THERMAL HYDRAULIC EVALUATION OF
ADVANCED WIRE-WRAPPED ASSEMBLIES

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1. INTRODUCTION

A thermal-hydraulic analysis has been performed to determine the coolant flow and temperature distributions in wire-wrapped assemblies. This analysis includes a study of the effects that various wire-wrap start geometries have on bundle mixing and peripheral flow, as well as a calculation of the hot-spot coolant temperatures for the locked-wrap design. The effect of circumferential swirl flow at the periphery of the wire-wrapped assemblies has also been investigated to determine its effectiveness in reducing temperature gradients near the channel walls.

The reference wire-wrap design is straight-start (e.g., FFTF, CRBRP). Advanced wire-wrap designs considered in this study are staggered starts, distributed wireless fuel rods, and locked wrap. The considerations used in the selection of the specific configurations studied are discussed. The emphasis of this report is to evaluate the thermal-hydraulic performance of these various designs as to the end-of-life bundle-to-channel interaction problem and to provide a fundamental thermal-hydraulic understanding of wire-wrapped fuel assembly designs.

In the design of a wire-wrapped LMFBR fuel assembly, coolant mixing caused by wire wraps, coolant flow area changes due to the presence or absence of wires, and circumferential swirl flow at the periphery of the assembly all play important roles in redistributing coolant flow in the assembly. The redistribution of coolant flow, in turn, causes a redistribution of energy.

The coolant flow mixing through the gaps between rods is the result of turbulent flow exchange, directed sweeping crossflow due to the helical wire wrap, and pressure-induced diversion crossflow. The pressure-induced diversion crossflow, which accounts for the momentum changes associated with changes in subchannel velocity, is largely due to the change of net coolant flow area. The most significant net coolant flow area change occurs in the locked-wrap design. A reduction of subchannel flow area by as much as 30% is observed for this design in which three wires touch (triple point).

In the other designs, the flow pattern is set by the wires in the interior of the assembly. Crossflow between interior coolant subchannels is predominantly by wire sweeping where the wires cross the gap between the rods. The sweeping

crossflow follows the direction of the wire wrap. Pressure-induced crossflow tends to equalize the velocities of adjacent subchannels.

Near the walls of the assemblies the behavior of crossflow is different from that in the interior. This circumferential flow in the outermost row of the assemblies is always in the direction of the wire wrap and is parallel to the channel walls. This flow is termed peripheral flow, or circumferential swirl flow. This uni-directional flow fluctuates along the channel walls, depending on the axial position and starting angle of the wire wrap.

In wire-wrapped fuel assemblies, an accurate prediction of flow distribution is most essential in predicting temperature distributions. Overall energy exchange between flow subchannels relies heavily on the aforementioned crossflow mixing and on energy transport by heat conduction.

The analyses of the flow and temperature distributions in a CRBRP 217-rod wire-wrapped assembly with different wire-wrap geometries were accomplished by the use of the GE-FBRD bundle mixing code, FULMIX-II. FULMIX-II is an improved version of FULMIX [5] which includes flow sweeping and forced crossflow mixing caused by the wire wrap accompanied by the change of net subchannel flow area. Computations were also made to determine the maximum fluid temperature in the wake region behind the triple point of a locked-wrap assembly, assuming worst case conditions of flow blockage.

The results of the study are presented in the form of subchannel temperature maps for both peripheral subchannels and assembly traverses. Radial subchannel temperature maps at the assembly outlet are also developed to show the penetration of the circumferential swirl flow towards the center of the assemblies. Qualitative comparisons between FULMIX-II and other subchannel analysis codes (e.g., COBRA, COTEC, THI-3D) on bundle temperature predictions are discussed.

2. SUMMARY AND CONCLUSIONS

The thermal-hydraulic analyses presented in this report are based on application of the subchannel concept in association with the use of bulk parameters for coolant velocity and coolant temperature within a subchannel. The interactions between subchannels are due to turbulent interchange, pressure-induced diversion crossflow, directed sweeping crossflow induced by the helical wire wrap, and transverse thermal conduction. The FULMIX-II computer program was successfully developed to perform the steady-state temperature predictions for LMFBR fuel assemblies with the reference straight-start design and the advanced wire-wrap designs. Predicted steady-state temperature profiles are presented for a typical CRBRP 217-rod wire-wrapped assembly with the selected wire-wrap designs.

The major conclusions of this study are as follows:

1. The locked-wrap design concept was found to be superior to the other wire-wrap designs based on its overall thermal-hydraulic performance. The locked-wrap design effectively reduces coolant radial temperature gradients near the channel walls and results in a uniform temperature distribution across the assembly, because of its inherent reduced edge spacing and localized transverse coolant mixing. The coolant hot-spot temperatures in the locked-wrap assembly were conservatively estimated and found to be insignificant in terms of overall thermal performance.

It is recommended that additional analytical and experimental work be conducted to develop this design concept. Additional experimental data defining the directed sweeping crossflow, pressure-induced diversion crossflow, peripheral swirl flow, and temperature rise behind a local partial subchannel flow blockage should be obtained and evaluated to provide the necessary information for analytical development.

2. The primary mechanism that results in the final temperature distributions in the wire-wrapped assemblies is the redistribution of coolant flow by virtue of wire sweeping and variations in the effective subchannel flow areas. In the locked-wrap assembly, the redistribution of

coolant flow seems largely due to the pressure-induced diversion crossflow caused by subchannel flow area change. Directed sweeping crossflow and pressure-induced diversion crossflow seem to play equally important roles in redistributing coolant flow in the other wire-wrap designs.

3. On a gross basis, along each inside surface of the hexagonal channel, a significant circumferential temperature difference occurs in the peripheral subchannels even with a flat radial power profile for all the designs except locked-wrap. This has important implications for fuel assembly channel wall temperatures when one considers these designs with radial power distribution other than flat profiles. However, conclusions should not be drawn from the superposition of a skewed radial power profile on a wire-wrapped assembly before the variation of the radial temperature distribution in the axial direction can be determined. In all cases, including the locked-wrap design, the peripheral subchannel temperature distribution shows a strongly periodic behavior in response to the wire wrap.
4. Minor local fluctuations of the peripheral subchannel temperatures indicate that the swirl flow in each peripheral subchannel is influenced by the other nearby subchannels. This also implies that crossflow through a gap is not solely dependent on the wire sweeping through that gap, but also on the pressures in the nearby subchannels.
5. The effects of the peripheral swirl flow penetrating about three rows radially inwards for the locked-wrap design and at least four rows for the other wire-wrapped designs are shown in Figures 6-13 through 6-16. In the interior region, where no noticeable peripheral swirl effect is seen, a slight periodic temperature variation is observed for the locked-wrap design while near uniform temperature distributions are found for the other three designs. Thus, it is concluded that the localized movement of wires in the locked-wrap design weakens the peripheral swirl flow and results in a more uniform overall subchannel temperature distribution. In summary, the overall wire-wrap effect of a locked-wrap assembly on thermal-hydraulic performance is local compared to that of the other designs.

It should be noted that uncertainties exist in this preliminary evaluation. Therefore, further study and testing are strongly recommended. The effectiveness of the wire-wrap in forcing crossflow must be verified. Verification of the overall model including peripheral swirl flow and the penetration of its effect is also needed. It is expected that less favorable displacements with respect to thermal-hydraulics will occur for the constant start than for the locked-wrap during bundle-to-channel interaction. Bundle compression tests in which displacement data will be obtained, will be available during GFY-1976. Such data can be used in FULMIX-II to further compare temperatures.

3. OBJECTIVES

The overall objective of the Wire-Wrap Assembly Engineering program is to develop a wire-wrapped fuel rod assembly capable of meeting LMFBR performance goals. A major part of this effort is to investigate and develop a better understanding of wire-wrapped fuel assembly response to relative bundle-to-channel growth and to develop advanced assembly designs which will minimize the effect of relative growth on bundle performance during operation. Therefore, an understanding of flow and temperature conditions within the fuel assembly and a proper thermal-hydraulic design that optimizes these conditions are necessary if the fuel assembly is to achieve maximum performance over its design life.

The objectives of this study were to complete the development of the FULMIX-II computer code and perform a preliminary evaluation of the thermal-hydraulic performance of LMFBR wire-wrapped fuel assemblies.

Development of the FULMIX-II code required a thorough examination of a number of basic fluid flow mechanisms. These basic mechanisms are:

1. Turbulent flow exchange, crossflow due to wire sweeping, and diversion crossflow due to pressure difference.
2. Free circulation of circumferential swirl flow at the periphery of wire-wrapped assemblies.
3. Pressure changes caused by large scale changes in net coolant flow area in the locked-wrap design.

The four different wire-wrap configurations considered in this evaluation study are:

1. Straight starts.
2. Staggered starts (0° - 30° - 60°).
3. Distributed wireless fuel rods.
4. Locked wrap.

These four bundle designs are described in the following section. The method of analysis and the mathematical models used in the FULMIX-II code are then discussed. The report concludes with a presentation of the coolant temperature distributions calculated for each design and a discussion of the design implications.

4. DESCRIPTION OF ADVANCED WIRE-WRAP DESIGNS

Since the discovery of irradiation-induced swelling, General Electric has been concerned about the ability of wire-wrapped assemblies to accommodate swelling effects. As early as 1969 GE considered the use of staggered wire-wrap start angles (0° - 30° - 60°) to disrupt the load plane of a straight-start assembly [1]. Later, assembly designs were proposed using both staggered and wireless fuel rods for increased flexibility [2]. The bases of these designs were early mechanical tests conducted by General Electric [1] and HEDL [3] on mechanical mockup assemblies compressed in a helical manner along their length.

Further structural evaluation of staggered-start arrays of 0° - 30° - 60° , 0° - 45° - 90° , and 0° - 60° - 120° by GE [2] indicated that larger relative rotations will result in greater reductions in assembly stiffness. With staggered-start designs the upper bound limit is approximately 0° - 60° - 120° , as greater rotations cause the wires to interfere with each other. Efforts were also made by GE to investigate the possibility of a staggered start beyond its upper start limit. The locked-wrap design, which is a unique adaption of the 0° - 120° - 240° staggered wire-wrap spacing technique with reduced wire diameter, was first suggested by GE [4] and a patent disclosure on this unique design has been submitted.

A general description of the various wire-wrapped designs follows.

4.1 Straight Starts

The basic, reference wire-wrapped design is the straight start. Almost all of the current thermal-hydraulic studies on wire-wrapped fuel assemblies are for this design.

Straight starts have constant start angles (e.g., 0° - 0° - 0° , 30° - 30° - 30° , 60° - 60° - 60° , etc.). Figure 4-1* schematically shows a typical straight-start 217-rod bundle starting at 0° .

Structurally speaking, lateral displacement of the bundle relative to the channel is physically restrained by the wire-wraps on the edge rods. This

*All figures are contained in Appendix C.

physical restraint occurs only at those axial locations on each flat where the wire-wraps of the edge rods contact the channel. For a wire-wrapped bundle with straight starts, this occurs along a single line at each flat, and these lines of displacement restraint are axially displaced from one hex flat to an adjacent hex flat by a distance equal to $1/6$ of the wire-wrap pitch. Along the axial length between such locations on a hex flat, no restraint occurs to maintain a uniform edge spacing between the edge row of the fuel rods and the channel. Thus the bundle deflects into a helical configuration.

It is desirable to soften the bundle compressibility characteristics by providing supplementary mechanisms to the helical bending of the bundle and the postulated dispersion mechanism. The ultimate mechanical objective is to decrease the contact loads under the wires and to maintain uniformity of the fuel rod pitch spacing and edge-rod-to-channel clearances. Staggered starts, wireless rods, and locked-wrap have been proposed.

4.2 Staggered Starts

A staggered-start bundle can be defined by considering the straight-start design and rotating selected rods by specified amounts. Figure 4-2 shows a schematic bottom cross-sectional view of a typical 217-rod staggered-start configuration, referred to as a 0° - 30° - 60° pattern. The three orientations are so used that any group of three rods contains one of each. In assembling such a bundle, once any two adjacent rods are selected, all the remaining rods are determined. In this report, the corner rod at 0° and its two successive neighboring edge rods in the direction of wire-wrap are consistently chosen to represent the tri-value of staggered starts.

The rods in this design are staggered using three start angles as this is the minimum number required to eliminate a pinch plane along any diagonal, which is one of the objectives of the design. The choice of an equal increment between angles is arbitrary (e.g., 0° - 30° - 60° , 0° - 45° - 90° , etc.).

4.3 Wireless Rods

An alternate softening procedure is to replace certain of the wire-wrapped rods with bare rods, dispersing the wireless rods throughout the bundle in such a way as to insure that no two adjacent rods are wireless, to avoid wireless edge rods, and to most efficiently disrupt the load path. There are many ways of constructing wireless rod patterns. A favorable and typical arrangement of bare rods within a 217-rod bundle with constant start angles is shown in Figure 4-3. A wireless rod bundle can have either a constant or a staggered wire-wrap start configuration. The configuration shown in Figure 4-3, when applied to a staggered-start configuration, results in the bare rods replacing only one "type" of the three different start angle rods at the interior. For example, for a 0° - 30° - 60° bundle, all bare rods would be 0° , 30° , or 60° .

4.4 Locked Wrap

The locked-wrap, 0° - 120° - 240° staggered-start array significantly differs from other staggered-start designs that have considerably less staggering, as shown in Figure 4-4. Attempting a 0° - 120° - 240° stagger with the previous staggered-start designs would cause the wires to interfere with each other in clusters of three, making assembly impossible. The locked-wrap design uses a reduced wire diameter (0.046-in. wire-wrap for a 0.286-in. rod pitch and 0.23-in. rod diameter as compared to the full wire-wrap of 0.56-in. diameter) so that there is no interference, and the three wires act together to space the rods as desired. This reduced wire diameter also reduces the edge spacing and channel size for the same rod-to-rod spacing. The manner in which the three wires engage each other tends to lock the rods together at each of the wire cluster locations.

Bundle compression will result in rod-to-rod nesting with a uniform helical bending of each fuel rod by three loads per wire-wrap helical pitch located at 120° intervals. The rods will be more uniformly loaded, with more near uniformity of deflected rod configurations than are predicted for the above-described wire-wrap configurations. The bundle-channel interaction should produce little or no helical bending of the bundle as a

whole, with rod-to-rod nesting being the predominant bundle compression characteristic. With rod-to-rod nesting, bundle size has less effect on rod deflections and loads, as each new row accommodates the extra interference with the channel that the increased size produces.

5. METHOD OF ANALYSIS

5.1 General

A thermal-hydraulic subchannel analysis code, FULMIX-II, has been developed specifically for LMFBR wire-wrapped assembly applications. FULMIX-II is a modified version of FULMIX [5]. The code can be used for hexagonally arranged bundles with 7 to 271 fuel rods (i.e., two to ten rows of rods).

The previous FULMIX code cannot be employed because of its limited capability when applied to selected advanced wire-wrap designs. The most important computational limitations are: (1) no provision for pressure-induced crossflow mixing, (2) lack of flow redistribution, and (3) inability to consider large-scale coolant flowing area changes. The addition of flow redistribution and area change subroutines to the FULMIX-II code removes these limitations. The primary function of these subroutines is to solve both axial and radial momentum equations of the coolant flow with forced crossflow mixing caused by the wire-wrap. Mathematically speaking, this expansion has changed the nature of the problem from a simple initial-value problem to a complicated boundary-value problem. The computational method employed also accounts for circumferential swirl flow at the periphery of the wire-wrapped assemblies. Proper modeling of this phenomenon is indispensable for any analytical method used in the thermal-hydraulic analysis of wire-wrapped designs.

The following subsections describe the method of flow subchannel modeling, the mathematical formulation, and method of solution for coolant flow in the wire-wrapped assembly.

5.2 Modeling of Flow Subchannels

One important problem in the development of a subchannel analysis code is the modeling of flow subchannels. The flow subchannel modeling for the outer row (edge row) of the assembly in the FULMIX-II code (and the earlier FULMIX code) is quite distinct from that in other established bundle thermal-hydraulics codes (e.g., COBRA, COTEC, THI-3D, FORCMX).

Flow subchannels are classified as interior, edge, or corner subchannels in FULMIX-II and in the other codes. Both modeling methods are illustrated in Figure 5-1.

As the name implies, interior subchannels occur in the interior of the bundle and are the tricuspid subchannels formed by three adjacent rods. Each interior subchannel is connected to three other subchannels: either three interior or two interior and one edge subchannel. Each interior subchannel is heated by three 60° fuel rod sectors.

Edge subchannels are formed by two adjacent peripheral rods and the channel wall. Each edge subchannel is connected to three other subchannels: one interior and two corner subchannels. Each edge subchannel is heated by two 60° fuel rod sectors.

Corner subchannels are formed by a peripheral rod and the channel wall. Each corner subchannel is connected to two other subchannels: either two edge subchannels or one edge and one corner subchannel. Each corner subchannel is heated by one 60° sector.

Since no corner subchannel is connected directly to any interior subchannel, the transverse flow in the corner subchannels truly represents the circumferential swirl flow. The perturbations of transverse flow and pressure between the interior and the peripheral corner subchannels can only be carried out through the medial edge subchannels. This has provided a great advantage in simulating the peripheral swirl flow. The finer peripheral subchannels in FULMIX-II (nearly twice as many as those of the other codes) are believed to have a significant effect on the convergence of solution. They also yield more detailed temperature and flow maps of the peripheral subchannels.

5.3 Mathematical Formulations of Coolant Flow and Heat Transfer

The solution of a thermal-hydraulic problem starts with the combination of appropriate conservation principles and some basic assumptions.

The modeling assumptions employed in the formulation are as follows:

1. The flow is single phase, steady and turbulent.
2. The coolant is incompressible.
3. The pressure-induced crossflow may be superimposed upon a directed sweeping crossflow.
4. Axial conduction heat transfer is negligible compared to radial conduction heat transfer.

The basic equations for subchannel analysis based upon the above assumptions can be developed by applying the conservation equations of mass, energy, and momentum.

Continuity Equation

Consider an axial distance increment δz of subchannel i which is connected to three adjacent subchannels for interior and edge subchannels and to two adjacent subchannels for corner subchannels, as is shown in Figure 5-1. The principle of conservation of mass gives

$$W_i + \delta W_i = W_i - \sum_{j=1}^N W_{s_{ij}}; N = 2, \text{ or } 3 \quad (5-1)$$

or,

$$\delta W_i = - \sum_{j=1}^N W_{s_{ij}} \quad (5-2)$$

where

W_i = the axial coolant flow into the increment, lb_m/hr .

$W_{s_{ij}}$ = the total crossflows into the i^{th} subchannel from the adjacent flow subchannels, lb_m/hr .

Momentum Equations

The derivation of the momentum equations is a little more complex than that for the continuity equation. The fluid flow problem in wire-wrapped assemblies is complicated by the mechanical action of the wire which forces fluid to flow in the direction of wire rotation and the induced-pressure difference between adjacent subchannels which causes additional transverse mass flow. It is obvious that the effects of crossflow mixing on the motion of coolant flow becomes extremely important in solving fluid flow problems of the wire-wrapped assemblies. Therefore, the derivation of the transverse momentum equation becomes indispensable in the mathematical formulation of the conservation of momentum.

According to the momentum balance, the sum of axial forces on an increment and the increase in axial momentum is equal to zero. Thus, the conservation of axial momentum yields

$$\delta P_i = - \frac{\tau_i H_i \delta z}{A_i} - \rho_i g \delta z + \frac{1}{A_i} \sum_{j=1}^N \left[(2u_i - u_{ij}^*) W_{s_{ij}} - \frac{1}{\rho_i A_i} W_{s_{ij}}^2 - (u_i - u_j) W_{t_{ij}} \right] \quad (5-3)$$

where

P_i = pressure of subchannel i , lb_f/ft^2 .

τ_i = wall shear stress of subchannel i , lb_f/ft^2 .

H_i = wetted perimeter of subchannel i , ft .

A_i = cross-sectional area of subchannel i , ft^2 .

ρ_i = coolant density of subchannel i , lb_m/ft^3 .

g = acceleration of gravity, ft/hr^2 .

u_i = velocity of subchannel i , ft/hr .

u_j = velocity of subchannel j , ft/hr .

u_{ij}^* = the effective axial velocity in subchannel i , or j carried by diversion crossflow, ft/hr .

$W_{t_{ij}}$ = turbulent interchange between subchannels i and j , lb_m/hr .

Normally the second order term $W_{s_{ij}}^2$ would be discarded as being small; however, for the locked-wrap design the sum of $W_{s_{ij}}^2$ is no longer small. Therefore, the term is retained in the axial momentum equation as given in Equation (5-3). The addition of the second order term is also thought to provide additional numerical stability.

Consider the crossflow passing through the gap between two parallel interconnected subchannels i and j . Applying the conservation of momentum in the transverse direction to a control volume placed in the gap between the two subchannels yields

$$\delta(u_{ij}^* w_{s_{ij}}) = \frac{s(\delta z)^2}{C_{ij}} (P_i - P_j) - \tau_{ij}(\delta z)^2 \quad (5-4)$$

where

s = spacing between two fuel rods, ft.

C_{ij} = centroid distance, ft.

τ_{ij} = friction loss due to crossflow, lb_f/ft^2 .

Energy Equation

Consider the increment shown in Figure 5-2. The energy equation for subchannel i based on constant coolant thermal conductivity and heat capacity gives

$$\delta(W_i h_i) = Q_i + \sum_{j=1}^3 \left[W_{s_{ij}} h_{ij}^* + W_{t_{ij}} (h_i - h_j) \right] \quad (5-5)$$

or,

$$\delta(W_i h_i) = q_i(\delta z) + \sum_{j=1}^3 \left[K(T_i - T_j)(\delta z) + W_{s_{ij}} h_{ij}^* + W_{t_{ij}} (h_i - h_j) \right] \quad (5-6)$$

where

h_i = enthalpy of subchannel i , btu/lb_m .

q_i = linear heat rate to subchannel i , $\text{btu}/\text{hr} - \text{ft}$.

k = thermal conductivity, $\text{btu}/\text{hr} - \text{ft} - ^\circ\text{F}$.

T_i = temperature of subchannel i , °F.

h_{ij}^* = enthalpy carried by crossflow between subchannels i and j , btu/lb_m.

The detailed mathematical formulation of the fuel rod heat transport, q_i , is given in a previously published version of FULMIX [5].

Sweeping Crossflow

A sweeping crossflow mixing model was originally developed for the FULMIX code. Initial calculations with FULMIX were not entirely satisfactory because the crossflow was solely used in the computation of energy redistribution rather than in the flow redistribution computation. The method of solution did not allow the sweeping crossflow to redistribute flow axially. The boundary-value type solution of flow redistribution used in FULMIX-II allows these calculations to be included on a more realistic basis. The following model is the one adopted in FULMIX-II.

The sweeping crossflow is commonly expressed as

$$W_{s_{ij}} = f_c \frac{\pi D_w (D + D_w)}{A_i} \frac{\delta z}{P_w} W_i \quad (5-7)$$

where

f_c = sweeping crossflow mixing parameter (dimensionless).

D_w = wire diameter, ft.

D = fuel rod diameter, ft.

P_w = wire-wrap pitch, ft.

The parameter f_c must be determined experimentally. This equation shows that a fraction of the subchannel flow W_i is diverted from subchannel i to subchannel j when a wire goes from subchannel i to subchannel j through the gap between them.

Local Fluid Temperature Rise in Locked-Wrap Design

The locked-wrap design results in flow obstructions at those locations where the three wire wraps touch as shown in Figure 5-3. A small-scale local

coolant blockage may arise from an accumulation of coolant impurities at the gap between the wires. The local coolant temperature rise close to such a partial subchannel blockage may be conservatively estimated by utilizing large-scale flow blockage data. The only published rod bundle large-scale sodium flow blockage data which show temperatures in the wake region are the results of tests reported by ORNL [6,7]. Data from 14-subchannel edge zone blockage in a 19-rod bundle show the maximum value for the measured dimensionless temperature behind the blockage to be

$$\frac{T_{\max} - T_{\text{in}}}{T_{\text{out}} - T_{\text{in}}} = 1.4 \quad (5-8)$$

where

T_{in} = average wake zone inlet temperature, °F.

T_{out} = average wake zone outlet temperature, °F.

$T_{\max}$ = maximum coolant temperature in the wake zone, °F.

The aforementioned method of considering small-scale local coolant blockage should be considered tentative until experimental data are available to check the validity.

5.4 Method of Solution

The coolant flow equations developed in the previous subsection are second-order and nonlinear and can be solved as a boundary-value problem. The computational method used is an iterative one. The inlet enthalpy, inlet flow, and inlet sweeping crossflow at the bottom of the reactor core are assumed to be known. The circumferential swirl flow at the periphery of the assembly (crossflow at the peripheral subchannels) at the inlet is first assumed, and then solved iteratively. Starting from the bottom of the core, at each axial plane, the set of coolant flow equations (5-5) and (5-6) are solved iteratively by the aid of the continuity equation (5-2) simultaneously for all the subchannels. Once the flow field is known, the energy equation (5-6) is decoupled and can be solved as an initial-value problem by a simple forward marching computation scheme. The calculation is then advanced to the next axial plane. This procedure is continued until the top of the reactor core is reached.

The boundary conditions for this boundary-value problem, as defined in many other codes [8,9], are the initial conditions for enthalpy, flow, and sweeping crossflow at the reactor core coolant inlet and the boundary condition for pressure at the core coolant outlet. The initial flow split plays an important role in attaining the converged solution to the problem and complying with the pressure boundary condition at the exit. A uniform velocity flow split was used to compute the initial inlet flow. A loose pressure boundary condition criterion was used, once the solution converged, to avoid exorbitant computer running times. However, it is felt that the results are adequate for this preliminary stage of analysis.

6. RESULTS

The quantitative aspects of the thermal-hydraulic evaluation of advanced wire-wrapped assemblies provided by the FULMIX-II code will be illustrated on a typical CRBRP 217-rod wire-wrapped fuel assembly with uniform radial power, but with different wire-wrap start angles. The wire-wrap start angles chosen for the different designs are 0° - 0° - 0° for straight-start and wireless rods configurations, 0° - 30° - 60° for the staggered-start configuration, and 0° - 120° - 240° for the locked-wrap configuration. A summary of the thermal-hydraulic parameters used in this study is given in Table 6-1.*

The results are presented in the form of subchannel temperature maps. Figures 6-1 through 6-4 show the predicted subchannel coolant temperatures at the top of the core for a lateral traverse from assembly flat-to-flat in the 30° - 210° direction for the various wire-wrap designs. Figures 6-5 through 6-8 are comparable to Figures 6-1 to 6-4 except that they are in the diagonal direction of 0° - 180° , and are developed to include the maximum subchannel temperatures for the straight-start and wireless rods designs. The temperatures of the hottest subchannel at the top of the core in each design are compared in Table 6-2.

Figures 6-9 through 6-12 illustrate the subchannel coolant temperature variations around the circumference (row 9) of the assembly for various wire-wrapped configurations as a result of circumferential swirl flow at the periphery of the wire-wrapped assemblies. Figures 6-13 through 6-16 show the penetration of the thermal effects of circumferential swirl flow radially inwards from the channel walls. The peripheral flow fluctuations result in temperature fluctuations around the assembly periphery. The interior region is essentially unaffected by the peripheral swirl flow fluctuations.

*All tables are contained in Appendix B.

7. DISCUSSION OF RESULTS

The results are discussed within the conceptual framework of the advanced wire wrapped designs considered by GE in comparison with the reference straight start design: to determine qualitative thermal-hydraulic performances for the different wire-wrapped assemblies. Other considerations, such as reduction in edge spacing for all the designs other than the locked wrap and increase or decrease of the wire-wrap pitch, which could affect the thermal-hydraulic performance of the wire-wrapped assemblies, are not included.

The prediction of flow and temperature distributions in a wire-wrapped assembly is complicated. This is due to the presence of the helical wires, the complex phenomena of pressure-induced crossflow, and the occurrence of circumferential swirl flow at the periphery of the assembly. The prediction becomes even more complicated when the extra parameters of wire-wrapped configuration and wire-wrap start angles are introduced into the thermal-hydraulic study.

The results shown in Figures 6-1 through 6-4 indicate that, with the exception of the locked-wrap design, all configurations studied result in a skewed coolant temperature distribution at the top of the core. A physical explanation follows as to why the locked-wrap design shows no temperature distribution skew and the other designs do, with the straight-start design having the most skewed distribution.

The wire sweepings between subchannels in the locked-wrap assembly are dispersed along each side of the channel wall. On the other hand, the wire sweepings along each side of the channel wall in the straight-start assembly act concurrently in one direction. Owing to the scatter of the wire sweeps in the locked-wrap design, some internal subchannels act as sinks to which the swirl flow and the corresponding circumferential pressure distribution can more easily dissipate. The staggered-start design with 0° - 30° - 60° start angles shows slight scattering and results in a slight temperature distribution skew.

Figure 6-1 indicates that, for the straight-start design, the wire-wrap start angle has a significant effect on the coolant outlet temperature distribution.

This may also answer the question raised by Collingham, et al., [10] about whether or not the measured skewed profile for the salt injection test was due to the experimental technique or to the influence of the wire. If confirmed experimentally, this effect is an important consideration in selection of the wire-wrap start angles (i.e., orientation relative to reactor core centerline) when a straight-start wire-wrapped assembly has a skewed radial power distribution.

Figure 6-4 shows local temperature rises, approximately 12° above the bulk subchannel temperature, are possible if the worst impact of a triple point* is assumed. The maximum coolant temperatures in the wake region behind a triple point in a locked-wrap assembly were computed on the basis of two very conservative assumptions. First, it was assumed that the tricuspid opening formed by three wires (see Figure 5-3) is clogged with the accumulation of coolant impurities and that a local blockage occurs. If the opening is not blocked, it will allow coolant to flow through as leakage flow. Leakage flow is very effective in reducing the wake temperature because as the leakage leaves the blockage, the small jet, as it expands, creates considerable turbulence. In conclusion, any leakage flow will reduce the wake fluid temperature, and therefore, the assumption of blockage is conservative. Second, it was assumed that the effect of the small-scale partial subchannel flow blockage could be predicted using large-scale flow blockage data. This introduces large conservatism. The increase in the wake temperature behind a blockage depends greatly on the blockage size. A larger blockage creates a larger wake with a larger drag coefficient, which, in turn, results in higher wake temperatures.

The hottest subchannels for the straight-start (0° - 0° - 0°) and wireless rods (0° - 0° - 0°) designs, as shown in Figures 6-5 and 6-7 or in Table 6-2, are located in the general direction of the wire-wrap start angles of 0° . Comparison of Figures 6-6 and 6-2 indicates that the hottest subchannels for the 0° - 30° - 60° staggered-start design are located in the direction of 30° . The results shown in Figures 6-4 and 6-8 indicate, based on the flat subchannel temperature distributions, no explicit hottest subchannel exists for the 0° - 120° - 240° locked-wrap design.

*The point where three wire wraps from adjoining rods touch.

The results shown in Figures 6-9 through 6-12 show that the circumferential swirl flow at the periphery of the wire-wrapped assemblies has a substantial effect on the temperature gradient near the channel walls. The fluctuations of the coolant temperature in the peripheral subchannels (row 9) are the result of the wire-wrap local position and the circumferential swirl flow as a whole. The wire-wrap start angles have a strong influence on the peripheral subchannel temperature fluctuations for all designs except the locked-wrap. The coldest peripheral subchannels for the straight-start (0° - 0° - 0°) and the wireless rod (0° - 0° - 0°) designs occur approximately at 180° as shown in Figures 6-9 and 6-11, while the coldest peripheral subchannels for the 0° - 30° - 60° staggered-start design shift by 60° from 180° to 240° . The locked-wrap design, as shown in Figure 6-12, has the least temperature fluctuation in the peripheral subchannels. In this case, local temperature fluctuations do exist due to wire sweeping at and near the periphery. These results lead to the conclusion that the peripheral swirl flow is more uniformly distributed for the locked-wrap design than for the other three designs. For the latter, the high peripheral swirl flows are following the overall wire movement by a phase angle of approximately 180° .

Comparison of the predicted temperature distributions for the locked-wrap design with those for the other designs shows that the locked-wrap design results in a reduction in coolant radial temperature gradient near the wall and a more uniform temperature distribution across the assembly. From the thermal-hydraulic point of view, the locked-wrap design is concluded to be superior to the other designs.

A recent independent subchannel analysis on a CRBRP 217-rod wire-wrapped assembly using the COBRA-IV, COTEC, and THI-3D codes by Westinghouse's Advanced Reactor Division [11] shows similar peripheral subchannel temperature fluctuations, although direct comparison is not possible due to different peripheral subchannel modeling techniques.

The results plotted in Figures 6-13 through 6-16 show that the effect of the circumferential swirl flow penetrates about three to four rows radially inward from the channel walls. The interior is almost unaffected by the swirl flow fluctuations.

APPENDIX A

REFERENCES

1. Ripley, C. C. , Faust, W. R., and Punches, J. R., "Fuel Assembly Development Task IV Final Report, Volume I," NEDC-13660, November 1970.
2. Baker, R. B., Blahnik, D. E., "CCTL Mark I and Mark II Prototype FFTF Subassembly Compression Test Development Work," WHAN-FR-18, August 1970.
3. Punches, J. R., Kaplan, S., "Advanced Wire-Wrap Assemblies Design Configurations and Rationale," Interim Report, GE-BRO CD001, January 1974.
4. Punches, J. R., "Wire-Wrap Fuel Assembly Engineering," Core Engineering 51st Quarterly Report, GEAP-10028-51, May-July 1974.
5. Magee, P. M. , "FULMIX - Turbulent Interchange Mixing Code for Fuel Bundle Thermal-Hydraulic Analysis," GE Core Development Memo 150-13, BRDO, GE, Sunnyvale, California.
6. Fontana, M. H., Kress, T. S., Parsly, L. F., Thomas, D. G., and Wantland, J. L., "Effect of Partial Blockages in Simulated LMFBR Fuel Assemblies," ORNL-TM-4324, December 1973.
7. Fontana, M. H. and Wantland, J. L. "LMFBR Safety and Core Systems Programs Progress Report for April-June 1974," ORNL-TM-4727, January 1975.
8. Rowe, D. S., "COBRA-IIIC: A Digital Computer Program for Steady-State and Transient Thermal-Hydraulic Analysis of Rod Bundle Nuclear Fuel Elements," BNWL-1695, March 1973 .
9. Sha, W. T., and Schmitt R. C., "THI-3D - A Computer Program for Steady-State Thermal-Hydraulic Multichannel Analysis," ANL-8112, July 1974.
10. Collingham, R. E., Thorne, W. L., and McCormack, J. D., "217-Pin Wire-Wrapped Bundle Coolant Mixing Test," HEDL-TME 71-146, November 1971.
11. Letter, P. W. Dickson to A. E. Mravca, May 8, 1975,""Clinch River Breeder Reactor Plant; Comparison of COBRA-IV, COTEC, and THI-3D Subchannel Analysis Predictions of Two Fuel and Four Radial Blanket "Reference" CRBRP Assemblies," WR-50687, LRA-75-33.

APPENDIX B

TABLES

Table 6-1

<u>Parameter</u>	<u>Value</u>
Assembly Flow Rate (lb/hr)	155,184
Average Linear Power (kw/ft)	6.6
Length of Fuel Region (inch)	36
Coolant Inlet Temperature (°F)	730
Pitch-to-Diameter Ratio	1.252
Fuel Pin Diameter (inch)	0.23
Wire Diameter (inch)	0.056*
Wire-Wrap Pitch (inch)	12
Axial Peaking Factor	1.23

*Wire diameter for locked-wrap design is 0.046 inches.

Table 6-2

Position and Temperature of Hottest
Subchannel at the Top of Core

Wire-Wrapped Design	Location		Temperature °F
	Row	Angle (Degree)	
Straight-Start (0°-0°-0°)	6	0	1086
Staggered-Start (0°-30°-60°)	6	30	1079
Wireless Rod (0°-0°-0°)	6	0	1079
Locked-Wrap (0°-120°-240°)	N.A.	N.A.	1068

APPENDIX C

FIGURES

DIRECTION OF 0° WIRE-WRAP ANGLE

DIRECTION OF
WIRE ROTATION

FIGURE 4-1
STRAIGHT-START BUNDLE CONFIGURATION

FIGURE 4-2
 0° - 30° - 60° STAGGERED-START BUNDLE CONFIGURATION

FIGURE 4-3
WIRELESS RODS BUNDLE CONFIGURATION

DIRECTION OF 0° WIRE-WRAP ANGLE

DIRECTION OF
WIRE ROTATION

FIGURE 4-4

LOCKED-WRAP BUNDLE CONFIGURATION

FIGURE 5-1
MODELING OF FLOW SUBCHANNELS

FIGURE 5-2. SUBCHANNEL MASS BALANCE

FIGURE 5-3. TYPICAL WIRE CONTACT IN LOCKED-WRAP DESIGN

FIGURE 6-1. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE FOR A LATERAL TRAVERSE FROM FLAT-TO-FLAT FOR STRAIGHT-START DESIGN (0°-0°-0°)

FIGURE 6-4. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE FOR A LATERAL TRAVERSE FROM FLAT-TO-FLAT FOR LOCKED-WRAP DESIGN (0° - 120° - 240°)

FIGURE 6-5. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE ALONG THE DIAGONAL DIRECTION OF 0° - 180° FOR STRAIGHT-START DESIGN (0° - 0° - 0°)

FIGURE 6-6. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE ALONG THE DIAGONAL DIRECTION OF 0° - 180° FOR STAGGERED-START DESIGN (0° - 30° - 60°)

FIGURE 6-7. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE ALONG THE DIAGONAL DIRECTION OF 0°-180° FOR WIRELESS ROD DESIGN (0°-0°-0°)

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FIGURE 6-8. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE ALONG THE DIAGONAL DIRECTION OF 0°-180° FOR LOCKED-WRAP DESIGN (0°-120°-240°)

FIGURE 6-9. PERIPHERAL SUBCHANNEL TEMPERATURE VARIATION AROUND ROW 9 POSITION AT THE TOP OF CORE FOR STRAIGHT-START DESIGN (0°-0°-0°)

FIGURE 6-10. PERIPHERAL SUBCHANNEL TEMPERATURE VARIATION AROUND ROW 9 POSITION AT THE TOP OF CORE FOR STAGGERED-START DESIGN (0°-30°-60°)

FIGURE 6-11. PERIPHERAL SUBCHANNEL TEMPERATURE VARIATION
AROUND ROW 9 POSITION AT THE TOP OF CORE FOR
WIRELESS ROD DESIGN (0°-0°-0°)

FIGURE 6-12. PERIPHERAL SUBCHANNEL TEMPERATURE VARIATION
AROUND ROW 9 POSITION AT THE TOP OF CORE FOR
LOCKED-WRAP DESIGN (0°-120°-240°)

FIGURE 6-13. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE IN ALL ROW POSITIONS FOR STRAIGHT-START DESIGN (0°-0°-0°)

FIGURE 6-14. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE IN ALL ROW POSITIONS FOR STAGGERED-START DESIGN (0°-30°-60°)

FIGURE 6-15. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE IN ALL ROD POSITIONS FOR WIRELESS ROD DESIGN (0°-0°-0°)

FIGURE 6-16. SUBCHANNEL TEMPERATURE AT THE TOP OF CORE IN ALL ROW POSITIONS FOR LOCKED-WRAP DESIGN (0°-120°-240°)