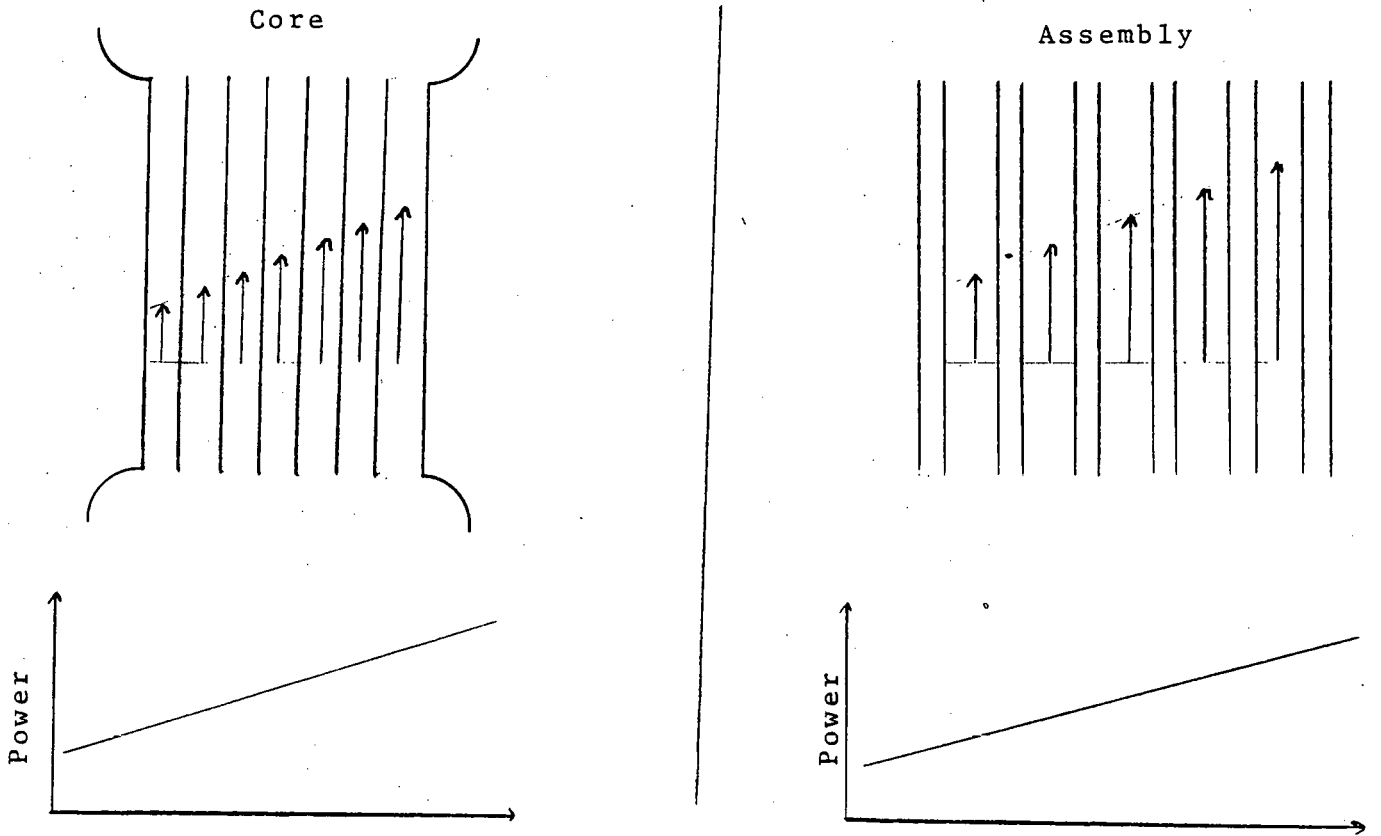


Figure 3

Moderate Radial Power Skew



Severe Radial Power Skew

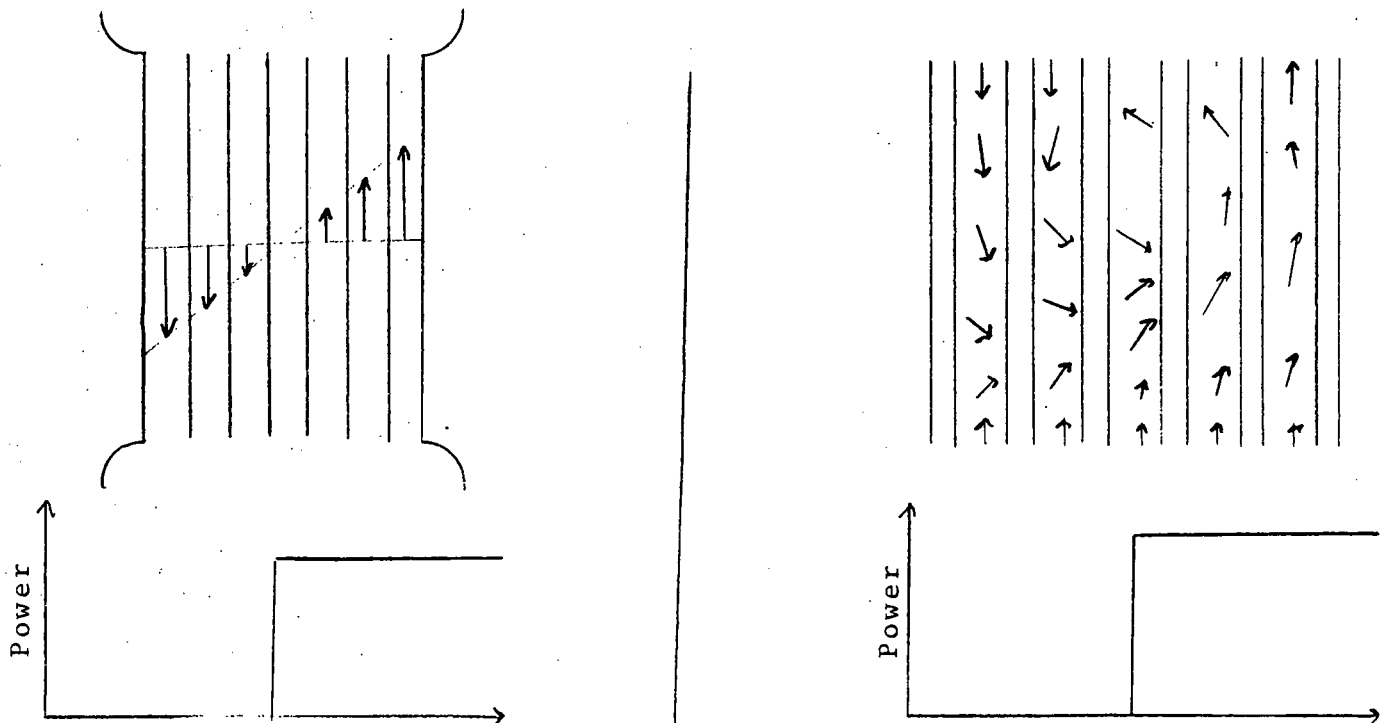


Figure 4

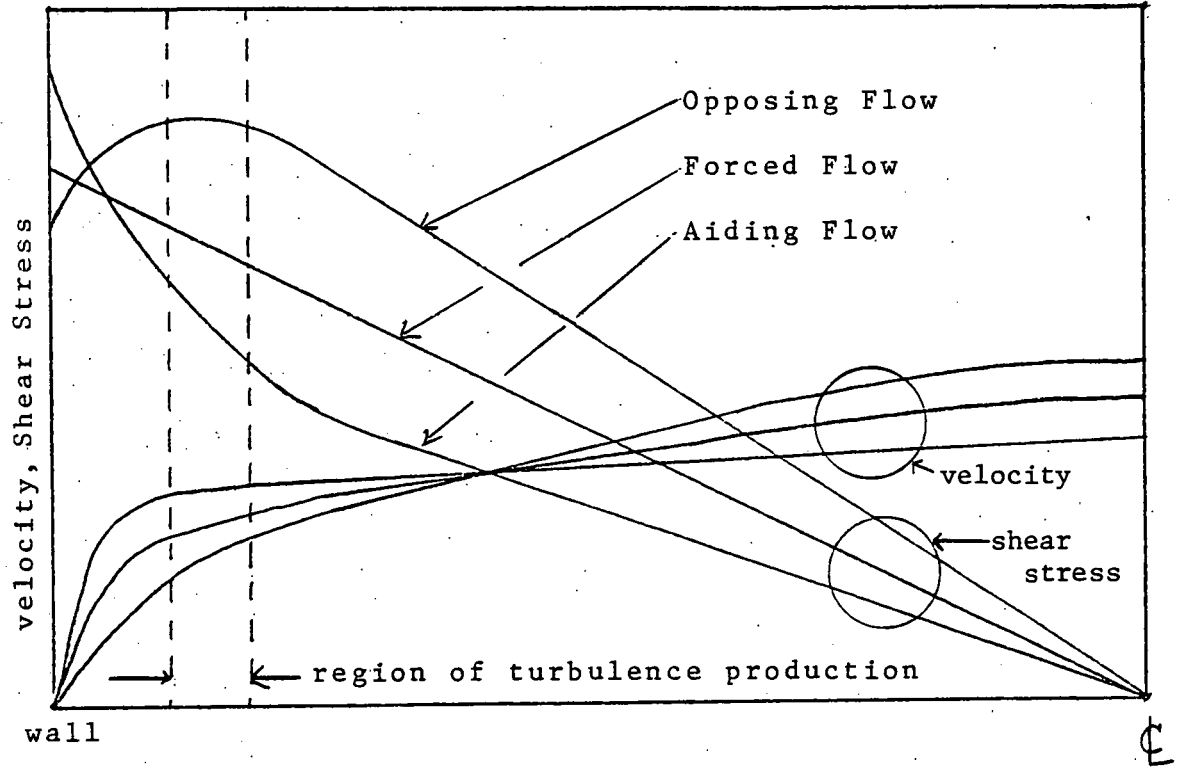


Figure 5

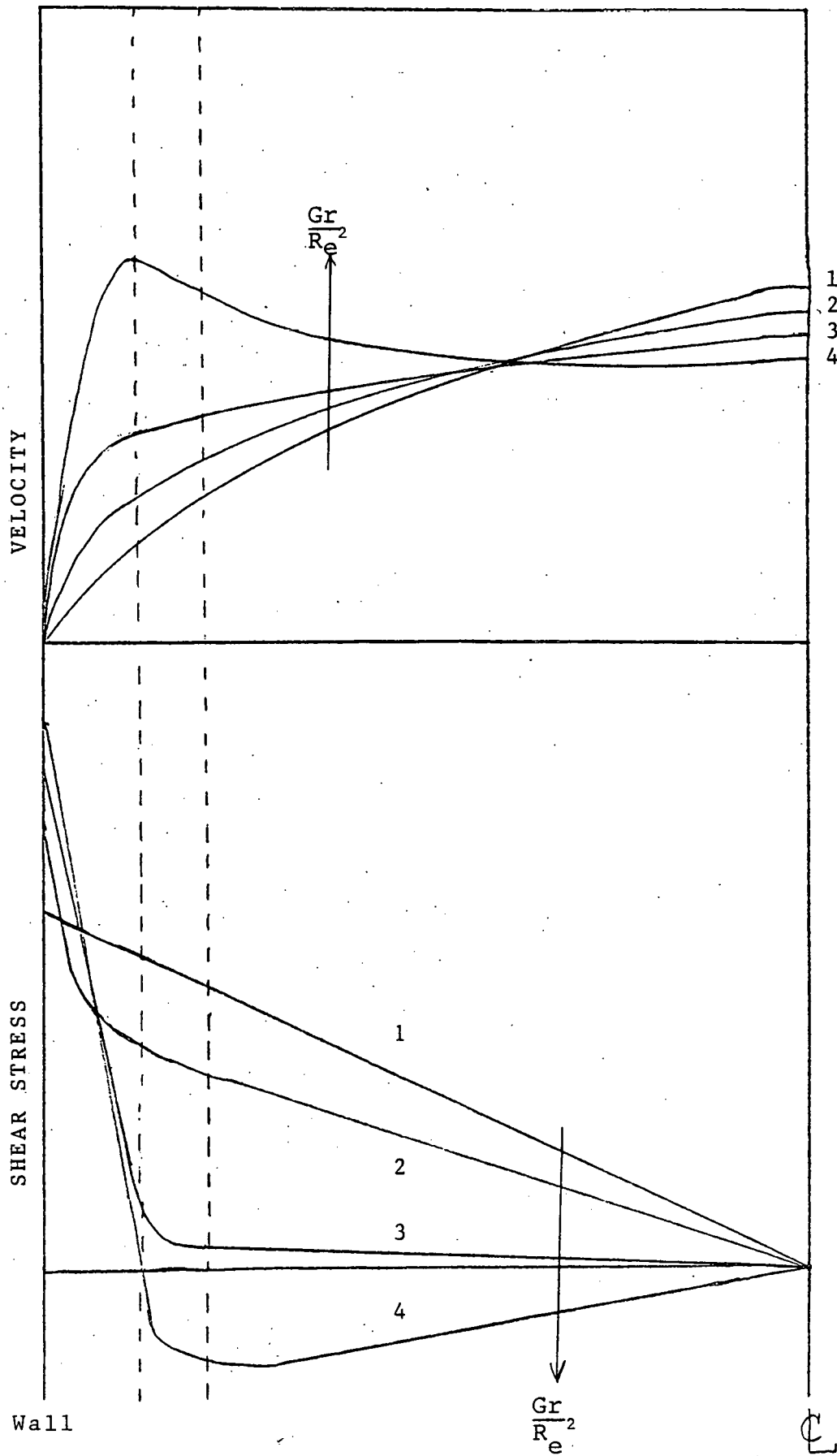


Figure 6

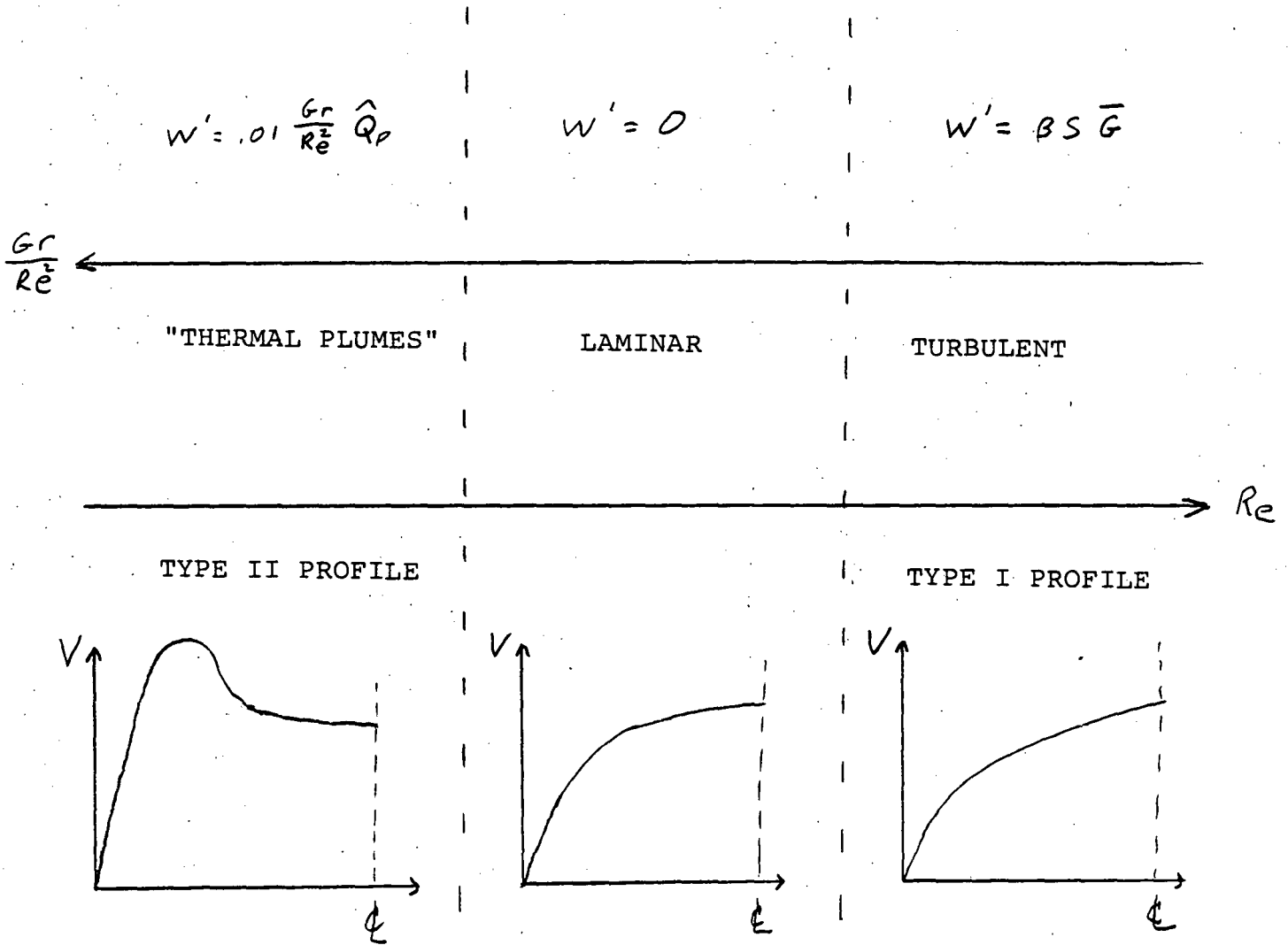


FIGURE 7a

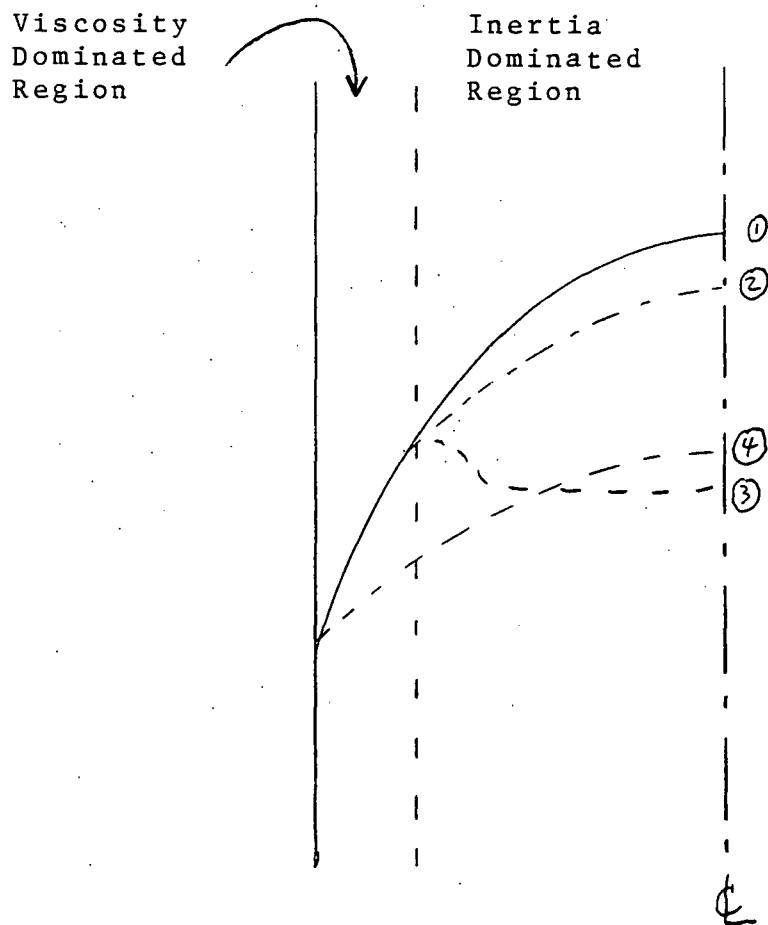


FIGURE 7b

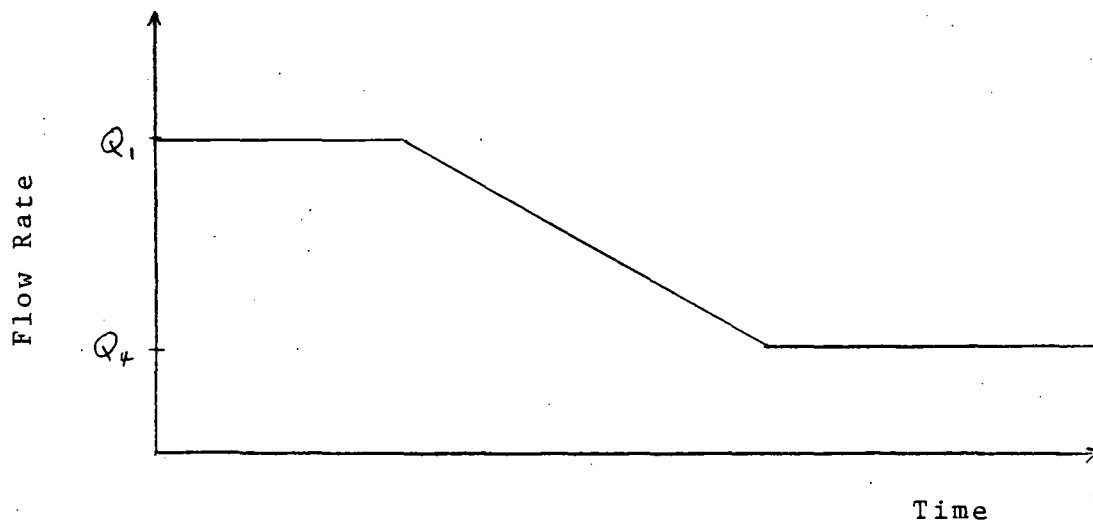
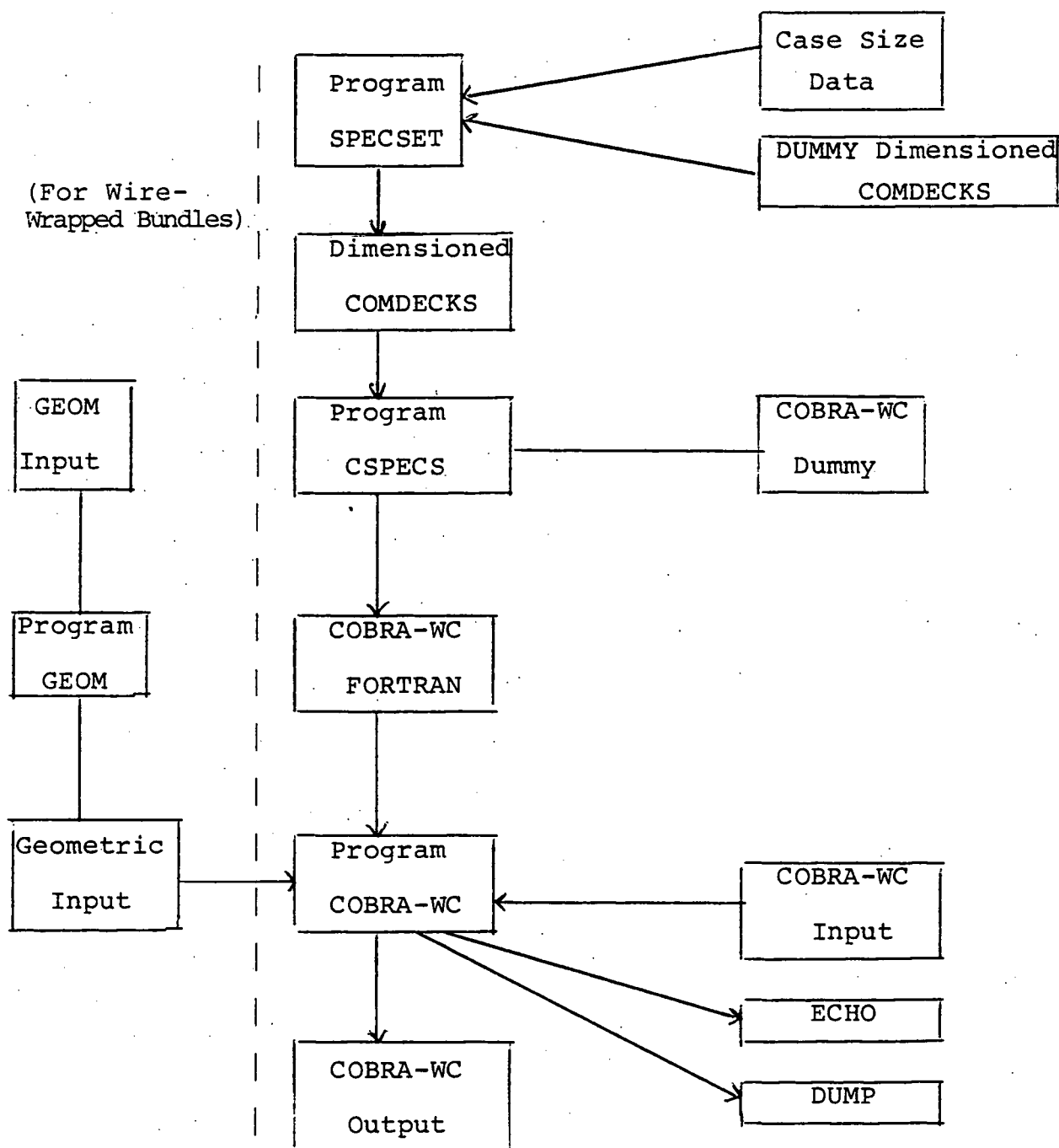


Figure 8

Flowchart for Running COBRA-WC



I.D.4.1 Models for Mixed Convection - Subchannel
(Song-Feng Wang)

Work in this area has been completed and will be reported in topical report DOE/ET/37240-73TR.

I.D.4.2 Models for Mixed Convection - Assembly
(Song-Feng Wang)

In this quarter, the construction of the test loop for mixed convection experiments and the conversion of the the BODYFIT code to our MULTICS system were completed. The BODYFIT code will be utilized to predict our test bundle performance.

The test loop, as illustrated in Figure 1, is a once-through water loop. The water flowing through the test section can be arranged for flow in either the upward or downward direction by adjusting various valves. With minor modification the test loop can be operated as close-loop with natural circulation developed between the test section and the driving tank.

To convert the 3D, distributed parameter code BODYFIT from the IBM system to MULTICS system, modifications of the code were made in the following areas:

- 1) Change the I/O statements such that they are compatible to MULTICS system.
- 2) Substitute the IBM system subroutines such as CLEAR, TLEFT, by the equivalent MULTICS subroutines.

3) Modified the high order nested DO-loop to lower order; for example, change the following statements:

```

DØ^1111^NQ = 1,6
DØ^1111^NP = 1, NPINS
IF (NPNQ (NP, NQ) .EQØ) ^GØ^TØ^1111
DØ^1111^K = 1, KMAX
DØ^1111^I = 1, NC
TCØLD (I, K, NP, NQ) = TCL (I, K, NP, NQ)

```

1111^CONTINUE to

```

DØ^1114^NQ = 1,6
DØ^1113^NP = 1, NPINS
IF (NPNQ (NP, NQ) .EQ.Ø) ^GØ^TØ^1113
DØ^1112^K = 1, KMAX
DØ^1111^I = 1, NC
TCØLD (I, K, NP, NQ) = TCL (I, K, NP, NQ)

```

1111^CONTINUE

1112^CONTINUE

1113^CONTINUE

1114^CONTINUE

4) Add the water thermodynamic property package.

The new H₂O package includes the following functions:

a) Liquid Internal Energy, E_{ℓ} (J/kg) ^[1]

$$E_{\ell}(P, T) = E_{\ell \text{ sat}} + (P - P_{\text{sat}})(a_1 + b_2 P_{\text{sat}}^2)$$

where:

$$P_{\text{sat}}(T) = c_1 [d_1(T+273.15) + e_1]^{f_1}, \text{ for } 0 < T < 380^\circ\text{C}$$

and

$$E_{\ell\text{sat}}(T) = a_2 + b_2 T + c_2 T^2 + d_2 T^3 + e_2 T^4, \text{ for } 0 < T < 275^\circ\text{C}$$

$$E_{\ell\text{sat}}(T) = a_3 + b_3 T + c_3 T^2 + d_3 T^3 + e_3 T^4, \text{ for } 275 < T < 338^\circ\text{C}$$

$$E_{\ell\text{sat}}(T) = a_4 + b_4 T + c_4 T^2 + d_4 T^3 + e_4 T^4, \text{ for } 338 < T < 380^\circ\text{C}$$

b) Liquid Density, ρ_ℓ (kg/m³) [1]

$$\frac{1}{\rho_\ell} = a_5 + b_5 P + c_5 P^2 + (d_5 + e_5 P + f_5 P^2) T + (g_5 + h_5 P + k_5 P^2) T^2$$

where P is in bar.

3) Liquid Specific Heat, C_{p_ℓ} (J/kg/K) [2]

$$C_{p_\ell} = \{ a_6 + b_6 P + [(c_6 + d_6 P) + e_6 + f_6 P] h_\ell \} h_\ell^{-1.0}$$

where

$$h_\ell = E_\ell + \frac{P}{\rho_\ell}$$

4) Liquid Thermal Conductivity (J/m/S/°K) [2]

$$k_\ell = a_7 + b_7 x + c_7 x^2 + d_7 x^3$$

where

$$x = \frac{E_\ell}{5.815 \times 10^{-5}}$$

5) Liquid Viscosity, μ_l (N.S/m) [3]

$$\mu_l = \frac{25.3}{(T+91)T-8.58 \times 10^{-4}}, \quad T \text{ in } ^\circ\text{K}$$

In above equations, the input data P is in N/m^2 and T is in $^\circ\text{C}$ unless otherwise stated. The constants a_i to k_i are listed in Table 1.

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TABLE 1

	a	b	c	d	e	f	g	h	k
1	$-8.33544E^{-4}$	$-2.24745E^{-17}$	$1.0E^{+5}$	$8.48896E^{-3}$	-2.1663837	4.48430493	--	--	--
2	$1.73671E^{+4}$	$3.7402E^{+3}$	4.02435	$-1.57294E^{-2}$	$3.1301E^{-5}$	--	--	--	--
3	$6.18527E^{+6}$	$-8.14547E^{+4}$	$4.46598E^{+2}$	-1.04116	$9.26022E^{-4}$	--	--	--	--
4	$2.2837885E^{+9}$	$-2.62215677E^{+7}$	$1.12948667E^{+5}$	$-2.16233985E^{+2}$.155283438	--	--	--	--
5	$1.00213623E^{-3}$	$-5.6327855E^{-8}$	$-8.97130477E^{-12}$	$-2.28287459E^{-8}$	$4.76596787E^{-10}$	$5.021318E^{-13}$	$4.10115658E^{-9}$	$-3.80398908E^{-12}$	$-1.42199752E^{-15}$
6	$2.394907E^{-4}$	$-5.19625E^{-13}$	$1.193203E^{-11}$	$2.412704E^{-18}$	$-3.944067E^{-17}$	$-1.680771E^{-24}$	--	--	--
7	.573738622	.253610355	-.14546827	$-1.3874725E^{-2}$	--	--	--	--	--

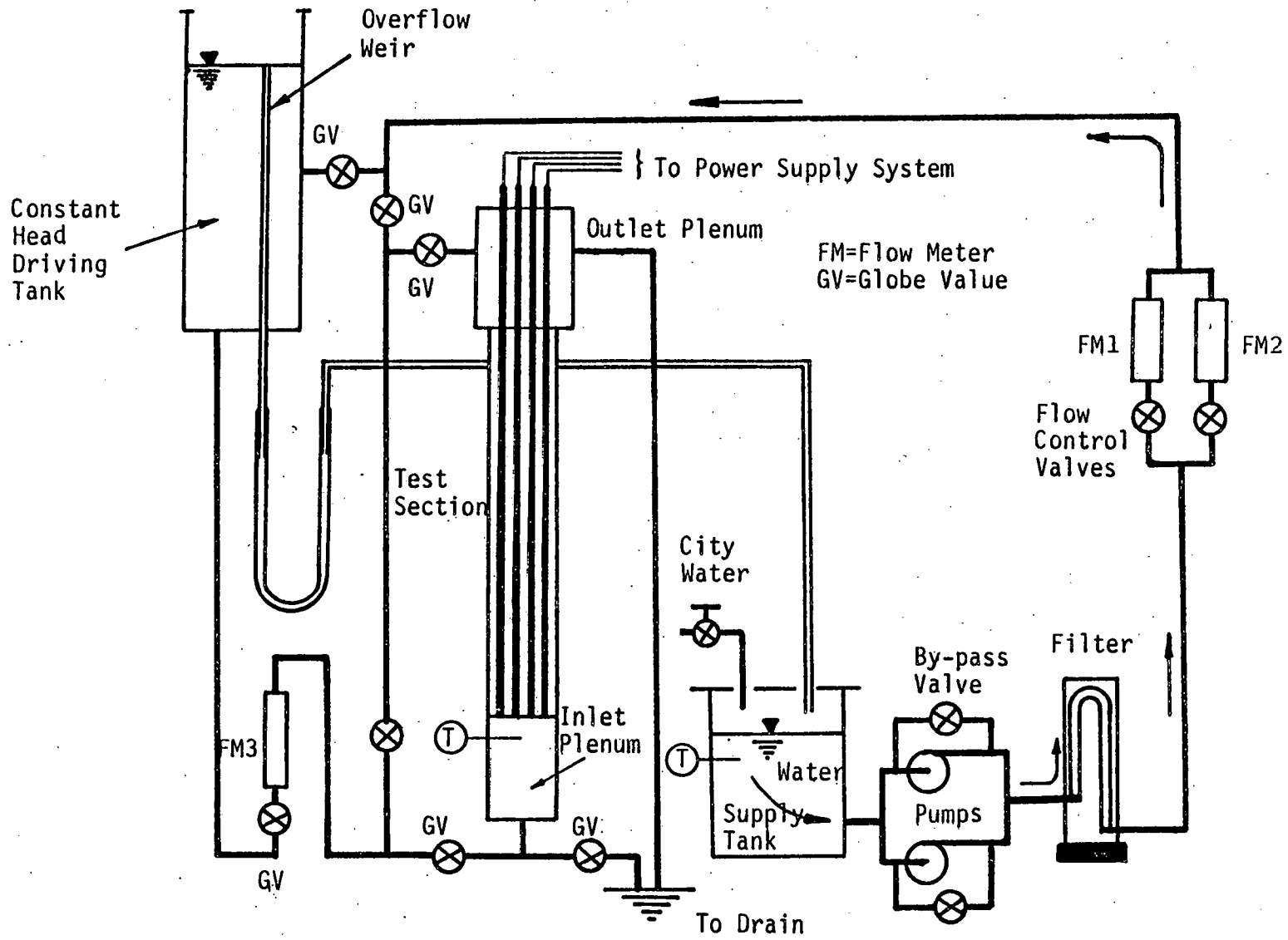


Figure 1 Design Scheme of the Test Section

I.D.4.3 Models for Mixed Convection-Core

(Paul Symolon)

Results of this work are reported under
I.D.4 of this report.

I.D.4.4 Predictors of Inception of Mixed Convection

(Tom Greene)

Work on this task was last reported in Report
No. DOE/ET/37240-76. The results of this work will
appear as a topical report in the near future.

I.D.5 Shape Factors for Transverse Conduction in

Rod Bundles

(Tom Greene)

No work was performed on this task during the
current quarter. The latest information in this area
was in Report No. COO-2245-72.

TASK II SUBCHANNEL GEOMETRY

This task was completed and last reported results appear in Report No. COO-2245-45TR, July 1977 which is listed under B.1-Original Topical Reports.

TASK III LMFBR OUTLET PLENUM FLOW MIXING

Three-Dimensional Steady Isothermal Flows
(Robert W. Sawdye)

During the period of this progress the student working in this area was at Batelle Northwest Laboratories working with Dr. D. Trent on TEMPEST development to become more familiar with the code.

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

Wire-Wrapped Rod Bundle Heat Transfer Analysis

(Chung-Nin Channy Wong)

Introduction

In the past quarter of the year, the computer code Flow 3DT has been upgraded so that it is capable of solving energy equation as well as momentum equations. Moreover, a turbulent mixing model which applies Prandtl's mixing length hypothesis has been added in the code. So, the present version of the code can handle any laminar or turbulent flow and heat transfer problem of simple geometry. Test problems have been run and their results will be discussed in section 2 and 3.

Before the turbulent mixing model and the energy equation solver were included in the code, the code had been modified by programming with object-time dimensioning scheme. The advantage of object-time dimensioning is to conserve storage space and increase efficiency.

Turbulent Mixing Model

The selection of the turbulent mixing model is based upon these following factors: 1) simplicity, 2) economy of computer time, 3) acceptable accuracy, 4) cases to be studied. For the wire-wrapped rod bundle problem, it is reasonable to believe that the swirling velocity around the pin rather than the eddy diffusivity is the driving force of the mixing phenomenon between subchannels. Therefore the investigators

decided to bypass the complicated 1-equation or 2-equation model and select the Prandtl's mixing length hypothesis in our first calculation. The Prandtl's mixing length hypothesis states that the temporal average of the cross-velocity fluctuation,

$$\overline{\rho v_r' v_z'}$$

can be written as the product of the turbulent viscosity, μ_t and the normal gradient of the axial velocity, v_z . The turbulent viscosity, μ_t is equal to the local product of the density of the magnitude of the mean rate of strain and the square of the characteristic length scale of the turbulent motion. In mathematical form, it simply says:

$$\overline{\rho v_r' v_z'} = \mu_t \frac{\partial v_z}{\partial r}$$

and

$$\mu_t = \rho \ell_m^2 \frac{\partial v_z}{\partial r}$$

The first test case is a simple circular duct flow problem. Nikuradse's formula for the mixing length distribution is used. It states:

$$\frac{\ell_m}{R} = 0.14 - 0.08 \left(1 - \frac{y}{R}\right)^2 - 0.06 \left(1 - \frac{y}{R}\right)^4$$

where R is the radius of the pipe
 y is the distance away from the wall.

This formula is fed into the code, and the code will calculate the turbulent viscosity and solve the flow problem. Figure 1 shows the axial velocity profile at two different levels at time = 9 seconds. Figure 2 plots the pressure distribution along the pipe. The friction factor, f which is defined as follows:

$$f = \frac{1}{4} \frac{\Delta P}{\left(\frac{1}{2} \rho U_0^2\right)} \frac{D_h}{L}$$

can be calculated by evaluating the gradient of the profile and taking one-half of this value. This gives 0.003232 from the graph, while according to Moody's chart it should be 0.006651. There is a factor of two difference between these two values. The best explanation of this difference is our calculation has not reached the equilibrium state after 9 seconds from the startup time. Longer running time is needed in order to reach steady state. Results from the second calculation will be discussed in the next progress report.

Solving the Energy Equation

In references 1 and 2 we have stated that the coupling between momentum and energy equations is extremely weak. This allows us to solve momentum and energy equations separately. Since in the momentum equation the convection term and the viscous term are treated explicitly, the size of the time step is limited according to the Courant condition in order to maintain the stability. When we solve the energy equation, we

we intend to keep the same value of the time step. Thus, in order to maintain the stability of the discrete energy equation in several cases, we have to treat the heat conduction term implicitly. At the present version of the code, if the Prandtl number of the working fluid is less than 1, the code will automatically treat the conduction term implicitly. This requires a successive over-relaxation iterative method to generate a solution for the coolant temperature.

Two cases have been studied. The first case is to study the slug flow heat transfer of a circular pipe. The other is to study the fully developed laminar flow heat transfer of a circular pipe. The temperature profile at different levels for those two flow regimes are plotted in Figure 3.

Future Work

The development of the computer code Flow 3DT for the wire-wrapped rod bundle geometry has been underway. Results and discussions will appear in the next progress report.

REFERENCES

1. C-N Wong, "Cooling Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients - Progress Report, December 1979-February 1980."
2. C-N Wong, "Cooling Mixing in LMFBR Rod Bundles and Outlet Plenum Mixing Transients - Progress Report, March 1980-May 1980."

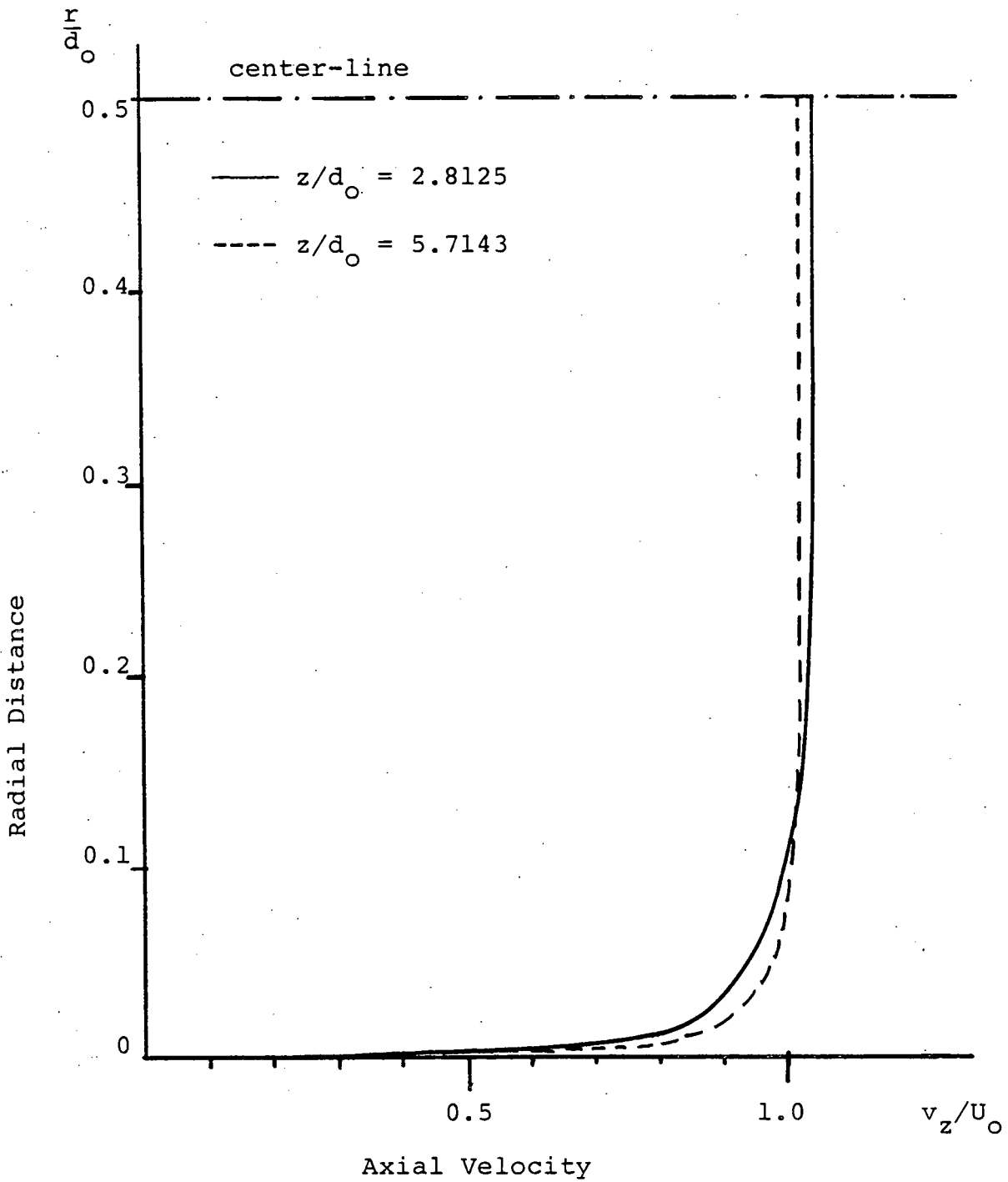


Fig.1 Axial Velocity Profile in a Smooth Pipe
(Dia.=1" , Re=20,000 , water property)

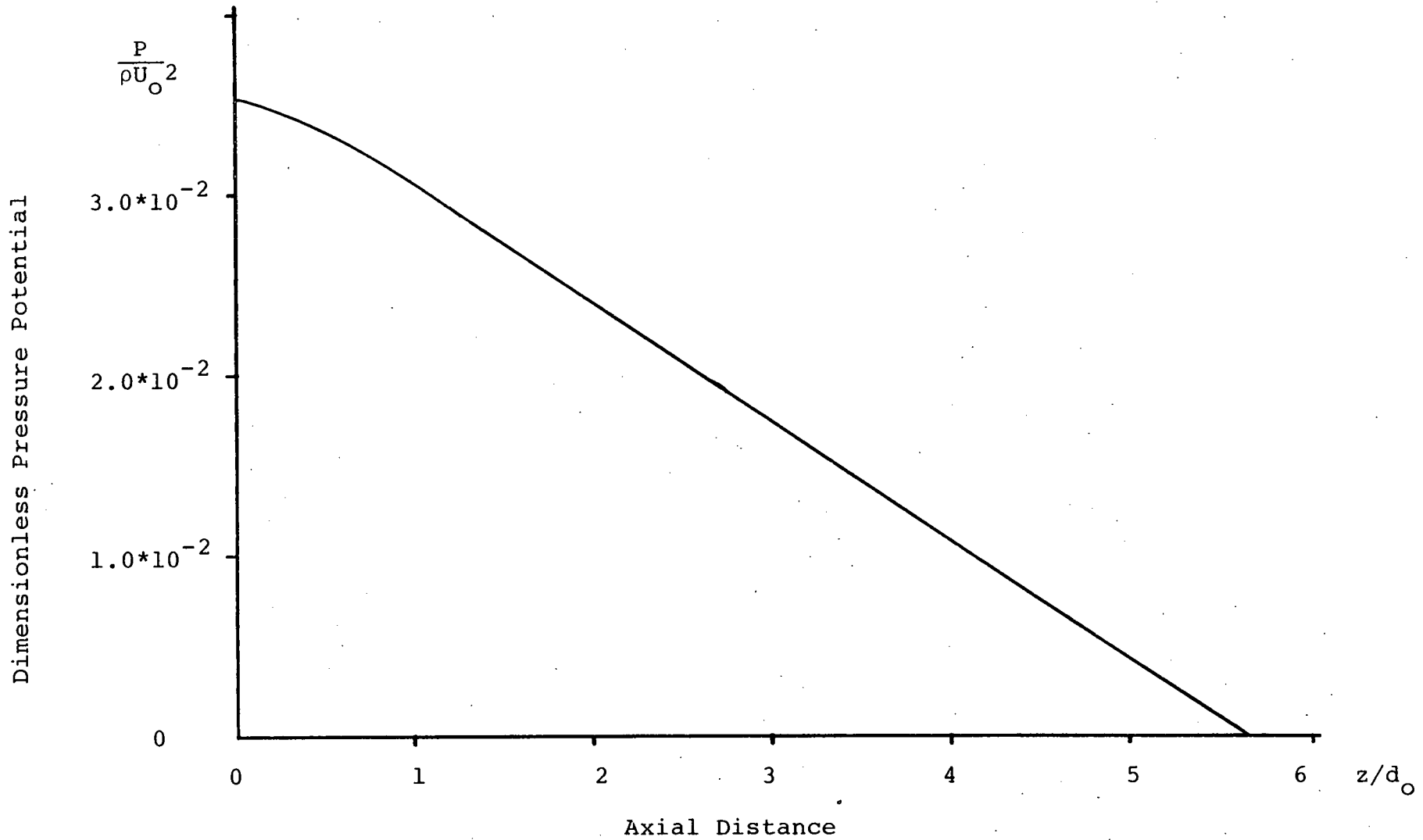


Fig.2 Pressure Distribution vs Axial Distance for a Smooth Pipe
 (Dia.=1" , Re=20,000 , water property)

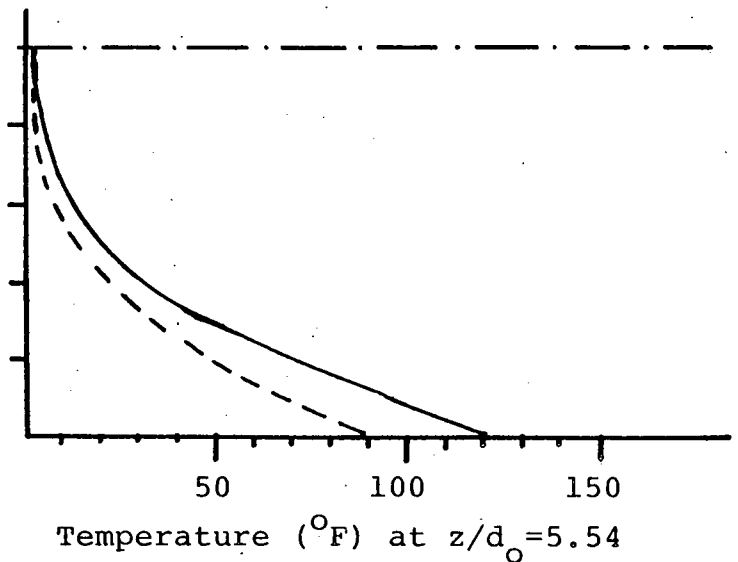
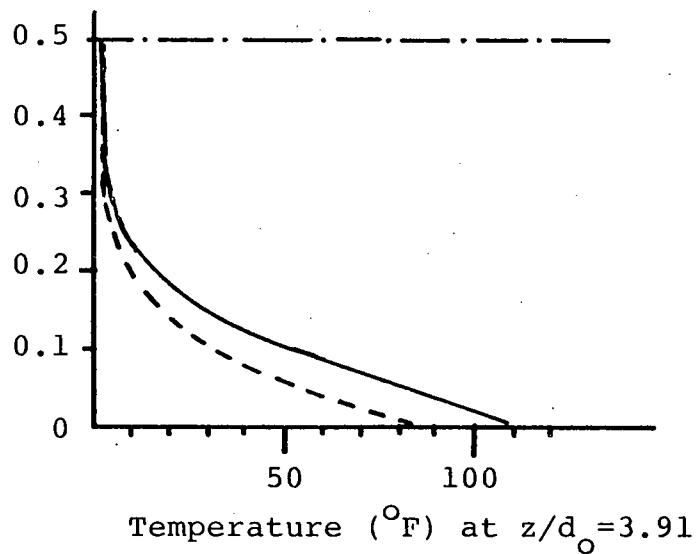
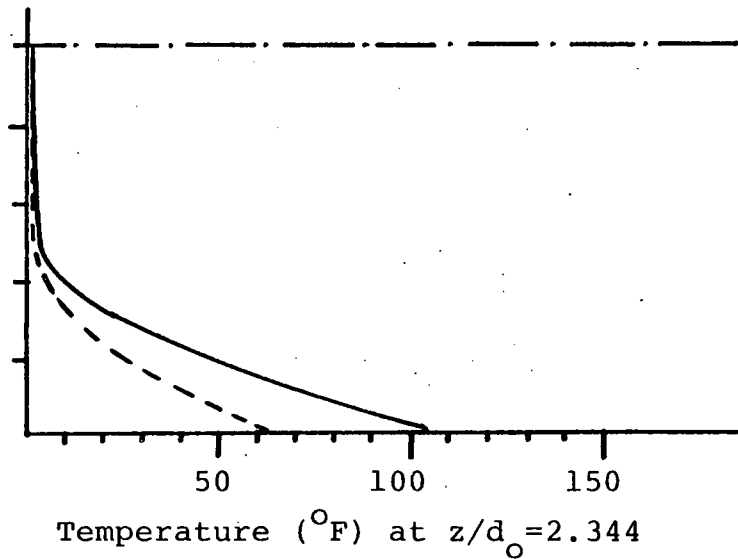
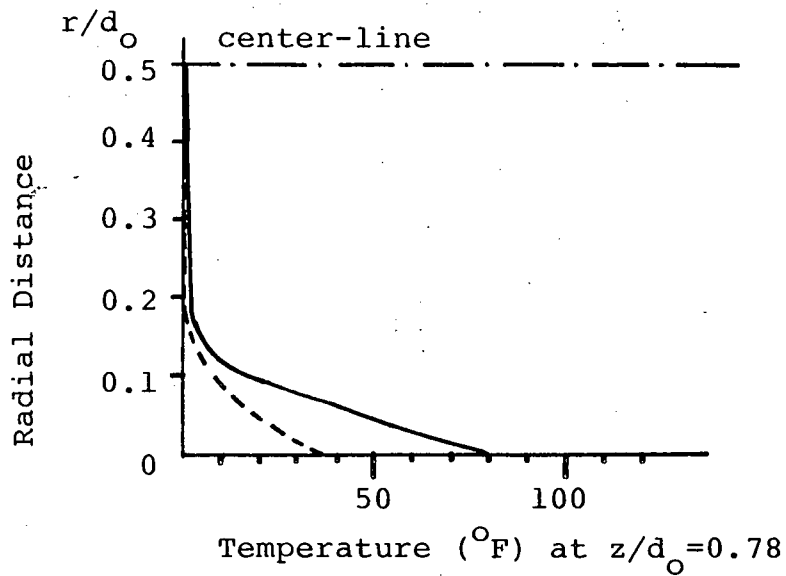


Fig.3 Temperature Profile of a Heated Pipe at different Axial Levels
 straight line (—) for Laminar Flow. dotted line (----) for Slug Flow
 (Dia.=1" , $q''=1 \text{ BTU/sec.ft.}^2$, water property, $Re=200$)