A REVIEW OF RECENT ANALYTICAL AND EXPERIMENTAL STUDIES APPLICABLE TO LMFBR FUEL AND BLANKET ASSEMBLY DESIGN

by

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1. **Introduction**: In this review the recent analytical and experimental efforts for predicting flow and temperature fields in LMFBR wire wrapped assemblies are critically discussed and the 'State of Art' presented. Points of similarity and differences between various studies in this area are indicated in an effort to form a coherent picture of the accomplishments and future analytical and experimental needs.

For the steady state, single-phase operating conditions of liquid metal fast breeder reactor, the mixing phenomena and their resulting fields are potentially significant for designing to limits in the following areas:

1. Cladding hot spot
2. Fuel and blanket assembly flow housing bowing and deformation
3. Sub-channel blockages

In addition to the above, the thermal hydraulic optimisation of the reactor blanket design requires accurate prediction methods for temperature fields. Thus a definite need exists for development of accurate methods for predicting temperature fields in rod arrays of different configurations and sizes and at various Reynolds numbers (Laminar to very high values of Re) and power skews across and along the bundle.
2. **Analytical and Experimental Studies**

Energy redistribution in a wire-wrapped fuel assembly takes place by the following mechanisms\(^{(2)}\):

(a) **Thermal Conduction** - characterised by the thermal diffusivity, \( \alpha \).

(b) **Turbulent Exchange on a Molecular Level** (including flow scattering) without a net transfer of fluid. The dimensionless group characterising turbulent exchange is, \( \frac{W_{Tij}}{\bar{W}} \), where \( W_{Tij} \) is the turbulent exchange rate and \( \bar{W} \) is the average bundle flow rate.

(c) **Cross-Flow** - any convection of fluid due to a radial pressure gradient can be classified as cross-flow. Cross-flow can be subdivided into two categories:

1. **Diversion Cross-Flow**: That fraction of the total cross-flow between any two sub-channels that occurs due to a pressure gradient set up by virtue of the dissimilarities in local hydraulic characteristics (either geometrically, hydrodynamically or thermally induced). For example, (figure 1) as the wire lead to diameter increases to very large values (\( \frac{h}{d} \rightarrow \infty \)) the hydraulic diameter of channels \( i \) and \( j \) would be locally different at various axial levels causing flow to redistribute itself by diversion cross-flow. Thus the varying axial and transverse flow resistance in the presence
or absence of wire wrap can cause diversion cross-flow.

Diversion cross-flow may be characterised by the term,

\[ W_{Dij}/\bar{W} \]

(2) Flow-Sweep: For wire-wrapped rod bundles of \( p/d > 1.18 \) the axial flow has no direct vertical path through the bundle (1) but at regular intervals crosses the wire and is swept from one channel to another due to the favorable pressure gradient set up by the wire. This sweeping effect of the wire would extend a small distance below and above the location where the wire crosses the gap. Thus the axial momentum of flow in a subchannel is periodically changed by the presence of the wire. The fraction of axial momentum carried by the sweep flow in the transverse direction can be considerably greater than that carried by diversion cross-flow, depending upon the wire lead to diameter ratio. For rod bundles with \( p/d < 1.18 \) a part of the fluid can flow vertically upwards in a bundle and part of it will be periodically swept into other channels. The flow field for such a bundle would be even more complex than for a bundle with \( p/d > 1.18 \).

Flow sweep may be characterised by the term, \( W_{Sij}/\bar{W} \) (or \( W_{Sij}/W_i \))

Swirl Flow: The sweep flow in the wall channels has characteristics which are different from that in the central channels. Whereas the sweep flow between two subchannels in
the central parts of the bundle changes direction periodically, the sweep flow between two wall channels is always in the same direction. This sweep flow along the housing wall is known as the swirl flow. The swirl flow, perhaps, fluctuates about a mean value. It is characterised by the term, \( V_0 / \bar{V} \), where \( V_0 \) is the velocity in the gap between the rod and the wall and \( \bar{V} \) average axial bundle velocity.

Most experimental effort has been to quantitatively determine these four mechanisms individually if possible and their dependence upon geometrical and flow parameters. The major emphasis has been in determining flow sweeping, perhaps because it is the least understood and the most important means of momentum and energy transfer. Once these mechanisms are known, they are direct input into the sub-channel analysis computer programs as they are now formulated.

2.1 Experimental Studies

Table 1 shows a list of experiments along with the bundle size which have been or shortly will be conducted. Most of these are for the fuel rod assemblies except for the Japanese, 19 pin tests, and WARD 7 and 61 pin tests, which are for the blanket assemblies. Most of the experiments use water as the working fluid since it is hydrodynamically similar to sodium. Tests with heat addition are the ORNL 19 pin and 37 pin tests which use liquid sodium as
coolant. The important features in these experiments are described below and also in Table II.

(a) 7-pin wire wrap mixing test (Ref. 3) The 7-pin tests were primarily conducted to test the isokinetic sampling technique to be employed later on a larger bundle and to determine the wire wrap induced sweep flow (listed as (d) in previous section). Reliable bulk concentration data have been obtained within the first spacer pitch. In addition axial subchannel flow rate measurements were made for both peripheral and central subchannels. It was found that the axial flow in the central channel measured at increments of 1/6th spacer pitch was constant. Although fluctuation probably does exist, on the average a uniform flow rate is a good approximation. The average flow rate in the central as well as the wall channels could be predicted using the program DROP,(4) which was based on existing pressure drop correlations (27) for calculating flow split and pressure-drops in wire-wrapped bundles. A sweep flow model was developed by the authors as follows:

\[ \frac{W_{SIJ}}{W_1} = \frac{p_S}{6} \cos \left( \frac{2\pi x}{p_S} + \alpha_{ij} \right) + \psi \]

For central subchannels \( \phi = 0.5, \; \psi = 0 \)

For wall subchannels \( \phi = 0, \; \psi = 2\phi \)

24%/in. for central subchannels
fluctuates between 24%/in. and
72%/in. for wall subchannels
The authors assume these correlations to hold constant regardless of bundle size. An interesting result is the existence of high swirl flows along the wall which can be 2 to 3 times greater than specified by the wire-wrap angles. Reynolds numbers were varied from 12000 to 60000 during the test with no appreciable dependence of sweep flow on Reynolds number.

(b) 19-pin hot water injection tests (Ref. 5). The hot water injection tests have the advantage over salt injection-conductivity probe tests in as much that striping effects would be reduced. However there is no reason to expect that they would provide any better bulk subchannel data than the isokinetic sampling tests described in (a). In addition to providing local sweep flow rates an additional feature of these tests are that it may be possible to determine local (averaged over a small axial distance) axial subchannel velocities, definitely a desired quantity, by recording the phase shift in response of two thermocouples located at a known axial distance in that subchannel. Thus by autocorrelation techniques significant data regarding the hydraulic performance of the bundle could be obtained.

The authors in their tests found that for central sub-channels, 

\[ \left( \frac{W_{Sij}}{W_1} \right) \approx 30\% / \text{in.} \]

It was found that the sweeping cross-flow induced by wire-wrap spacers, is strongly dependent on location both in regard to magnitude and direction. It is interesting to note that
the maximum sweep flow is of the same order of magnitude for two geometrically dissimilar bundles (Ref. 3 and Ref. 5).

(c) 91 pin tests on scaled model of wire wrap bundle (Ref. 6)
The pitot tube measurement of actual velocity profiles across a wire-wrapped assembly shows several interesting features. The axial velocity profile across the bundle was similar at two different axial levels, showing flow was fully developed at about \( \frac{L}{d_e} \approx 50 \). Also in the subchannel immediately next to the wall subchannel there is a dip in the average axial velocity. Some of the codes like THI-3D show this dip in their calculation. Another interesting result is that the subchannel peak velocity does not occur at the subchannel centroid.

(d) 91-pin isokinetic-sampling test. These tests will be a continuation of the 7-pin tests described in (a) and would independently confirm the findings of the 91-pin hot water injection tests described below. Also the larger bundle results would provide valuable insight on scaling swirl flow and sweep flow with bundle size.

(e) 91-pin hot water injection tests: (Ref. 7)
The tests are extensions of the 19 pin hot water injection tests (b) to 91 pins. Apart from valuable information on scaling laws for swirl flow, these tests being conducted at present, would provide the following additional information:
(a) Inlet radial pressure gradient

(b) Effect of injection geometry and velocity will be thoroughly investigated. This would help in interpreting results from those previous experiments where this affect was not fully established.

(c) Cross-flow measurement

(d) Subchannel local velocity measurements as described in (b)

(e) M.I.T. confirmation of wall channel axial and peripheral velocity using Laser Doppler Velocimeter.

(f) Effect of entrance conditions

A few preliminary results have been reported in Ref. 8. It was found that swirl flow does exist and a few of our manipulations (see below) show that $\overline{V}_\theta / \overline{V} \approx 0.140$ where $\overline{V}_\theta$ is the average circumferential velocity and $\overline{V}$ is the average bundle axial velocity. It is necessary to note that represents the mean peripheral velocity at the rod gaps. It is interesting to indicate that the M.I.T. analysis of the Oak Ridge 19-pin data shows $\overline{V}_\theta / \overline{V} \approx (0.12-0.14)$ [Manipulations: wire wrap angle is given by $\tan \theta = \frac{\pi (d+t)}{p} = 0.078$

$$\overline{V}_\theta / \overline{V} = \frac{\overline{V}_\theta}{\overline{V}} \cdot \frac{V}{V} = 0.078 \times 1.6 \times (1.109) = 0.14$$

where a factor 1.3 reported in Ref. 8 is omitted as it is assumed that it is entirely due to diffusion effect.

(f) ORNL 19 heated pin (sodium coolant) data (Ref. 10)

The Oak Ridge data in the FFM-2A bundle has been analysed
at M.I.T. and a computer program 'Energy' was developed. Analysis of FFM-2A data shows existence of a large swirl component of flow along the duct wall. A unique feature of these experiments is the existence of an exit rake containing thermocouples that can measure coolant temperatures in sub-channels. Most of the other data, except wall thermocouple data, is hard to reduce into a readily usable form. Effect of bundle size on mixing and swirl flow will be determined by experiments on 37 heated pins shortly to be conducted.

(WARD 7 and 61 pin tests (Ref. 11))

The radial blanket in the LMFBR must be designed to accommodate steep spatial gradients in thermal fluxes which change with time. The wide range of operating conditions of the radial blanket assemblies and their drastic design differences from core assemblies necessitates detail investigation of heat transfer performance. The WARD 61 pin tests are, perhaps, the first blanket assembly experiments which will be conducted in liquid sodium. The blanket assemblies are geometrically dissimilar to fuel assemblies (e.g., d=0.52 in., p/d=1.077, d_w=0.037 in., wire pitch ~ 2 to 4 in.) with thermal flux across the bundle as high as 3.5:1, while the flow may be either in the laminar, transition or turbulent flow regime. The existing analytical methods would have to be modified to include the effect of buoyancy. These tests would provide an independent source of data with which the current analytical methods would be verified.
(h) **M.I.T. 61 pin test** (Ref. 12)

The M.I.T. experiments will use salt injection - conductivity probe detection scheme to determine flow sweeping for a wide range of geometrical and flow conditions. Laser techniques are being currently employed to determine the swirl flow component in the wall channels.

(i) **Battelle - 7 pin water tests**: Tests are planned for flow and cross-flow measurement in a 7-pin wire wrap assembly using the laser technique.

(j) **AI - 217 pin tests** (Ref. 13) AI performed tests with a salt tracer in a 217 pin wire wrapped rod bundle. AI reported that the tests showed that the average wall channel velocity equals the bulk average axial velocity for the assembly over one axial pitch length of the wire wrap. In addition, the tests clearly show that the lateral peripheral velocity vector angle has about the same magnitude as the wire wrap angle. A complete set of data has not been published and hence is not available for our inspection.

(k) **JAPANESE (19 and 61 pin) Tests** (Ref. 14). The Japanese 19-pin experiments were conducted for the blanket assembly and the 61 pin tests for the fuel assembly. Pressure drop, velocity distribution at the exit of the bundle, vibration and deformations, as well as mixing was measured. These
experiments are unique in as much as the above mentioned four different types of measurements were conducted on the same bundle.

The most interesting feature of these tests are the velocity distributions both for the blanket and fuel assemblies. The results are strikingly similar to those of Bump and Monson (6) in that there is a dip in the axial velocity of the channel directly connected to the wall channel but the velocity near the central regions is higher. The velocity distribution in a transverse direction is W-shaped. In addition, the peak velocity does not occur at the centroid of the channels but is shifted in the direction of the wire wrap for all channels. The axial velocity profiles at three different flow rates are very similar. There appears to be asymmetry in the axial velocity profile across the bundle. The size of the pitot tube used in this study is not stated.

The mixing experiments were not as sophisticated as the ones described earlier. The distance between the salt injection plane and the salt detection plane was fixed. Salt detection probes were many inches downstream (approx. 4-5 wire-wrap pitch) as a result of which the tracer was uniformly dispersed in the cross-section of the bundle, at the measurement plane. Consequently a simple solution to the diffusion equation was found to be adequate to describing the transverse tracer concentration at the detection plane. An interesting result was that the eddy diffusivity varied linearly with Reynolds number for the fuel assembly in the turbulent flow
regime. A similar dependence was observed in Ref. 9 on analysing the ORNL 19-pin data. However, the blanket assembly does not show a similar dependence.

It is not clear if sensitivity studies on different types of injection geometries and injection flow rates were made by the authors. Thus it is difficult to determine if the difference in results of the fuel and blanket assemblies can wholly be attributed to the difference in geometries or to the difference in injection geometry and flow rate. Recent studies (8) show that for injection normal to the main flow stream as adopted in the Japanese blanket tests both the injection hole size as well as injection velocity affect the results. Axial injection was found to be most reliable. In view of this the absolute magnitudes of mixing coefficients obtained from the Japanese data may be in some doubt. The ANL studies were, of course, made for wall channels but, lacking any other data, for the time being it may be safe to assume a similar result holds for injections in interior channels.

(1) HEDL 217 pin data (Ref. 15) The HEDL 217 pin data uses salt tracer and conductivity probe detection technique to determine sweep cross flow and mixing coefficient rates as well as swirl flow rates at the wall. The data does not appear to be good within one wire-wrap pitch of the injection point due to striping effects. Also wall channel injection data does not appear to be within the same degree of accuracy as the rest of the data. It may now be assumed as indicated previously in (k) that this may be due to the effect of injec-
tion geometry and injection techniques. Nevertheless, the average interior total channel sweep cross flow was found to be 20% of channel axial flow per inch. This is not too far from the results of Refs. 3 and 5. In addition there was definite evidence of the existence of a swirl flow along the wall whose average direction was slightly greater than half the helical wire wrap angle. An interesting result was that the flat-to-flat pressure difference measured for the bundle were as high as one psi. Such large radial pressure differences, if they actually exist, would necessitate further development of new analytical models for describing the flow field.

Swirl flow distribution in the transverse direction perpendicular to the wall needs to be studied to further check if the swirl flows for the 217 pin bundle are actually lower than for smaller bundles or if the distribution of swirl flow is such that the range of sensitivity of the conductivity probes which are mounted on the rods is incapable of sensing its existence.

2.2 Analytical Studies

The analytical/computational effort leading to code development has been classified into five distinct categories (Table 3).

Category 1: The calculation technique developed by Okomoto et al (14) is a single region model for the whole assembly. The diffusion equation is solved to determine the tracer concentration axially downstream. At 4-5 wire wrap pitch down-
stream good agreement with data is obtained. The method is similar to other subchannel analysis codes which do not have a directional forced sweep flow model in them. HEDL data (15) was originally analysed using the COBRA II code which employs a non-directional mixing model. Reasonably good results were obtained many inches downstream of injection point.

Category 2: The ENERGY computer program (9) is a simplified approach developed for the designer. It employs a two-zone model to describe the mixing process in wire wrapped fuel assembly. It has been possible to normalise the two coefficients in this model using a portion of the ORNL data to predict the remaining ORNL data which covered a wide range of Re and power skews. A detailed topical report will shortly be published.

Category 3: The COBRA IIA (16) computer program is similar to COBRA II but it includes the effect of subchannel flow area variation as the wire sweeps in and out of it.

Category 4: Category 4 includes marching codes (initial value problem - no iteration) which were developed, with considerable simplifications, so that reasonable temperature mapping of the LMFBR core could be obtained in a short code running time. These codes generally omit axial momentum and pre-specify entrance velocities to each channel and cross-flow
between coolant channels. These codes cannot fundamentally handle flow blockages.

The ORRIBLE code (17) employs some of the basic COBRA analytical models. The local axial flow area does change due to the presence of wire. The axial momentum in each coolant channel is conserved by allowing diversion cross-flow to occur. Radial momentum is not conserved. The wire forces the flow in phase through each of the three lateral gaps during a 60° wire rotation by using a 1/2(1+ cos 30) function; with no forced lateral flow occurring during the following 120° of wire rotation in each respective gap.

The FULMIX code (18) also does not change the vertical flow area for the channels as a function of wire position. The wire is assumed to force the flow laterally through the gap by a step function that acts for ±60° of wire rotation (i.e., 60° on each side of the position where the wire fills the gap between two rods). There remains a 30° interval on each side of the ±60° step function for each lateral flow path where the lateral flow is not forced. Thus a lateral iteration is performed at each axial step to satisfy the continuity and energy equations. The axial coolant velocities remain constant.

The CÔTEC code (19) does include the local area change due to the presence of wire in a coolant channel, thus diversion cross-flow effects are included. The sweeping effect of the wire is accounted for by a square wave step function
that acts during the $60^\circ$ wire rotation increment immediately preceding the gap closure by the wire. This leaves $120^\circ$ of wire rotation with no forced flow component, for each of the three respective lateral flow paths. Thus a lateral iteration on continuity equation is required. The local vertical velocities oscillate due to the pumping action.

The FORCMX code (13) assumes the local area of flow channel to be unchanged due to the presence of the wire resulting in a constant average vertical coolant velocity for the interior flow channels. The local lateral and vertical flow components are adjusted in the near-wall and wall channels by using a simple potential flow model to account for the presence of the housing wall. The analytical models are adjusted by experimental data from AI fuel assembly hydraulic tests. The cross-flow mixing rate is included as an adjustable constant. The flow field is explicitly defined with the help of existing hydraulic flow data.

Category 5: The COBRA III (20) and THI-3D (21) computer programs are two of the few subchannel analysis codes that attempt to solve a boundary value problem. For PWR inter-assembly mixing calculation the THINC I-A (22) and TOAD (23) computer programs also solve a boundary value problem, though in a slightly different manner. The THI-3D iterative scheme is similar to that of THINC codes.

The COBRA III C program solves the continuity, axial
momentum, transverse momentum and energy equation for each channel simultaneously. The inlet flow distribution as well as the exit pressure distribution, two of the required boundary conditions, must be known. The program incorporates a forced cross-flow mixing model for flow sweeping. A more complete transverse momentum equation that includes spatial acceleration of the diversion cross flow, is included. The COBRA programs suffer from the drawback that for their particular application to full size LMFBR rod bundles excessive computational time and storage is required. This was one of the motivations for producing codes like ORRIBLE, COTECH, etc. However, its capability to handle flow blockages and transient capabilities make it an attractive tool.

The THI-3D computer program was particularly developed for LMFBR mixing and subchannel flow blockage applications. The boundary conditions known are the inlet enthalpy, density and the inlet and exit pressure distribution. The inlet flow is iterated upon until the exit pressure distribution is satisfied. The code solves the continuity, energy and axial momentum equations for each channel with cross-flow coupling. The coolant properties are evaluated at each axial step as a function of both temperature (like other codes) as well as pressure. The author uses correlations for sweep flow, turbulent exchange and diversion cross-flow to calculate the flow coupling terms. Variation of channel area due to the presence of wire is taken into account and the axial velocity distribution obtained. The subchannel division in THI-3D is
Unlike other computer programs. Usually a subchannel is formed by 3-adjacent rods. THI-3D uses a hexagon around each rod as a subchannel, as this reduces the total number of channels and thus reduces the code running time.

The running time for a 217 pin entity is about 1 hour/iteration and each run requires about 4 iterations. The author justifies the large computational times required by the rigorous nature of the code. That is, "the rigorous code would require much less empirical calibration and the calibrating experiments, while requiring precise instrumentation and geometric control, need not be as prototypic with respect to bundle size and geometry."

To date THI-3D has not shown its versatility in handling different geometries. For example, the code was calibrated with ORNL 19-pin mixing tests. It over-predicted the swirl in the 217 pin HEDL tests (15) and underpredicted it in the ANL 91 pin tests (8). This does not necessarily mean that the code will not be able to meet its goals if further improvements in the models are made.
3.3 Discussions, Comments and Suggestions

The current state of the art is discussed after identifying the various areas which appear to be important for LMFBR mixing. These are listed below.

A. Hydrodynamic Aspects
   1. Mixing Mechanisms – Resulting Flow and Pressure Field
      a. Turbulent exchange including Flow Scattering ($W_{Tij}/\overline{W}$)
      b. Cross-Flow
         1. Diversion Crossflow ($W_{Dij}/\overline{W}$)
         2. Flow Sweeping by the wire ($W_{Sij}/\overline{W}$)
         3. SWIRL Flow along the duct walls ($V_{\theta}/\overline{V}$)
   2. Development of flow field-entrance effects
      and length required to obtain fully developed flow
   3. Effect of bundle size on hydrodynamics – wall effects

B. Instrumentation and Measuring Techniques – Future Experiments

C. Computer Programs – Analytical Effort and Possible Improvements and Needs
3.3.1 Summarized - Recommendations

A. Hydrodynamic Aspects

1. Work needs to be done to understand the interaction between the various modes of mixing.

2. Effort to determine cross-flow resistance between non-similar subchannels is required.

3. New correlations for sweep flow at low h/d ratios and low Reynolds numbers needs to be developed.

4. Axial and cross-flow resistance for corner, side and central subchannels for a wide range of Re should be determined.

5. The entrance length required to attain fully developed flow and correlations for its determination must be determined. In addition the effect of bundle inlet geometry and influence of inlet hydrodynamic parameters on downstream flow must be investigated.

6. Effect of rod to wall spacing, bundle size and wire-wrap lead on swirl flow must be determined.

7. Experiments on point velocity measurement are desired to understand the 'mixing' phenomenon.

8. Measurement of transverse pressure gradient across the bundle at various axial locations is desired.

9. Experiments on heat transfer coefficients in the presence of entrained gases are needed to
relate existing temperatures measured by thermocouples on rods and wire wraps to subchannel mean temperatures.

B. Instrumentation and Measuring Techniques

1. The injection geometry, location of injector and effect of injection velocity needs to be investigated in order to obtain consistent and accurate results for both wall and central channels.

2. Optimum location of detection instrumentation (thermocouples, conductivity probes) needs to be studied to obtain results that can be used with convenience to compare with predictions from the present thermal analysis codes.

C. Analytical Effort and Computer Programs

1. Entrance length required to attain fully developed flow needs further analytical study.

2. Analytical methods to predict point temperatures distribution should be developed for wire wrapped bundle - to help in interpreting data properly as well as to determine the optimum channel configuration for use in subchannel analysis codes.

3. At present the need for codes that solve a boundary value problem for predicting steady state temperature distribution in unblocked wire wrapped assemblies is not clearly established. Until it is, continued uses of type 2 and type 4 codes is acceptable with the following modifications:
a. Buoyancy effects should be included to extend the applicability of the codes to blanket assemblies.

b. The treatment of wall channels should be more spatially detailed to allow the prediction of temperature gradients as necessary for the interpretation of wall thermocouple data.

4. The following expansions to the boundary value formulations is suggested.

a. Transverse momentum balance should be included in the formulation of the boundary value codes in order to maintain consistency of the hydrodynamic description of the flow field with the detailed input boundary conditions.

b. Inlet pressure or flow distribution is one of the required boundary conditions for boundary value codes. This boundary condition is an unknown for any practical situation. It is recommended that this boundary condition be determined by the method outlined.
A. HYDRODYNAMICS

1. Mixing Mechanisms: It is extremely desirable, but very difficult, to predict the individual effects and their interactions, i.e. turbulent exchange, diversion cross-flow and flow sweeping, on 'mixing' within rod bundles (Rec.1). In any experiment these occur simultaneously. From previous experience (24) in bare rod bundles it has been observed that for a uniform geometry (i.e., no blockages, all channels with uniform area, etc.) the effect of turbulent mixing on velocity distribution is small, especially in the presence of large cross-flows (25). There is no reason to expect the contrary for wire-wrapped bundles where significantly larger cross-flows and axial momentum changes occur. Thus cross-flow results from tracer and hot water injection experiments would not be greatly affected by the turbulent exchange mechanism. However, a knowledge of turbulent mixing is desirable for it can, under certain circumstances, (e.g. behind a flow blockage turbulent intensity greatly increases (31)) play an important role in energy exchange. Thus most computer programs include a correlation for non-directional cross-flow mixing due to turbulence.

Correlations for diversion cross-flow being used are of the same form as used for bare rod bundles in CØBRA (24). More work needs to be done to get a better understanding of this mixing process in the presence of wire wrap. In the wire wrapped bundle diversion cross-flow is occurring between
non-similar channels (one with wire wrap to one without) and methods developed for bare rod bundles may have to be modified (Rec. 2). In addition the wire-wraps change the direction of flow continuously, causing a part of the axial momentum to be transferred laterally by flow sweeping.

Therefore it is possible due to pressure gradient established by the wire wraps that the net pressure difference and hence the direction of diversion cross-flow can occur from a channel containing a wire wrap (small hydraulic diameter channel) to an adjacent channel without wire wrap. This could be in disagreement with the predictions of initial value codes like COTEC, ØRIBLE, FØRCMX, etc. If the net flow exchange is not accounted for properly, velocity distributions in axial and transverse directions can be incorrectly predicted. Codes like THI-3D can take this into account to some extent.

Differences in subchannel axial velocities as shown by the Japanese (6) data can be explained on the basis of this type of reasoning. However, there are other ways of explaining the Japanese (6) velocity profiles. For example, the pitot tube axial resistance could divert flow to an adjacent channel thus reducing the axial flow being measured. This would be especially true for channels near the wall channels. Since the wall channel axial flow resistance is considerably smaller than that of the central channels, any additional resistance in the latter (due to pitot tubes) could
easily divert flow to the wall channels. Axial velocities (point wise) are certainly (Rec. 7) required to understand the complex flow field, but the pitot tube may not be the desired method for their measurement unless more expensive large scale tests (2 – 3 times bundle size) are performed.

Velocity profile data obtained from pitot tube measurements need to be supplemented by measurements by another means before they can be relied upon. The ANL (7) 91 pin experiments should provide another set of independent axial velocity measurements. Axial velocity measurements would provide better insight into the importance of drag forces in determining flow fields i.e., if the theoretical flow split combined with superimposed cross-flow mixing is good enough to describe the basic flow field. In addition to velocity measurements, the transverse pressure difference across the flats should be measured at various axial planes (Rec. 8). The HEDL (15) data shows large pressure gradients exist across the bundle. The magnitude of differences measured appear to be higher than expected. A further check will be available from the ANL(7) 91 pin experiments.

Flow sweeping effects predominate the mixing phenomenon in wire-wrapped rod bundles. Consequently, several experiments have been almost completely devoted to further its understanding. In general the cross sweep flow should depend upon the following factors.
\[
\frac{W_{Si,j}}{W} = f(p/d, h/d, z/d, Re)
\]

Theoretically (2),
\[
\frac{W_{Si,j}}{W} = \frac{\pi(d+t)t}{h.A_f}
\]

where \( h \) is the lead of the wire wrap and \( A_f \) is the axial flow area of \( i \). Experimenters have correlated \( \frac{W_{Si,j}}{W} \) as follows, using the empirical constant, \( C_s \), as shown below:
\[
\frac{W_{Si,j}}{W} = C_s \frac{\pi(d+t)t}{h.A_f}
\]

The 7 pin isokinetic sampling tracer tests (3), the 19 pin hot water injection tests (5), the 217 pin HEDL tests (15), (18), all show that for a wide range of geometrical parameters and bundle sizes, \( \frac{W_{Si,j}}{W_i} \) for similar interior channels is within the range of 24\% to 33\% per inch. Results for wall channels are lacking.

The small range in which cross-flow prediction lie for varying geometries is an encouraging result. However, all these experiments have a lead/diameter ratio of 40 and above. As shown in a recent analysis of the hydraulic data (26, 27) flow slippage past the wire changes very slightly above \( h/d \) of 40. For blanket assemblies for \( h/d \sim 10-20 \), new correlations would have to be developed (Rec. 3). At present, it appears that the only data which can be used to correlate sweep flow at these low wire pitch to diameter ratios will be from the
M.I.T. experiments (12). Most of the experiments run so far show little if any dependence of flow sweeping on Reynolds number in the Reynolds number range of 10000 to 60000.

The analytical methods developed so far only partially or not at all account for the interactions between various mechanisms for momentum and flow exchange. Before swirl flows can be predicted with any degree of accuracy from a pure analytical computation these interactions will have to be further investigated.

Swirl flow can play an important role in reducing circumferential temperature gradients along the housing wall. Analytically one can represent it as follows (for a given fluid),

\[
\frac{V_\theta}{V} = + (h/d, p/d, w/d, z/d, R_e, \theta/\theta_0, D/d)
\]

The ORNL 19-pin experiments clearly indicate the existence of a large swirl flow. M.I.T. analysis (9) shows that for these tests \( V_\theta/V \approx 0.12 \) and is almost constant at Reynolds numbers of design range. The 91-pin ANL tests (8) indicate a similar result. However, the HEDL swirl flows appear to be much lower. It is not fully resolved if this was due to instrumentation, stripping effects or the swirl flow actually diminishes for the large bundle, or if the instrumentation is only capable of measuring bulk swirl flow (in the channel) which is much lower than the
swirl flow in rod to wall gap.

In addition to the experiments planned or conducted so far, it may be worthwhile to experimentally determine flow resistances in the axial and transverse directions for the side and corner wall channels. Thus a transverse momentum balance on a control volume in these channels could determine the portion of the incoming cross-flow which flows axially upward and the fraction that flows peripherally. This flow division would be very sensitive to flow resistances in the wall channels. A similar transverse momentum balance should be made across the bundle. Presently none of the formulations include this.

2. Flow Field Development: The entrance length required to attain a fully developed flow needs to be investigated (Rec. 5). Until now the characteristic dimensions used to determine entrance length was the hydraulic diameter of subchannel. Based on experience with circular tubes and similar geometries it was generally assumed that an $L/d_e$ of about 50 (6-10 in) would be sufficient to attain a fully developed flow field. It is possible that for bare rod bundles this may be an adequate criterion. But for wire-wrapped bundles surrounded by the hexagonal can it is conceivable that the equivalent housing diameter or a dimension intermediate between the housing diameter and channel hydraulic diameter, may be the required characteristic dimension for predicting entrance length. If the last
speculation is true the flow may never really fully develop. The changing flow field, as it develops, would effect the energy redistribution. Experiments at ANL (8) may resolve this question.

The entrance flow and pressure distributions can persist for considerable distances downstream and entrance effects can become important. Thus investigation of entrance length and entrance effects are of considerable importance (Rec. 5).

3. Effect of Bundle Size on Hydrodynamics - Wall Effect:
As the number of pins increase the ratio of central to wall channels increases rapidly. Consequently the effect of wall and of the wall channels on the rest of the bundle will diminish. It has not been established yet how far into the rod bundle these boundary effects extend. Until this is completed it would be difficult to extrapolate small bundle data to large bundles.

However, from data obtained on sweep flow it appears that the magnitude of the maximum sweep flow ($W_{s1j}/W_1 \sim 2^{14 - 33\%}$) has not significantly changed from the 7-pin tests of Lorenz and Ginsberg to the 217-pin HEDL tests. If the hexagon can size were a criterion for entrance length requirement, it is obvious that smaller bundles tested in the laboratory would have fully developed flow whereas the full size bundle would never attain this. This would significantly alter the plans to conduct experiments on several small bundles (61-91 pin) except for the axial blanket.
Perhaps the flow in the HEDL tests have not fully
developed, resulting in a swirl flow field in its initial
stages of development (other reasons for this have been
previously discussed).

Even if swirl flow were to remain the same for the full
size bundle as it is for the smaller ones, its effect in
reducing circumferential wall temperature variations would
be relatively reduced. If swirl flow is indeed much
smaller for the large bundle then two alternatives present
themselves. The spacing between the rod and wall could be
reduced by wrapping a smaller diameter wire on the rods
next to the wall. This would divert more flow towards
the central channels thereby causing exit temperatures to
be more uniform. The other alternative would be to decrease
the wire pitch for the rods near the wall in the hope that
greater mixing and/or swirl flow would reduce temperature
gradients in the wall. These two approaches would be
especially attractive for the blanket assembly design. The
M.I.T. tests may cover these parametric studies.

B. INSTRUMENTATION AND MEASURING TECHNIQUES - FUTURE
EXPERIMENTS

Experiments in the area of LMFBR wire wrap mixing can
be classified by virtue of three boundary conditions:

1. Point injection of tracer into a subchannel
centroid.

2. Planar tracer injection uniformly into a
subchannel.
3. Heat addition from heated rod source, each rod having different heat fluxes but uniform inlet coolant temperature.

The technique of point tracer (usually a salt solution) injection and conductivity-probe detection has been found to be a convenient method of determining tracer redistribution, thereby obtaining a quantitative estimate of the mixing mechanism. However, the technique suffers from several drawbacks. One of them is striping (15). Another shortcoming of the method is due to the flow perturbation in the subchannel into which the tracer is injected. At the time of the HEDL (15) tests a thorough investigation into the most desirable injection geometry had not been made. Recently experiments at ANL (dye injection) and M.I.T. (28) have been conducted to determine the optimum injection geometry, location and injection velocity. In addition the best location for conductance probes have also been studied. Results to date on wall injections indicate that injections normal to the flow stream are undesirable since both the size and the flow rate affect the mixing results. Axial injection at the centroid of the subchannel was found to be most desirable. For axial dye injection the flow disturbance persisted less than two inches and the initial rate of spreading of the dye was not affected by injection mass flow rate. The M.I.T. results (28) to date have shown that if the injection velocity is greater than the subchannel velocity the mixing results are affected. It was also found desirable to suspend
the conductance probe into the subchannel coolant at the bundle exit. "It was found that the probe suffered electrical interference if positioned too close to the rod array so that, as a rule of thumb, the probe surfaces should be at least 1/32" (preferably 1/16") away from any material in order to avoid electrical interference."

For hot water injection and heated rod tests the accuracy, response time and location of the thermocouples are important to obtain accurate results. The existing subchannel analysis codes calculate average fluid temperatures within each channel. Experimental measurements appear to indicate extensive temperature gradients within subchannels (29). If thermocouples are located in the rod walls and in the wire wrap it would be difficult to relate it to the subchannel mixed mean temperature. Any attempts to do so would involve introducing considerable errors, thereby losing confidence in the results. Therefore it is desired that work be done in the area of predicting local point wise temperature distributions in wire wrapped subchannels. Both analytical and experimental effort is required in this area. At the same time it is necessary to determine local heat transfer coefficients for LMFBR assemblies containing wire wrap. Studies of hot spots under the wire, and effect of entrained gas on heat transfer should be extended. Until some of these studies are completed it would be best to locate thermocouples in a manner such that avg. or close to
mean coolant temperatures are directly measured. The exit thermocouple rake in the ORNL 19-pin experiment was found to yield a most useful set of temperature data.

Experimenters should also attempt to measure transverse pressure gradients across the housing of the assembly at several axial locations. In addition the radial distribution of inlet flow and pressure should be perturbed by a known amount and effort should be made to see how far downstream the perturbations persist. This should be fed back into the analytical model development and iterations between analysis and similar experiments be made before choosing the optimum analytical or computation model.

C. ANALYTICAL EFFORT AND COMPUTER PROGRAMS - IMPROVEMENTS AND NEEDS

1. Entrance Length: Analytical effort should continue to (Rec. 1) predict the entrance length required to attain fully developed flow in wire wrapped bundles. This would supplement the experimental program in this area. It would in addition, provide a tool for predicting entrance lengths for geometries not covered by experiments.

2. Interpretation of Thermocouple Data: Our analysis of the Oak Ridge FFM-data shows that the exit rake thermocouples provide temperatures that could be used most conveniently for comparison with 'ENERGY' predictions. The thermocouples imbedded in the rod walls and in the wire-wrap cannot be directly used since steep temperature gradients
can exist in the subchannel. These codes do not have capability of predicting subchannel temperature gradients and only predict a channel average temperature. In addition the heat transfer coefficients between the wall and coolant cannot be predicted within the desired range of accuracy. Consequently any attempts to extrapolate subchannel mean temperature from a wall measurement or vice versa would involve considerable errors. It is suggested that analytical methods be developed (Rec. 2) to determine point temperature distributions for wire wrapped channels in an attempt to fully utilise existing and future data and thus to improve upon our understanding of the mixing phenomenon.

The point temperature distribution would help to decide the best subchannel configuration for use in subchannel analysis codes. Presently the area between three adjacent rods is the subchannel used in these codes. Ref. 32 recommends the use of hexagonal channels for the following reasons. Hexagonal channels (one around each rod) would minimise transverse interactions occurring at the boundaries of these channels. In addition the radial temperature gradients can be reasonably approximated as either uniform or linear and the number of channels for a rod bundle would be minimised. The present authors feel the necessity of further investigation of these recommendations of Ref. 31 before the best configuration of the subchannel can be established.
For wire wrapped bundles the presence of the wire causes inherent asymmetry in the flow field around a rod at any axial plane. Thus a temperature gradient could exist circumferentially. Magnitude of this temperature gradient needs to be determined. The velocity measurement data of Ref. 6 shows very low axial velocities were measured when the pitot tube was axially above but close to a wire wrap. Also circumferential flow around each rod can exist and must be accounted for. This causes undue complexities.

In addition the use of hexagonal configurations between subchannels may not necessarily decrease the number of equations to be solved simultaneously to determine cross-flow; the number of equations depend upon the number of subchannel connections and not subchannels.

The major attractiveness of the hexagonal array is in the simplifications it presents when any coupling between thermal-hydraulic and nuclear effects is desired.

3. Type 2 and 4 Codes: At present transverse pressure measurements at various axial planes of a wire wrapped bundle are not available. When this is obtained as a function of Re, the need for codes that solve a boundary value problem could be fully justified (except for flow blockages and transients where the boundary value codes must be used). Until then the use of Type 2 and 4 codes is recommended (Rec. 3). for determining energy redistribution since the flow splits calculated seem to be accurate. One must consider that the results so obtained would have an error band associated with them, and the results
should be used in a conservative manner. The Type 5 codes have not predicted data for various geometries to an overall degree of accuracy better than predicted by Types 2 and 4. The following modifications to the codes of Type 2 and 4 are suggested:

a. Bouyancy effects should be included to enhance their capabilities for handling thermal-hydraulic parameters in the design range of blanket assemblies.

b. Special treatment of wall channels to handle swirl flow and steep temperature gradients in the wall boundary layer.

If transverse pressure gradients are large at the Reynolds numbers of fuel assembly design range, the Type 2 and 4 codes could still be used for the blanket assemblies. For the low flow rates required by these assemblies transverse pressure gradients in the bundle would be considerably smaller than in the high flow rate fuel bundle.

4. Boundary Value Codes: The boundary value codes should be able to describe the flow field accurately in the presence of large pressure gradients by inclusion of a transverse momentum balance (as in COBRA IIIC) or equivalently by using correlations for cross-flow that include effect of axial inertia on cross-flow resistance. Obviously these correlations must be experimentally determined.
The Type 2 and 4 codes require two and four empirical constants for each bundle before predictions for temperature distributions can be made. A preliminary attempt to extend the constants in ENERGY (Type 2), for various size assemblies containing rod bundles of different geometries within them, has been made (26) and continues. The boundary value problem requires in addition complete specification of at least two other boundary conditions, one at the inlet and one at the outlet (pressure or flow at inlet and pressure or flow at exit). In practical situations these boundary conditions are not known.

The boundary value solution to the set of non-linear equations encountered in 'mixing' in rod bundles can generally be classified into two categories. One is the Pressure-Velocity method approach and the second is the Vorticity-Velocity method approach. Whereas THI-3D follows the first, COBRA-III follows the second.

In specifying boundary conditions it is more convenient to specify pressure boundary conditions for the first and flow boundary conditions for the second. Both of these inlet boundary conditions are difficult to obtain for a fuel assembly in an operating reactor. A method developed for PWR's (23), described below, may be considered as an approach to determining these boundary conditions.

In PWR's isothermal Vessel Model (VMFT) Flow Tests (23)
are performed on a core that hydrodynamically simulates the prototype. Cross-flow resistance between assemblies is measured by independent experiments and fed into an isothermal computer program that calculates the inlet pressure distribution in the VMFT for a known inlet flow distribution. The measured and predicted inlet pressure distributions are compared to check accuracy in predictions. This pressure distribution then acts as a boundary condition for the case when heat is added to the coolant. When heat is added the inlet flow distribution is iterated upon until the exit pressure boundary condition is satisfied. Thus a combination of the two approaches, mentioned earlier for boundary value problems, is employed. The major advantage, of course, is that testing can be done at isothermal and low pressure conditions. Several similar tests are being performed for the LMFBR bundle (an assembly in PWR's would correspond to a subchannel in an LMFBR in the tests just described) and it would be convenient to follow this procedure (Rec. 5) in order to determine the boundary condition.
Nomclature

\(d\)  \quad\text{rod diameter}

\(p\)  \quad\text{rod pitch}

\(h\)  \quad\text{wire wrap pitch}

\(w\)  \quad\text{spacing between rod and wall}

\(z\)  \quad\text{axial distance}

\(D\)  \quad\text{hexagonal can equivalent diameter}

\(\theta\)  \quad\text{angle along circumference}

\(\theta_o\)  \quad\text{reference angle}

\(t\)  \quad\text{wire diameter}

\(C_s\)  \quad\text{correlation constant}

\(d_e\)  \quad\text{hydraulic diameter}

\(\bar{V}\)  \quad\text{bundle average velocity}

\(V_\theta\)  \quad\text{swirl velocity}

\(\bar{V}_\theta\)  \quad\text{average swirl velocity}

\(W_{Dij}\)  \quad\text{diversion cross-flow from }i\text{ to }j

\(W_{Tij}\)  \quad\text{turbulent cross-flow from }i\text{ to }j

\(W_{Sij}\)  \quad\text{sweep cross-flow from }i\text{ to }j

\(\bar{W}\)  \quad\text{average bundle flow (axial)}

\(W_i\)  \quad\text{subchannel }i\text{ flow (axial)}

\((W_{Sij})_{\text{MAX}}\)  \quad\text{sweep flow where wire crosses the rod gap (maximum sweep flow)}.

\(Re\)  \quad\text{Reynolds number}
References Cited


14. Y. Okamoto, N. Akino, K. Emori, M. Taneda, 
"Hydraulic Tests on FBR Fuel Sub-Assemblies", 

15. R.E. Collingham, W.L. Thorne, J.D. McCormack, 
"217-Pin Wire-Wrapped Bundle Coolant Mixing Test", 
HEDL-TME 71-146, Nov. 1971.

16. C. Wheeler, "COBRA II A - A Program for Thermal-
Hydraulic Analysis in Very Large Bundles of Fuel 

17. J.L. Wantland, "ØRRIBLE - A Computer Program for 
Flow and Temperature Distribution in LMFBR Fuel Rod 

18. P.M. Magee, "Modeling of Flow Sweeping Effects 
in Wire-Wrapped Rod Bundles", Trans ANS, Vol. 15, 
No. 1, June 1972.

19. E. Novendstern, "Mixing Model for Wire Wrap Fuel 

20. D.S. Rowe, "COBRA III C - A Digital Computer Pro-
gram for Steady State and Transient Thermal-
Hydraulic Analysis of Rod Bundle Nuclear Fuel


Fig. 1: Diversion Cross Flow Due To Spacers
<table>
<thead>
<tr>
<th>No. of pins</th>
<th>7</th>
<th>19</th>
<th>37</th>
<th>61</th>
<th>91</th>
<th>127</th>
<th>217</th>
<th>Comments</th>
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<tr>
<td>Wire Wrapped Bundle Size</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>ANL</td>
<td>X (2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>91 pin grid spacer program not described</td>
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<tr>
<td>ORNL</td>
<td></td>
<td>X Na (3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>37 pin to start shortly</td>
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<tr>
<td>WARD</td>
<td>X (3) Na</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>for blanket assemblies</td>
</tr>
<tr>
<td>MIT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>laser as well as salt injection</td>
</tr>
<tr>
<td>Battelle</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>to be conducted</td>
</tr>
<tr>
<td>AI</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19 pins for blanket assy</td>
</tr>
<tr>
<td>Japanese</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X (2)</td>
<td></td>
<td></td>
<td>complete details not available</td>
</tr>
<tr>
<td>HEDL</td>
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<td></td>
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<td>GE</td>
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<td></td>
<td></td>
<td>X (1)</td>
<td></td>
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<tr>
<td>Karlsruhe</td>
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<tr>
<td>Cadarache</td>
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(1) hot water injection
(2) Salt Inj.
(3) Heated Pin
(4) Pitot Tube
<table>
<thead>
<tr>
<th>No.</th>
<th>Affiliation</th>
<th>Experimenters</th>
<th>Measurement Technique</th>
<th>Material</th>
<th>( \bar{x} ) of ( x )</th>
<th>( \bar{L} )</th>
<th>Special Features</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HEDL</td>
<td>Collingham et al [HEDL-TME71-146] Nov. 1971</td>
<td>Salting and Conductivity probes using flowing H₂O</td>
<td>Duct-stainless steel wire - 5.5 in.</td>
<td>Pins - 3 types, a/ Dummy - s.s. Instrument - Phenolic Injection - s.s.</td>
<td>217 0.23 .056 11.9</td>
<td>Inj. to flow direction. 1st 4% NaNO₃ salt solu. used. Both all injection and unit channel injections studied.</td>
<td>Appears striping affected the results up to 6-12” from injection. Swirl flow exists.</td>
</tr>
<tr>
<td>2</td>
<td>ANL</td>
<td>Bump &amp; Monson ANL-6549 (Feb. 1969)</td>
<td>Pitot-Static Photometric</td>
<td>Duct - s.s.</td>
<td>wire - brass</td>
<td>Pins - brass</td>
<td></td>
<td>Axial velocity measurement first of its kind. Also pin drop measurement</td>
</tr>
<tr>
<td>3</td>
<td>Japanese</td>
<td>Okamoto et al JAPN-24</td>
<td>Potassium Iodite salt injection and detection by conductivity probes also exit velocity measurement</td>
<td>(Apparently) all stainless steel</td>
<td></td>
<td></td>
<td>BUNDLE I</td>
<td></td>
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**Table II: Summary of Recent Experiments Conducted or Shortly to be Conducted for Wire Wrapped Assemblies**
<table>
<thead>
<tr>
<th>No.</th>
<th>Affiliation</th>
<th>Experimenters</th>
<th>Measurement Technique</th>
<th>Material</th>
<th>D of heat exch. (in.)</th>
<th>Width (in.)</th>
<th>Comments</th>
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<tr>
<td>4</td>
<td>ANL</td>
<td>Lorenz and Ginsberg</td>
<td>Nacl injection Isokinetic sampling</td>
<td>(apparently) all stainless steel</td>
<td>7</td>
<td>0.5</td>
<td>0.1</td>
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<tr>
<td>4a</td>
<td>ANL (to be conducted)</td>
<td>Lorenz and Ginsberg</td>
<td>Nacl injection Isokinetic sampling</td>
<td>(apparently) all stainless steel</td>
<td>91</td>
<td>PIN EXTENSION of 4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>ANL</td>
<td>Chawla et al</td>
<td>Hot water injection &amp; thermocouples</td>
<td>Stainless steel</td>
<td>19</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td>5a</td>
<td>ANL (being conducted)</td>
<td>Pedersen et al</td>
<td>Hot water injection &amp; thermocouples</td>
<td>Stainless steel</td>
<td>91</td>
<td>0.25</td>
<td>0.05</td>
</tr>
<tr>
<td>No.</td>
<td>Affiliation</td>
<td>Experimenters</td>
<td>Measurement Technique</td>
<td>Material</td>
<td>No. of pins</td>
<td>dia.</td>
<td>dw.</td>
</tr>
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<td>-----</td>
</tr>
<tr>
<td>6</td>
<td>M.I.T.</td>
<td>Theoress and Hanson</td>
<td>Salt injection and conductivity probes (water)</td>
<td>Stainless steel</td>
<td>19</td>
<td>0.25</td>
<td>0.0625 to 0.50</td>
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<tr>
<td>7</td>
<td>ORNL</td>
<td>FONTANA</td>
<td>Heated pins thermocouples (sodium)</td>
<td>Stainless steel</td>
<td>61</td>
<td>0.230</td>
<td>0.056</td>
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<tr>
<td>No.</td>
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<td>Experimenters</td>
<td>Measurement Technique</td>
<td>Material</td>
<td># of pins</td>
<td>Wire dia.</td>
<td>h/d</td>
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<tr>
<td>8</td>
<td>WARD</td>
<td>Markely</td>
<td>Heated pins thermocouples (sodium)</td>
<td>Stainless steel</td>
<td>61</td>
<td>0.52</td>
<td>0.056</td>
</tr>
<tr>
<td>9</td>
<td>AI</td>
<td>Graves</td>
<td>Salt injection and conductivity probes (water)</td>
<td>Not available</td>
<td>217</td>
<td>0.25</td>
<td>0.065</td>
</tr>
</tbody>
</table>

* after Ref. 1 (Todreas and Turi)

Special Features: Cosine axial heat flux is a unique feature of these tests. Most tests will be at low Reynolds numbers characteristic of blanket assemblies. Peaking ratios across bundle will be severe and several.

Comments: The 7 and 61 pin tests are particularly for blanket thermal-hydraulic conditions. The 7 pin tests will enhance confidence in measurement technique and accuracy.
<table>
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<tr>
<th>No.</th>
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<th>Organization</th>
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<td>1</td>
<td>JOYO</td>
<td>Okomoto et al.</td>
<td>Japanese Atomic Energy</td>
<td>1</td>
<td>Non-directional, Infinite Bundle Model</td>
</tr>
<tr>
<td>2</td>
<td>ENERGY</td>
<td>Khan</td>
<td>M.I.T.</td>
<td>2</td>
<td>Two-Zone Model (Directional - Non-Directional Model)</td>
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<td>3</td>
<td>CÔBRA II A</td>
<td>Wheeler et al.</td>
<td>Battelle</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>CÔTEC</td>
<td>Novendstern</td>
<td>WARD</td>
<td></td>
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<tr>
<td>5</td>
<td>FÔRCMX</td>
<td>Graves</td>
<td>A.I.</td>
<td>4</td>
<td>Marching Codes</td>
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<tr>
<td>6</td>
<td>FULMIX</td>
<td>Magee</td>
<td>G.E.</td>
<td></td>
<td>Include Directional Sweep Flow Correlation</td>
</tr>
<tr>
<td>7</td>
<td>ÒRRIBLE</td>
<td>Wantland</td>
<td>O.R.N.L.</td>
<td></td>
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</tr>
<tr>
<td>8</td>
<td>CÔBRA III</td>
<td>Rowe</td>
<td>Battelle</td>
<td>5</td>
<td>Boundary Value Problem Solved, Boundary Conditions Must Be Known Input, Can Handle Blockage</td>
</tr>
<tr>
<td>9</td>
<td>THI-3D</td>
<td>Sha</td>
<td>ANL</td>
<td></td>
<td></td>
</tr>
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</table>

The computer programs SWEEP and SIMPLE, both ANL, fall in Category 4.