BUNDLE DUCT INTERACTION STUDIES
FOR FUEL ASSEMBLIES

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I. INTRODUCTION AND SUMMARY

It is known that the wire-wrapped rods and duct in an LMFBR are undergoing a gradual structural distortion from the initially uniform geometry under the combined effects of thermal expansion and irradiation induced swelling and creep. These deformations have a significant effect on flow characteristics, thus causing changes in thermal behavior such as cladding temperature and temperature distribution within a bundle. The temperature distribution may further enhance or retard irradiation induced deformation of the bundle. Depending on material used for the components and the operating conditions, significant tightening or loosening may occur during life. If the bundle is too tight, peripheral rods hot spots due to rod-duct contact or close proximity may occur. If the bundle is too loose, relatively unpredictable cladding wear and bundle temperature may result.

This report summarizes the results of the continuing effort in investigating the bundle-duct interaction, focusing on the need for the large development plant.

The use of distributed wireless pins in large assemblies was reviewed as part of the design effort to minimize wear due to bundle looseness. The principal design fix to minimize wear is to decrease the fuel pin wire wrap helical pitch. The use of the wireless bundle can compensate for the increased pressure requirement caused by the reduced pitch. In addition, the distributed wireless pin may result in a decrease on cladding wear potential, since

- Hydrodynamically induced forced vibration may be less, resulting in smaller deflection amplitudes
- Requires approximately a one-mil per ring less as-built porosity needed for bundle insertion

- Lower differential pressure across the duct wall due to lower bundle pressure drop, resulting in a decrease in bundle loosening of approximately one-mil per ring.

Within GE-ARSD, a preliminary thermal-hydraulics/structural mechanics code has been developed to study the effect of bundle-duct interference. Due to the limitation of memory capacity of the current computer system, difficulty is anticipated in analyzing large size assemblies. A partial version of the updated code XEBRA was used to analyze a 127-pin fuel assembly with a bundle-duct interference (BDI) of 50 to 100 mils that is conceivably representative of the FTR driver fuel assembly at end of life. The results show that as BDI increases, central flow channel temperatures decrease, edge flow channel temperatures increase, and edge flow channel thermal gradient decrease. At 100 mils BDI, the maximum edge subchannel coolant temperature ΔT increases ~10%; this allows about a 60°F local clad hot spot due to edge pin/duct contact. This indicates that the edge pins may be more important in design consideration than the limiting temperature of central pins analyzed with uniform geometry.

The long term code development needs for the LDP design are discussed in consideration of BDI, with a detailed description of the pattern approach for possible simplification of the structural mechanics portion of the existing code.

II. EFFECTS OF BUNDLE LOOSENESS

A. Current Situation

Reference 1 indicated that the use of alloy D9 as the cladding and duct material for the Large Development Plant (LDP) would result in a fuel pin bundle loosening with irradiation time. This was due to the net effect of swelling and creep of the duct, cladding, and wire spacer. Subsequently, revised creep and swelling correlations for alloy D9 were made available. ⁽²⁾ The revised correlations, which indicated a significant increase in creep and a shifting of peak swelling to a lower temperature range, resulted in the prediction of an even greater bundle looseness to occur.

A principal concern for a fuel pin bundle with large looseness is the potential for cladding wear resulting from flow-induced vibrations. Utilizing the current predictive model ⁽³⁾, it is observed that the wire spacer helical pitch is an important design parameter affecting the susceptibility of cladding to wear in the presence of bundle looseness. A smaller pitch decreases the potential for wear, relative to a larger pitch. For the current LDP environment and fuel assembly design, it has become necessary to decrease the reference wire spacer helical pitch from the CDS Phase II value of twelve inches to a value in the range of six to eight inches. An adverse consequence of such a design change is to significantly increase the bundle pressure drop. Figure 1 non-dimensionally shows the increase in bundle pressure drop for the LDP fuel assembly design parameters that results from decreasing the helical pitch. Figure 1 was calculated using the method of Reference 4.

For the current CDS effort, the impact of the bundle pressure drop increase presents a burden to the reactor system design because of a limited available pressure head. However, the increased bundle pressure drop resulting from the reduced helical pitch could be compensated by using the distributed wireless pin advanced wire-wrapped configuration. Figure 2 schematically depicts a 217-pin wireless configuration, which is characterized by omitting the wire spacer from a limited number of pins that are distributed about the bundle in a prescribed manner. All wireless pins are surrounded by six-wrapped pins, and all edge pins are wrapped to provide pin to duct spacing. For a 271-pin bundle, the LDP reference design, 73 pins are wireless. Based on both hydraulic testing ⁽⁵⁾ and analyses using modifications to the method of Reference 4, ^(5,6) it is expected that the distributed wireless pin bundle, if implemented in the LDP fuel assembly, will decrease the bundle pressure associated with a given helical pitch by 10-12%.

If the LDP is to use the distributed wireless pin bundle configuration, several concerns arise. One is a concern that the effect on cladding wear is unknown. A second is that the thermal hydraulic behavior of the distributed wireless configuration lacks the degree of understanding existing for the fully wrapped pin bundle.

B. Cladding Wear for a Distributed Wireless Pin Bundle

Concerning the possible effect of the wireless configuration on wear, an apparent concern is that the distributed omission of wire spacers results in "average" or "effective" length of pin lateral support intervals that are the equivalent of a large helical pitch. Reference 7 (unreferenceable in open literature) reports on vibration testing at G.E. in 1971 of single pins laterally supported by a simulation of the "staggered-grid" spacer. (The staggered-grid spacer is characterized by an axial sequence of one-way, alternating lateral supports to the pin. A one-way support implies that the pin is constrained from moving toward the support, but free to move away from the support.) The tests conclusively demonstrated that the presence of alternating one-way supports on a single pin resulted in nodal points (zero lateral deflection) occurring at the supports. The alternating supports were at three-inch intervals. In the distributed wireless pin bundle, omitting the wires disrupts the pinch plane across rows of pins by systematically removing many interior pin two-way supports while leaving a one-way support at the pinch locations. See Figure 3. For all pins, the distance between one-way lateral supports, oriented along a given pinch direction, is one-half the helical pitch. For a 6-inch helical pitch, the lateral support spacing with wireless pins bears significant similarity to that in the single pin vibration tests.

Speculatively, the distributed wireless bundle may perform in a manner that results in a decrease in cladding wear potential. Consider the flow-induced forced vibration of the pin bundle as it may differ between the fully wrapped and partial wireless configurations. Two near-field noise energy sources in the coolant flow are believed to sustain the flow-induced pin bundle vibrations:

- Turbulent boundary-layer pressure fluctuations around the cylindrical pins are spatially non-uniform. When integrated around the pin circumference, random lateral loads occur.
- As part of the subchannel flow turbulence, the swirl and transverse velocity drag component fluctuations result in random lateral loads.

The hydrodynamically induced forced vibrations may be less for the partial wireless bundle configuration resulting in smaller deflection amplitudes and less wear. Both the cross-flow component and the subchannel turbulence magnitude caused by the wire wrap, and the random fluctuations of those characteristics, may be significantly reduced. (Note that the resulting decreased mixing expected in the partial wireless bundle is thermal-hydraulically compensated by the more favorable flow area distribution, with the increased flow area at the interior of the bundle as demonstrated in Reference 6.) The turbulent boundary-layer pressure fluctuations are also expected to be less when fewer wires traverse the boundary layer.

Two other advantages with respect to minimizing wear occur (or can occur by design) for a distributed wireless bundle with the same helical pitch as a fully wrapped bundle:

- Approximately a one-mil per ring less design as-built porosity is needed for the partial wireless bundle to facilitate bundle insertion into the duct based on previous out-of-pile testing at G.E. (8)
- The lower bundle pressure drop also means a lower differential pressure across the duct wall (or thinner ducts, if you choose). The result is a decrease in bundle loosening of approximately one-mil per ring.

Loading the bundle into the duct could be a future fabrication concern, particularly for a reduced helical pitch-to-pin diameter ratio compared to the current FTR/CRBR reference value. The same mechanism that makes it easier to insert the partial wireless bundle into a duct, bundle radial compression compliance, should make it more difficult for either a smaller helical pitch and/or a larger pin diameter. Using the FTR mils/ring criteria for fabrication is thus non-conservative. This could be of considerably more significance if the development plant fuel assemblies are fabricated on a Secured Automated Facility (SAF) line, using remote handling.

C. Further Thermal-Hydraulic Considerations of the
Distributed Wireless Bundle

To perform thermal-hydraulic subchannel analyses for the distributed wireless pin bundle, the current procedure is to perform the analyses on fully wrapped bundle models, only accounting for wireless geometry changes, but not for semi-empirical constants, etc. This is done both for flow distribution and pressure drop calculations. Such analyses have been done to support the irradiation testing of the AW-1 and the AAD-3 FTR irradiation tests which use 217-pin bundles with 55 distributed wireless pins. It is important that sufficient flow testing and model development is performed on the distributed wireless pin bundle to provide confidence in the analytic predictions and to provide validation support to the method.

Included in the testing and understanding is the performance of the distributed wireless bundle for transient as well as for steady state conditions. As an example, during natural circulation the increased flow area toward the bundle interior (wires are omitted only from interior pins) may aid the buoyant flow through the assembly. On the other hand, it must be demonstrated that recirculation will not occur within the duct.

III. EFFECTS OF BUNDLE TIGHTNESS

A. Thermal-Hydraulics Mechanical Code Development

Under conditions of high temperature and neutron irradiation, the swelling and creep of the pin, wire spacers and duct may result in significant interference and bundle geometry deformation in the latter part of the assembly life. This can cause a sharp decrease in the coolant flow channel area, direct pin-pin and pin-duct contact, all resulting in excessive cladding temperature. Existing fuel bundle thermal-hydraulic models can only handle the uniform, beginning of life bundle geometry; the use of these models to predict distorted bundle thermal-hydraulics can lead to erroneous results. Hence, there is a need for a predictive method to evaluate the complex interaction between thermal-hydraulics and structural mechanics within an assembly. Within GE-ARSD, a thermal-hydraulic/structural mechanics code — THYME ⁽⁹⁾ was developed to quantify the problem's nature and scope. The THYME code is composed of three originally independent codes — COBRA-WC ⁽¹⁰⁾, BUNDUC and DARED 3 — each of which has its own designated purpose. The COBRA-WC code, developed by PNL, is a thermal-hydraulics code which solves the momentum, mass and energy equations on a subchannel basis. The code can accept non-uniform subchannel areas and gaps. BUNDUC and DARED3 were developed within GE-ARSD. BUNDUC calculates the bundle-to-duct interaction by predicting the fuel rod, wire and duct growth during the operating time. DARED3, an empirical structural code, provides the assembly geometry of deformed bundles by combining the effects of unconstrained growth of the bundle and the bundle pin displacements measured in the out-of-pile compression tests. These three modules are organized such that the structural variations during reactor operation are continuously analyzed. Thus, the assembly thermal-hydraulic phenomena can be evaluated throughout a lifetime operation. The original THYME code has been tested on a 7-pin assembly for a core length of 15 inches.

Recently, the thermal-hydraulics/structural mechanical code THYME has been updated and renamed XEBRA. In addition to cold work 316 stainless steel and D9, HT9, D21 and D68 have been added to the material correlation library subroutines in BUNDUC. DARED4, replacing DARED3, eliminates redundant coding and variables, and provides options thus increasing the coding capability.

The capability of using XEBRA to analyze the large assembly is limited by the computer memory capacity. In the CDC 7600 computer system, difficulties are anticipated in analyzing assemblies larger than 127 pins. Since COBRA-WC requires at least one node every $2/3$ of an inch for convergence, the CDC 7600 core memory is marginal to handle the full version of XEBRA on the 127-pin case. In the preliminary investigation of analyzing assembly coolant subchannel temperature response to significant bundle-duct interference, only a partial version of XEBRA was used. The details of this study are described in the following section.

B. Thermal-Hydraulic Analysis of a Fuel Assembly with
Bundle Duct Interference

In this investigation, only DARED4 and COBRA-WC modules of XEBRA were used. A specific bundle duct interference was used in the code instead of using BUNDUC. A fuel bundle similar to the FTR driver fuel assembly was studied.

To facilitate the deformed geometry analysis and to minimize computing cost, a 127-pin bundle was used instead of a full-size, 217-pin FTR fuel bundle. However, it is expected that the general thermal-hydraulic response of the 127-pin bundle to deformed geometry shall be similar to that for a 217-pin bundle since the difference in number of fuel pin "rings" (7 vs. 9) is small. The COBRA-WC wire wrap mixing parameters used for this analysis were those derived from uniform geometry test data.

The hypothetical fuel assembly design and operating conditions are as follows:

Pin Outer Diameter (in)	0.23
Cladding Thickness (in)	0.015
Diametral Gap (in)	0.0055
Fuel Length (in)	36
Pitch/Diameter	1.24
Duct Wall Thickness (in)	0.12
Duct Inside Flat-to-flat (in)	4.335
System Pressure (psia)	30
Inlet Enthalpy (Btu/lbm)	359.7
Inlet Temperature (°F)	680
Nominal Mass Flux $\left(\frac{\text{million lbm}}{\text{ft}^2 \cdot \text{hr}}\right)$	4.37
Nominal Power Density $\left(\frac{\text{million Btu}}{\text{hr} \cdot \text{ft}^3}\right)$	82.8
Average Linear Power (Kw/ft)	7.0

Cases of 75 and 100 mils bundle-duct interference were investigated. They are conceivably representative of the FTR driver fuel assembly at end of life. The expected axial variation of BDI is shown in Figure 4.

The expected reduction of the flow channel area of the 127-pin assembly were extrapolated from the 217-pin compression test data, as illustrated in Figures 5 and 6.

Both uniform radial power distribution and 1.1/0.9 radial power skew cases were investigated. The axial power was assumed to be constant along fuel length. The normalized temperature distribution at 35.7 inch elevation are shown in Figures 7 and 8.

These results indicate that as BDI increases, the central pin temperature decreases while the edge pin temperature increases. As shown in the radial skew power case, the coolant temperature in the left side edge channel approaches the assembly bulk temperature. This allows only nearly 60° C for local cladding hot spot due to edge pin-duct contact. This reveals that under a large amount of BDI, the critical area may be the edge pin instead of the central pin. As the temperature profile flattens out under BDI, the edge pins are subjected to a lower thermal gradient; thus, this can be expected to be somewhat relieved in the bowing consideration.

C. The New Structural Code Approach

As mentioned previously, the capability of using XEBRA to analyze large size bundle is limited by the memory capacity of the computer. Difficulties are anticipated in analyzing bundle size larger than 127 pins. To handle the LDP size bundle, the code must be simplified or streamlined. One approach to simplifying the structural portion of the code which may be worth pursuing is described as follows.

G.E. compression test data for 0° - 0° - 0° straight start assembly are given in Figures 9 and 10. The load was applied at the 10 o'clock flat. Despite the erratic displacement of some of the corner pins, some general observations are apparent.

- All pins move inward toward a centroid.
- The amount of an outer pin displacement is always greater than that of an inner pin.

Based on these observations, a symmetrical pattern to characterize the assembly deformations can be utilized to develop a new structural code.

1. Assumptions

Several assumptions were made for the proposed pattern geometry geometry structural code:

- (1) Maximum bundle deformation occurs at the cross section where the wire is located between the duct and the pin.
- (2) Bundle uniformity is maintained until tight bundle is reached.

- (3) Bundle deformation is synchronized with the centroid movement. The centroid moves perpendicularly to the face at which the wires touch the duct wall.
- (4) All pins move toward the centroid.

2. The Pattern Idea

If the above assumptions are valid, then, a pattern structural code to characterize the assembly deformation is proposed. The pattern is described in Figure 11. The as-fabricated assembly at the beginning of life has an original center located at the intersection of the X and Y axes when the pins are distributed uniformly. For a period of operation, the pins, wires and duct grow to such an extent that a tight bundle is reached. However, the original center as well as all the locations of the individual pins remain unchanged due to the assumption of uniformity (Assumption 2). Beyond this period of operation, the pins, wires and duct keep growing such that the assembly deformation starts to develop. The development of assembly deformation would cause the original center to move away from the duct edge where the wire is located between the pin and the duct, i.e., in the negative Y direction, to a new centroid. The distance in which the centroid moves will depend on the thermal and irradiation environments to which the assembly is exposed. Meanwhile, all the pins in the assembly will move toward the new centroid. The pin further away from the new centroid undergoes more displacement than the pin near the new centroid. The length of pin movement vector is proportional to the distance from the pin to the centroid.

3. Statistical Data Analysis

There is a need for compression test data analysis to check the validation of the proposed pattern geometry approach. The statistical analysis of the two sets of compression test data (Figures 9 and 10) are presented. The statistics generated by two sets of data are not necessarily accurate. Therefore, it is suggested that more compression tests be conducted to provide an adequate data base which should include a variety of test parameters such as size and number of pin, wire lead to pin diameter ratio, etc.

Since there are only two sets of data currently available, it is reasonable to average each pin's movement by vector analysis. The pin displacement vector obtained was then decomposed into the angle and the quantity of displacement. Note that the assembly is divided into two mirror image sections along the Y axis. Therefore, the angle and displacement of each pin are averaged again for these two images. (If there are sufficient data, there is no need to do this averaging. At present, the average between these two images would reduce some pin movement uncertainties.)

The direction and magnitude of pin displacement for a deformed assembly are shown in Figures 12 and 13. In Figure 12, the angle without a plus sign in the measure of the clockwise angle from the X-axis and the angle with a plus sign is the counterclockwise angle from the X-axis. It can be seen that the pin moves fairly well along the angular line toward the newly postulated centroid which is empirically selected. In Figure 13, again, the pin displacement is linearly proportional to the distance between the pin and the new centroid. Note that the edge pins do not follow the observations above. These two figures verify the proposed approach for pattern geometry structural code.

4. The Computer Programming Outlines

Some basic rules to implement the pattern geometry structural code are outlined below.

- (1) Apply a numbering system so that the pins are divided into two symmetrical groups along the Y-axis.
- (2) The original pin location is defined by the Cartesian system for the X-Y axes.
- (3) Evaluate the new centroid for assembly deformation. The distance of centroid movement would be a function of thermal, neutronic, irradiation, and mechanical effects.
- (4) Redefine the location of each pin (only for half assembly due to mirror image) for the X-Y system.
- (5) Evaluate the bundle-to-duct interference (BDI).
- (6) Decompose the BDI into two proportional quantities along the new centroid, Y_1 , and Y_2 as shown in Figure 6.
- (7) Each pin's displacement can be evaluated along the Y axis using the new centroid as the center point.
- (8) Transform the deformed pin location from the X'-Y system to X-Y system to obtain the final pin location.

This code can be readily developed and integrated with a thermohydraulic code for analyzing deformed fuel assembly performance.

D. Other BDI Modeling Needs

Besides the simplification of the thermal-hydraulic-mechanical code for the LDP design the long term code development needs are:

- Effect of edge pin bow — a method of solution for edge pin bow due to thermal gradients should be considered for incorporation into the BDI code.
- Effect of pin-pin and pin-duct contact or close proximity — local thermal-hydraulic analysis is necessary to determine the circumferential temperature distribution of pins for the pin-pin or pin-duct contact situation.
- Adequacy of using average bundle temperatures and fluence for BDI analysis — one of the assumptions used in the XEBRA code is that the interactions of bundle and duct can be adequately predicted using the average bundle temperature, the average duct temperature, and the average fluence. Verification of this assumption requires appropriate PIE data on FFTF assemblies for which such temperature information is known.
- Modification of code for distributed wireless bundle — current code is only suitable to perform the analysis on a fully wire-wrapped bundle. In the LDP, distributed wireless pins may be used. It is necessary to modify the existing code to provide an adequate predictive method. Some of the features in the FULMIX-II⁽¹¹⁾ computer program, developed by G.E. and suitable for the wireless bundle study, may be used for this modification.

FIGURE 1.
LDP BUNDLE PRESSURE DROP CORRECTION WITH HELICAL PITCH

FIGURE 2
217-PIN BUNDLE 0°-0°-0°/WIRELESS

FIGURE 3.
WIRE SPACER POSITIONS AT TWO AXIAL LOCATIONS

FIGURE 4. BUNDLE-DUCT INTERFERENCE

FIGURE 5. SUBCHANNEL AREA REDUCTION OF FTR 217-PIN FUEL
BUNDLE WITH 0.100 IN. ACROSS FLATS UNIFORM COMPRESSION

WIRE WRAP
DIRECTION
(Top View)

**SUBCHANNEL AREA
REDUCTION LEGEND:**

Note: Average Area
Reduction = 14.4%

FIGURE 6. SIMULATED SUBCHANNEL AREA REDUCTION OF 127-PIN FUEL
BUNDLE WITH 0.100 IN. ACROSS FLATS UNIFORM COMPRESSION

FIGURE 7. NORMALIZED TEMPERATURE DISTRIBUTION
AT 35.7" ELEVATION, UNIFORM POWER DISTRIBUTION

FIGURE 8. NORMALIZED TEMPERATURE DISTRIBUTION AT 35.7" ELEVATION
UNIFORM AXIAL POWER DISTRIBUTION 1.1/0.9 RADIAL SKEW

FIGURE 9. 0° - 0° - 0° PIN DISPLACEMENTS, TEST 1.1.4, 4.300 TO 4.230

FIGURE 10. 0° - 0° - 0° PIN DISPLACEMENTS, TEST 1.2.1, 4.300 TO 4.230

FIGURE 11.
CONCEPT OF PATTERN GEOMETRY FOR BUNDLE DEFORMATION

FIGURE 13.
COMPRESSION TEST DATA ANALYSIS FOR DISPLACEMENT PATTERN

$$Y_1 + Y_2 = BDI$$

FIGURE 14.
THE EVALUATION OF PIN DISPLACEMENT UNDER DEFORMATION
USING THE PATTERN GEOMETRY APPROACH

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