COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Progress Report

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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

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, Sept. 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, Sept. 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.

COOLANT MIXING IN LMFBR ROD BUNDLES AND
OUTLET PLENUM MIXING TRANSIENTS

Contract AT(11-1)-2245

Quarterly Progress Report

December 1, 1974 - February 28, 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

TASK I: BUNDLE GEOMETRY (WRAPPED AND BARE RODS)

TASK IA: Assessment of Available Data (Ehsan Khan)

Efforts in this area are reported under Task ID for this period.

TASK IB: Experimental Bundle Water Mixing Investigation

1) 61-Pin Fuel Experiment (Alan Hanson)

During this quarter work was completed on the collection of data from the first 61-pin fuel bundle which has a 6-inch wire-wrap lead length. Extensive pressure measurements were made in addition to mixing experiments. Figure 1 shows the location of the four pressure taps drilled in the metal flow housing walls at each of two axial locations. The axial levels chosen were exactly two feet apart. An exact multiple of the wire-wrap pitch was chosen to eliminate the effects of local pressure variation and dynamic effects when the pressures at the two levels were subtracted -- the need for the careful spacing was confirmed by the data obtained. The wall taps were placed in the center of each face where they are opposite a rod instead of a flow channel, since this location was expected to have flow parallel to the face. The wall taps at each level were manifolded in such a way that the pressure on an individual face could be measured or any combination of the four faces could be averaged. In addition, pressure differences between the faces at a given level could be measured. To obtain axial pressure gradients, the average pressure on all four tapped faces was measured at each level at high flowrates using absolute pressure gages; at low flowrates the pressure drop between two levels was measured directly using a dual-bellows differential pressure gage. Axial pressure gradients were reduced to friction factors based on an assumed flow split described by Novendstern [1]. The dependence of friction factor on Reynolds number is shown in Figure 2. The experimental data exhibit several interesting characteristics:

- (a) The data lie in general above Novendstern's correlation but within the 14% error band he suggests for the correlation.
- (b) The apparent slope of the data in the turbulent range, 3000-30,000 Reynolds number, is steeper than both the smooth tube correlation and Novendstern's correlation.
- (c) There seems to be no distinct laminar-turbulent transition as in smooth tube flow. Instead the data gradually approach both the turbulent and laminar line asymptotically. This behavior has also been observed by Rehme [2].

Pressure difference across the flats of the hexagonal flow housing were measured directly using the differential pressure gage and found to be quite large. Figure 3 shows these pressure differences as a function of the bundle flowrate. Note that this radial pressure difference exhibits an approximately second order dependence on bundle flowrate as does the axial pressure gradient. In fact the ratio of the radial pressure drop to the axial pressure gradient seems to be a constant. For example, the pressure drop from face C to face F is roughly 47% of the axial pressure drop per wire-wrap pitch over the range of flows in Figure 3.

The most interesting pressure data was obtained by the novel technique of using the salt injection rods as axially traversing pressure taps. The injection rods are ideal for this purpose since they have a small opening, can travel over about 26 inches axially, and are easily disconnected from the salt injection system and connected to the differential pressure gage. By moving the injector rod up in 1/2-inch increments, it is possible to see the axial development of the local static pressure. Figure 4 shows this development for an edge sub-channel at two different flowrates. It is clear from this figure that the axial pressure gradient is highly non-uniform and periodic with the same period as the wire-wrap pitch. The deviation of the local pressure gradient from the average gradient (shown as a dashed line in Figure 4) is substantial. Similar data was taken for a centrally-located interior subchannel; although this data also showed some periodicity, the deviations from the average gradient were very small relative to those observed in the edge channel.

A complete set of salt tracer mixing experiments was also run on the 6-inch lead bundle. The series of four runs which were made are listed in Table 1; this series was done for both an edge channel injection and for an interior channel injection. The first two runs are to demonstrate the axial development of the salt distribution in laminar and turbulent flow regimes. The next two runs are used to determine if there is any effect of Reynolds number on the mixing. Data from these experiments are currently being analyzed and will be reported next quarter.

Work on the data reduction code was continued and largely completed this quarter. The availability of large quantities of experimental data made possible the testing of the code in its entirety. Calibration and mass balance routines were found to function well as expected. New plotting routines were added to facilitate data analysis. The following plots can now be generated offline on a CALCOMP plotter:

- (a) Mass balance vs. axial injection location
- (b) Subchannel salt concentrations vs. circumferential channel location at a given axial location.

In addition online plots of the planar salt distribution for a given axial injector location can be produced. Some minor refinements to the data reduction code still are necessary and will be carried out in the next quarter.

In addition to analysis of the 6-inch data and code refinements already mentioned, work during the next quarter will include installation and experimentation with the 12-inch lead bundle to delineate the effect of wire-wrap lead on pressure fields and mixing.

2) 61-Pin Blanket Experiments (Carl Oosterman)

During the quarter construction of all experimental apparatus was completed. Probe construction is shown in Figure 5. The soldered connection between the platinum wire and the lead wire was coated with epoxy and covered with heat shrinkable insulation after assembly the probe tube was backfilled with polyurethane plastic. The insulation and polyurethane will minimize the possibility of leakage which could short the leads. The probe and upper rod support system is shown in Figure 6. The rubber gland was included to ensure probe positioning would be unaffected by vibration.

The salt injector scheme described in the previous quarterly report was successfully constructed with 30° injection holes. The injector operated perfectly when tested.

The blanket bundle has been completely assembled in a dry run and no problems were encountered. The flow housing has been leak tested without the fuel rods and found tight. The conductivity probes are in the process of being tested for short circuits. Once this is complete the probes can be platinized and the whole bundle assembled in the flow loop. At present both test positions in the flow loop are being utilized. Experiments will begin as soon as one of the positions open, hopefully before the end of March.

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

Due to the unavailability of the hydraulic facility associated with the 61-pin blanket bundle, peripheral velocity measurements were not initiated during this quarter. Present estimates show that the hydraulic facility should be available by early April.

During this period, the following tasks were accomplished:

- (1) The procedure developed by Carajilescov for cross-point alignment of four laser beams with traverse frequency shift using the differential operational mode was exercised.
- (2) Positions errors of the laser beam cross-point were determined due to:
 - (a) Optical unit/test section misalignment
 - (b) Optical bench/test section misalignment.

Task (1)

In this task, four laser beams were produced using two optical units in parallel. A single beam from the laser unit was split into two beams by way of an external beam splitter with supplementary external mirrors (see Fig. 7). Each of the resulting two beams was directed to an optical unit in order to be split into two additional beams (see Fig. 8). Hence, using two optical units, four beams were able to be produced in which the plane formed by one pair of beams was mutually perpendicular to the plane of the other pair of beams. This would potentially enable direct sequential (point-wise) velocity measurements in two mutually perpendicular directions under the condition that all four beams cross at the same measuring point. Since it is anticipated that the traverse velocity component would be relatively small compared to the axial velocity component, and more likely to be subject to 180° directional ambiguity in flow measurements (reverse flow), the frequency unit was applied to the traverse beam pair. The physical effect of the frequency shift unit is to produce a deflected traverse beam pair in addition to the original (undeflected) traverse beam pair. (see Fig. 9).

The final step in the four beam alignment process was to align the cross-point of the axial beam pair to the deflected (or frequency shifted) traverse beam pair.

Task (2)

This task pertains to the determination of beam cross-point position errors due to optical unit/test section misalignment and optical bench/test section misalignment.

The model used to determine the position errors associated with optical unit/test section misalignment is shown in Fig. 10. The beam cross-point positions (x or y) plotted as a function of the misalignment angle γ , is shown in Figs. 11 & 12. (Note that characteristic measurement distances from the test section wall are used -- approximately 0-40 mil range for the blanket bundle.)

The model used to determine the position errors associated with optical bench/test section misalignment is shown in Fig. 13. The beam cross-point position displacement ($l\Delta x$) plotted as a function of optical bench displacement (Δr) for various values of the misalignment angle β , is shown in Figs. 14 and 15. It should be noted that the position errors associated with optical unit/test section misalignment is less severe than the errors associated with optical bench/test section misalignment. However in both cases actual errors will be reduced in practice by realigning beams to one or more reference position in the bundle.

TASK ID: Analytical Methods Development

(a) Ehsan Khan

The analytic models developed include

- ENERGY I - no capability for buoyant effects
- ENERGY II - buoyancy capability through friction and gravitational pressure losses in the axial momentum equation.
- ENERGY III - same as ENERGY II plus convective terms in axial momentum equation included on same principles as the THINC-II [2,3] code.

During this period three topical reports have been prepared which 1) summarize the analytic model development performed to date, 2) present the three codes, and 3) present input data recommended for use in the three codes. These reports which will be issued next quarter are:

- 1) 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 1974.
- 2) E. Khan, W.M. Rohsenow, A.A. Sonin, N. Todreas,
"Input Parameters to the ENERGY Code (to be used with the ENERGY Code Manual) COO-2245-17TR, MIT,
- 3) E. Khan, W. Rohsenow, A. Sonin, N. Todreas,
"Manual for ENERGY Codes I, II, III," COO-2245-18TR, MIT.

(b) Interassembly Heat Transfer Study (Brian Chen)

The existing code, ENERGY, is capable of predicting the temperature distribution for a single assembly with insulated wall condition. By using the prediction of the ENERGY code for each individual assembly in a reactor core, it is not difficult to see that a moderate amount of heat transfer occurs between some neighboring assemblies. In order to estimate these heat transfer effects, a parametric study has been done to estimate the percentage changes of the temperatures in an assembly due to this heat loss or heat gain. After normalizing the percentage change of the temperature by the ratio of the heat loss to the average heat generated within the assembly, we get a two-dimensional map for the temperature change which is independent of the assemblies. This assembly independent map would be very useful in judging whether the inclusion of the interassembly heat transfer would significantly change the temperature in the assembly.

When the inclusion of the interassembly heat transfers are important, a calculation procedure which includes these effects should be used. For this purpose we are preparing a new code capable of predicting the temperature distribution for any combination of any number of fuel and blanket assemblies. Great progress has been achieved in preparing this new code. It is now capable of predicting any combination of any number of blanket assemblies. It has the option of predicting the temperature distribution for insulated assembly as well as for interconnected assemblies with heat transfer between them. It has been structured to require much less input data, better output format and more economical storage space than ENERGY-I.

Future efforts will be on extending the code to include fuel assemblies and to do another interassembly parametric study with this new code.

A separate study was done to determine whether buoyancy effects are important for the design conditions of the Clinch River Breeder Reactor. We found the buoyancy effects are not important for all the assemblies in the core by comparing the calculated Gr^* with Gr_c .

Based on this conclusion thermal predictions of Clinch River blanket assemblies were performed for WARD using ENERGY I. However, these predictions did not yet include the effect of interassembly heat transfer.

(c) Generation of Input Data for Wire Wrapped Bundles
(Frank Carré)

* The study consists of determining the three parameters (ϵ_H , Cl and flow split) needed by ENERGY I and tries to match the theoretical results from this code with the experimentally measured temperatures in each of the following bundles:

-- ORNL bundle 5C (for low and high Reynolds numbers)
Reference [3]

-- W11:1 Scale test Reference [4]

-- Karlsruhe 61 pin bundle.

ORNL Bundle 5C

The parameters ϵ_H^* and Cl have been determined for four experiments. (Tests 46-101, 46-104, 47-101, 47-103, Reference [3]).

The range of Reynolds numbers investigated is (27,000 65,000)

The data obtained from the tests run at the Oak Ridge National Laboratory show heat balances lower than 95% for smaller values of Reynolds number and the present version of ENERGY I does not yet take this heat loss into account. The values

$\epsilon_H^* = 0.006$ and $Cl = 0$ lead to a good fit for the studied cases; they are included in the range of predictions ϵ_H^* (0.0057; 0.0086) Cl (0.0995; 0.2066).

W11:1 Scale Test

This test presently run by the Westinghouse Electric Corporation consists of injecting a gaseous tracer in an air flow streaming through operation of a 217 pin bundle. This experiment aims to simulate a sector of the FTR/CRBRP 217 pin fuel assembly. The ENERGY I code has been converted into a form suitable for gaseous tracer concentration calculation. Two runs have already been done, using the actual geometrical parameters and Khan's prediction for the simulated bundle (Injection channels are a central channel and a wall channel). These predictions will have to be compared with the experimental results to be published next quarter.

Karlsruhe Bundle

No available data from Karlsruhe has been received yet. Nevertheless a comparison of the predictions of both codes will be accomplished in Task (e). Three runs precedently done in Germany using the parameters of the Karlsruhe bundle as input data, have been very useful. Assuming that these runs represent the best fit with the experimental data, it is possible to determine the best parameters (ϵ_H^* and C_1) for ENERGY I.

(d) Generation of Input Data for Gridded Bundles (Frank Carré)

The study takes into account an axial variation of the dimensionless eddy diffusivity parameter ϵ_H^* and tries to match the theoretical results with the experimentally measured temperatures in each of the following bundles:

- Swiss, Japanese bundles
- Karlsruhe bundle
- L.W.R. data (General Electric, Italian)

Only very few data have already been published for heated pin or tracer injection tests in gridded bundles. The only available data for the Swiss or Japanese bundles are friction factor and pressure drop measurements.

Some data relative to the Karlsruhe 61-pin bundle allowed work to start in this area. [Reference 5]

One type of grid (Honeycomb) has already been investigated and the value of ϵ_H^* matching the exit temperatures has been determined. Unfortunately, temperature measurements at a single axial elevation do not allow to determine any axial variation of this parameter. If an exponential variation of

$$\epsilon_H^* = \epsilon_{H_0}^* \cdot e^{-\mu z}$$

is assumed between two adjacent grids, only the average value

$$\epsilon_H^* = \epsilon_{H_0}^* \cdot \left(\frac{1 - e^{-\mu H}}{\mu H} \right)$$

seems to influence the exit temperature.

(e) Comparison: MISTRAL II - ENERGY I (Frank Carré)

The German thermohydraulic code MISTRAL II (Reference [6]) uses two parameters (μ and EF) as input data. The theoretical flow split is calculated the same way as in ENERGY I. It would be interesting to derive a relationship between those two sets of parameters and to express, analytically or numerically (ϵ_H^* , Cl) in terms of (μ , EF). There are presently very few data available and the 61-pins Karlsruhe bundle (Reference [7]) is the only one which has been studied by both codes. This comparison involves several runs of ENERGY I and MISTRAL II with the same geometrical input data.

The study of the finite difference equations used by both programs and the comparison of the scheme of resolution, lead to an analytical relationship between the mixing parameters (ϵ and μ). Using the values of (μ and EF) this relationship yields values of ϵ_H^* in good agreement with the experimentally determined values and Khan's predictions.

The codes use a completely different approach to account for the swirl flow taking place in the wall channels, and the comparison of the finite difference equations valid in this region leads to questionable results. Another point is that Khan's predictions have a wide range of uncertainty (+35% for Cl) and that the runs of MISTRAL II from Germany are assumed to represent the best fit with the still unavailable Karlsruhe data.

Besides the progress reported above, several modifications (conception of a new subroutine generating an automatic way of numbering the subchannels of an hexagonal bundle) have improved the ENERGY I code and runs done with 2A bundles data confirm the results previously obtained. A short translation of the report [6] has been done too.

Next quarter will be spent in further investigation of the three described steps:

- *Analysis of Karlsruhe data as soon as they are available
- *Analysis of gridded bundles data as soon as they are available.
- *Determination of whether or not a good correlation between the parameters (ϵ_H^* , μ , EF) can be analytically derived.

TASK II: SUBCHANNEL GEOMETRY (BARE RODS)

TASK IIA: Assessment of Available Data

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

TASK IIB: Experimental Investigation (Joseph Kelly)

No significant new information was developed this quarter. Data acquisition should be initiated next quarter.

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

TASK IID: Analytic Model Development - Subchannel (Pedro Carajilescov)

During this quarter experimental measurements and analytic work by this investigator were completed. A summary (Appendix I) of this work follows (note the page numbers, figures and references have not been made sequential with this progress report since the summary has been prepared as a document which stands alone). A detailed topical report on this investigation will be issued next quarter.

TASK III: LMFBR OUTLET PLENUM FLOW MIXING

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

During the past quarter work has been carried on in preparation for velocity and temperature measurements in test cells similar to the LMFBR outlet plenum, and analytical work has been performed in anticipation of receipt of the code VARR-II [8], which will be used to predict the behavior of the experiments.

In the temperature measurement effort the primary interest is in developing an optical method of sensing temperature fluctuations, since it is recognized that mechanical means (thermocouples) are unattractive for this purpose, since they disturb the flow and since they have response-times (100 msec) greater than the time scale of the fluctuations (1-10 msec). The method being pursued uses a Mach-Zehnder interferometer, and is described more completely in Appendix II. For the demonstration experiment the needed optical components (mirrors, beam splitters, and mounts) have been obtained, along with the experimental mounting bed (two 12 in. wide flange beams). The experimental cell is currently being fabricated, along with some other minor equipment items. It is expected that the experiment will be set up during the coming quarter.

In the velocity measurement effort the necessary equipment is assembled at MIT, but is currently being used in Subtasks I and II of this project. The test section for the velocity measurements (to be performed using the DISA Laser Doppler Anemometer) is shown in Fig. 16, and is currently being fabricated. It is expected that the experiment will be assembled, and check-out tests performed during the coming quarter.

A major portion of the work in this task has been devoted to the analytical effort -- in an extensive literature survey, and in preparing modifications to the code VARR-II, which will be implemented when it is received (anticipated in early April). The literature survey has been concerned with compiling a library of published zero-, one-, and two-equation turbulence models; and with understanding their differences and the tests to which they have been subjected. This survey is continuing, since the body of literature to be examined is large.

Approval has been obtained for the proprietary code VARR-II to be provided to the project, and in anticipation of receiving it the code description manual has been used in planning required modifications. These involve adding a transient energy equation to be solved along with the equation set currently in the code (this is required if non-convective energy transport effects are to be accounted for in calculating local density), examining how the code must be modified in order to accommodate alternative turbulence models (in most new-turbulence equations will be required), and investigating what programming changes would be required to operate using the IBM-360 computer of the MIT Laboratory for Nuclear Studies. (The code was written for a CDC system, and the major necessary modifications are expected to involve the input/output statements.) It is expected that the code will be received, and made operational at MIT during the coming quarter.

References

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TABLE 1
MIXING EXPERIMENT PARAMETERS

<u>RUN</u>	<u>FLOWRATE</u>	<u>REYNOLDS NUMBER</u>	<u>FLOW REGIME</u>	<u>INJECTOR AXIAL LOCATION</u>	<u>INJECTION CONCENTRATION</u>
1	55 GPM	5645	Turbulent	1" - 26" *	4%
2	10 GPM	1026	Laminar	1" - 26" *	4%
3	5-1156 GPM**	513-11804	Laminar- Turbulent	12"	4%
4	5-1156 GPM**	513-11804	Laminar- Turbulent	24"	4%

* Data takes at 50 different axial locations.

** Data takes at 10 different flowrates.

61 PINS
 $D = .250''$
 $P/D = 1.26$
 $L = 6''$

PRESSURE TAPS LOCATED AT 1'
FROM EXIT AND 3' FROM EXIT.
TAPS LOCATED AT CENTER OF
FACES, 4 SIDES ONLY.

FIGURE 1
PRESSURE TAP LOCATIONS

FIGURE 2 - FRICTION FACTOR VS. REYNOLDS NUMBER RELATION

FIGURE 3- RADIAL PRESSURE DROP

Probe Construction
Figure 5

Probe and Rod Support Scheme

Figure 6

Fig. 1

Fig. 8

Fig. 9

Fig. 10

OPTICAL UNIT/TEST SECTION MISALIGNMENT

X vs δ (Fig. 11)

Case 2 : $m = 680 \text{ mils}$
 $T = 1'' = 1000 \text{ mils}$

Y vs γ (Fig 12)

Case 2: $m = 680 \text{ m/s}$
 $T = 1'' = 1000 \text{ m/s}$

Fig 13

Optical Bench / Test Section
Misalignment Model

Fig 15 $|Ax|$ vs Δr (Vertical Displacement)

Fig. 16 Velocity Measurement Test Cell