XEBRA Evaluation of the Mechanical and Thermal-Hydraulic Performance of Distorted Fuel Pin Bundles

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SUMMARY

Active fuel region components of liquid metal fast breeder reactor (LMFBR) fuel assemblies undergo large distortions due to large swelling and irradiation creep strains of the stainless steel parts. A major mode of distortion is that referred to as bundle-duct interaction (BDI) in which a differential lateral growth occurs between the fuel pin bundle and the duct, producing an interference. This, in turn, causes the fuel pin bundle to be compressed by the relatively rigid outer duct, and results in a coolant subchannel geometry distribution which can be significantly distorted from the uniform subchannel geometry which is assumed when thermal-hydraulic analyses of fuel assemblies is performed.

A procedure has been developed to evaluate the interacting structural mechanics and thermal-hydraulics analyses of fuel assembly pin bundles which are subjected to large BDI. A major requirement to develop this procedure was to determine a structural model capable of describing the complex mechanical behavior of large fuel pin bundles, i.e., bundles consisting of up to 271 fuel pins (10 hex "rings"), and to perform the structural analysis rapidly so that many evaluations could economically be performed over an assembly lifetime. This is required in order to determine the fuel pin cladding history for subsequent detailed fuel pin performance evaluations and to allow an interacting feedback of calculated thermal behavior into the structural model, in order to continually re-evaluate the temperature-dependent BDI. The structural model used was that of implementing fuel pin displacement data that was determined experimentally from large bundle compression testing.

The analytic procedure developed is called the XEBRA procedure. This paper focuses on the basis and validity of the structural model. It also presents typical results from a XEBRA analysis, which demonstrates the effect of the distorted bundle geometry on temperature calculation, and reviews a current criteria related to the acceptance of the non-distorted thermal-hydraulic geometry model.

INTRODUCTION

Operating under conditions of high temperature and high neutron irradiation during its lifetime, a liquid metal fast breeder reactor (LMFBR) fuel assembly using wire wrapped fuel pin spacers will experience structural behavior known as bundle-to-duct interaction (BDI). The interaction is the result of the differential lateral displacements between the fuel pin bundle and the hexagonal duct, resulting from the irradiation induced swelling and creep strains of those components. BDI may result in significant interference between the pin bundle and the duct in the latter part of the assembly life, compressing the pin bundle and inducing significant distortion to the pin bundle geometry. The distortions produce a non-uniform decrease in the local coolant flow channel areas and potentially may result in an increased clad temperature by causing maldistribution of the coolant flow and by decreasing the flow velocity due to increased friction losses.

Previously analytic development and evaluations were performed by Miki [1,2] to determine the effects on LMFBR fuel assembly performance of the fuel bundle distortions occurring early in the assembly lifetime due to the pin bowing associated with the differential thermal expansion and the differential swelling across the pin diameter. That combined structural and thermal-hydraulic analysis is appropriate until the initial as-fabricated bundle looseness (i.e., the clearance between the duct and the geometrically compact bundle) is eliminated due to the lateral differential expansion between the bundle and the duct. The fuel assembly bundle structural and thermal-hydraulic performance commencing at that time, and continuing through the latter part of life, is the subject of this presentation.

An analytic procedure to predict distorted fuel pin bundle thermal-hydraulics was recently developed by Chen, et al. [3], and used to evaluate the combined structural and thermal-hydraulic performance of a large LMFBR fuel assembly subjected to significant BDI. Presently, an interference equivalent to one wire spacer diameter is used as a fuel assembly design allowable to limit peak cladding temperatures to approximately the same magnitude calculated by using uniform geometry subchannel analysis methods. That allowable was empirically founded in the absence of a rigorous analytic capability to perform thermal-hydraulic analysis on distorted bundles. The results of Reference [3] demonstrated that an increase in the BDI magnitude to 1½ to 2 wire diameters results in peak subchannel coolant temperatures which remain below those which are derived from a uniform subchannel geometry idealization.

This paper discusses the basis and validity of the structural model of Reference [3], which has been developed using out-of-pile mechanical test data. Key results of Reference [3] have been summarized herein so as to provide insight into the relationship between the bundle distortions and the temperature perturbation caused by the distorted geometry, and to set the stage for future analyses to evaluate the local cladding hot spots at conditions of large BDI.

STRUCTURAL MODEL

A rigorous analytical description of the fuel bundle distortions due to BDI is considered non-tractable because of the large number of pins (e.g., 271 pins for a commercial size plant), and large number of wire contact points, even when the available recurrence features and symmetrical and anti-symmetrical boundary conditions are imposed. The major complexity arises from the random imperfections of the geometric structural features of the pins combined with the unstable load paths along rows of pins associated with cladding-to-wire spacer-to-cladding interacting surfaces.

The positions of all pins at an in-pile bundle cross-section subjected to BDI can be determined by a linear superposition of two sets of displacements; that due to the free or unconstrained growth of the bundle and the duct, and that due to the mechanical interaction at the inner surface of the rigid duct as it compresses the bundle at its outer periphery. When compressing the bundle outer periphery, the duct to bundle loading is applied helically about the bundle periphery, following the wire spacer pattern, as shown in Figure 1. Figure 2 shows the characteristic lateral displacement components of the fuel pins at a single plane shown as a section through Figure 1, a plane at which the boundary loads are applied to the pin bundle at the 10 o'clock hex flat. The final pin positions are the vector sums of the unconstrained radial bundle growth displacement, which is a trivial calculation, plus the displacements at the plane due to compressing the bundle to satisfy displacement compatibility between the pin bundle boundary and the duct inner surface. These latter displacements have been well-characterized by Kaplan [4] from mechanical testing. The schematic replica depicted in Figure 2 warrants further description.

Mechanical compression tests of Reference [4] were performed on 217-pin and 91-pin wire-wrap spaced pin bundles with measurements made for the lateral displacements of all pins at a single plane. Typical test data is shown in Figure 3 for a 217-pin bundle. The bundle has been compressed under a helical, boundary loading, with the pin displacements of Figure 3 representing those at a plane where the boundary loading occurs at the bundle 10 o'clock hex flat. The displacements reveal the true complexity of the pin displacements' characteristics. If only an idealized perfect and stable geometry occurred, it might be expected that all the pins would displace with similar magnitudes and in near parallel directions, consistent with all pins having parallel lengthwise deflection patterns of helical configuration. Thus, when a line load is applied to the pins at the 10 o'clock edge, it might be expected that the pins along the 4 o'clock edge (as well as all other pins in the bundle) would have approximately the same displacement as that imposed at the 10 o'clock edge row. The observation that all pin displacements in the plane are not parallel and equal is due to an internal compliance mechanism acting in series with the bundle gross helical bending mechanism whereby the pins have random lateral displacement components. This distorts the idealized pin triangular pitch spacing assumed for fuel assembly thermal-hydraulic subchannel coolant analyses. Also distorted are the edge region flow subchannels, which, under idealized non-distorted bundle conditions are uniform about the bundle periphery. For the distorted bundle, the edge region subchannel varies from a maximum at the wire spacer location (the 10 o'clock flat for the orientation under discussion) to a minimum at the 4 o'clock flat, which is at the mid-elevation between wire spaced axial locations. At that 4 o'clock position, the edge region subchannel width would be expected to decrease by the same magnitude as the across-hex interference between the bundle and the duct if the structural mechanism of bundle compression compliance was due only to the helical bending mode of the pins. However, the internal compliance mode, which is commonly referred to as dispersion, accommodates approximately half of the interference, and the 4 o'clock edge pins deflect into the edge region by only half the magnitude of the interference. As the width of the edge subchannel is equal to the diameter of the wire spacer, when an interference between the bundle and the duct equal to two wire diameters occurs, the 4 o'clock edge pins will mechanically displace an amount equal to one wire diameter and will thus result in contact between the cladding surface and the duct wall.

The observed random lateral displacements result from the mechanical instability of the load transfer between pins, enhanced by geometric imperfections of the pin (the tube and the wire). The resulting internal compliance mechanism and its complexity are the primary bases for declaring a non-tractable assessment for a successful rigorous structural analysis.

To implement the bundle compression data into a thermal-hydraulic subchannel analysis two alternate procedures have been formulated. One is the direct implementation and scaling of the bundle compression test data. To evaluate 271-pin bundles (characteristic of commercial size LMFBRs) using the 217-pin data (FFTF and CRBRP size bundles) an extrapolation is required to include the additional "ring" of fuel pins. A second method that has been implemented is the use of a fictitious bundle using the general pattern of pin displacements as statistically reduced from the bundle compression data so as to characterize the planar pin displacements by a limited number of parameters.

A brief discussion of the validity of using the mechanical test data to simulate in-pile behavior in the presence of creep is appropriate. Structural components located in the active core region of a fast reactor are subjected to two classes of creep phenomena, "thermal creep" which is highly non-linear with stress and occurs at the upper range of cladding temperature, and "irradiation creep" which has been correlated linearly with stress and occurs over the moderate range of cladding temperature. The temperatures and stress levels associated with BDI result in stress relaxation of the fuel pin bending stresses that is determined almost totally by linear creep behavior. Thus, the displacements determined by the bundle compression testing are applicable to in-pile behavior governed by a constitutive relationship of linear elasticity plus linear creep.

During BDI, the duct dilates from an initial regular hexagon to a configuration having bulging of the duct faces due to the coolant pressure loading. The elastic bulging is considerably magnified by irradiation creep. In implementing the bundle compression data into the structural model, it is assumed that the fuel pin bundle is constrained by an "effective" across-flats duct dimension of a fictitious, regular hex duct that has the same area as the dilated duct. Such an effective duct behavior was observed, during the bundle compression testing, to produce similar mechanical performance with respect to pin displacements as observed for simulated bulged ducts that were tested.

The design of the compression test rig was that of an open, strong-back type structure, with individually activated loading pads. The load pads simulated the duct wall in dimension and alignment and were located only at the discrete elevations at which the duct wall contacts the row of pin bundle edge wires. Bundle compression was achieved by controlled, limited displacement movement of the load pads. Use of such individual load pads allowed including such test conditions as the simulating of the bulged duct surface, the application of a planned axial variation of BDI, and a combination of those two conditions. The open design allowed direct visualization and measurement of the edge pin displacements relative to the stationary strong-back, to supplement the principal source of pin displacement measurements, an optical telescopic arrangement mounted on a dual axis micrometer indexing platform.

APPLICATION OF THE METHOD

The analytic procedure, designated as the XEBRA procedure, consists of implementing three basic models. The first model determines the bundle-to-duct interference by calculating the differential growth of the fuel pins, wires and duct due to swelling and creep during irradiation. The second model, based on out-of-pile bundle compression test data, determines the position of each pin at each axial location in conjunction with the differential bundle and duct growths derived from the first model, and then determines the local flow areas and related hydraulic parameters throughout the distorted bundle. The third model determines the thermal hydraulics of the distorted assembly. The COBRA-WC code [5] has been implemented for the thermal-hydraulic subchannel analysis model. This code can accept non-uniform subchannel areas and gaps. These three models are implemented so that the time-dependent effects of BDI on the assembly thermal-hydraulic behavior can be evaluated throughout lifetime. A forward stepping procedure is used whereby BDI is calculated considering temperatures at the previous time step. The distortions associated with that BDI are then used to determine temperature for the next time step.

A 271-pin fuel assembly of a stainless steel alloy for the duct, the cladding, and the wire spacers was investigated. The dimensions and the in-reactor environment were consistent with the current commercial-size plant requirements. The fuel pins used 0.275-inch diameter cladding with 0.048-inch diameter spacer wires.

BDI varies in the assembly both axially and as a function of time. Figure 4 shows a characteristic BDI history at the axial mid-core elevation, for an assembly lifetime of two years, the mid-core location experiencing the maximum BDI. At beginning-of-life an initial looseness occurs due to the as-built clearance, slightly diminished by differential thermal expansion between the bundle and the duct. Early in life the looseness increases slightly due to the creep induced duct dilation. During the mid-life range, the rate of increased looseness diminishes as the pin plenum pressure buildup results in increased cladding creep. Until this time swelling of the stainless steel components has not occurred; an incubation period is required before swelling commences. Toward the end of life the looseness diminishes and eventually the bundle is compressed as the swelling incubation fluence is exceeded. The bundle swelling rate considerably exceeds the duct swelling rate in accordance with the swelling temperature dependency. At the end of life a large bundle tightness occurs. The analysis was performed up to the time of BDI equal to two wire diameters.

The calculated coolant temperature distribution under different amounts of BDI during an assembly lifetime is shown in Figures 5 and 6. Important results to be noted are a temperature profile flattening as the edge channel coolant temperatures increase, and the interior channel coolant temperature decrease with the increase in bundle-to-duct interference.

It is also calculated that the increase in the edge channel coolant temperatures is higher along the edge of the bundle where the wires contact the duct wall than that of the edge channels opposite the non-wire contact region. At the channel region that includes the wires contacting the duct, even though the edge channel flow areas have not been diminished by the BDI, the interior channels have been considerably distorted, producing a significant decrease in flow areas and in coolant flow. At the opposite side, although the edge channels are considerably reduced in area as the cladding approaches the duct wall, very little distortion occurs to the pin array in that general region, and the interior flow channels in that general region remain relatively undistorted.

CONCLUSIONS AND DISCUSSION

Out-of-pile bundle compression test data which produced mechanical displacements that could be used to model in-pile pin positions for an assembly subjected to BDI, were used to perform a distorted bundle thermal-hydraulic analysis for a 271-pin fuel assembly operating for a two-year lifetime. The analysis was conducted up to a BDI value equal to two wire spacer diameters, at which time the analysis was discontinued. The compression test data is not applicable beyond a BDI equal to two wire diameters because the displacement boundary conditions imposed on the bundle change from those used in the compression program. The analysis showed that for up to 2 wire diameters of BDI, the redistribution of the flow channel geometry resulted in decreasing the peak temperatures which occur at interior subchannels for non-distorted bundle geometries, while increasing the temperatures at the edge subchannels, with the edge channel temperatures remaining below the peak temperatures that occurred at the bundle interior early in life. The temperatures calculated represent the global effects of BDI and do not account for the local hot spot effects associated with large BDI, as, for example, contact between the edge pin cladding and the duct wall. However, the global conditions provide the thermal-hydraulic boundary conditions which can provide the basis for an improved local hot spot analysis.

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[5] E. U. Khan and J. M. Bates, "A Validation Study of the COBRA-WC Computer Program for LMFBR Core Thermal-Hydraulic Analysis," NUREG/CP-0034, Proceedings of the Topical Meeting on Advances in Reactor Physics and Core Thermal Hydraulics, Vol. 2, September 1982

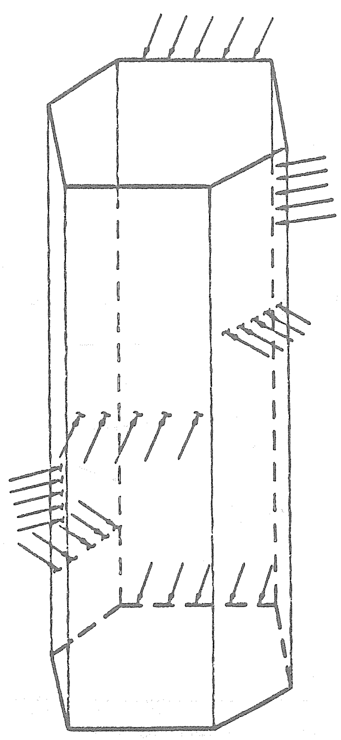

FIGURE 1.
HELICAL LOAD DISTRIBUTION APPLIED TO FUEL-PIN BUNDLE

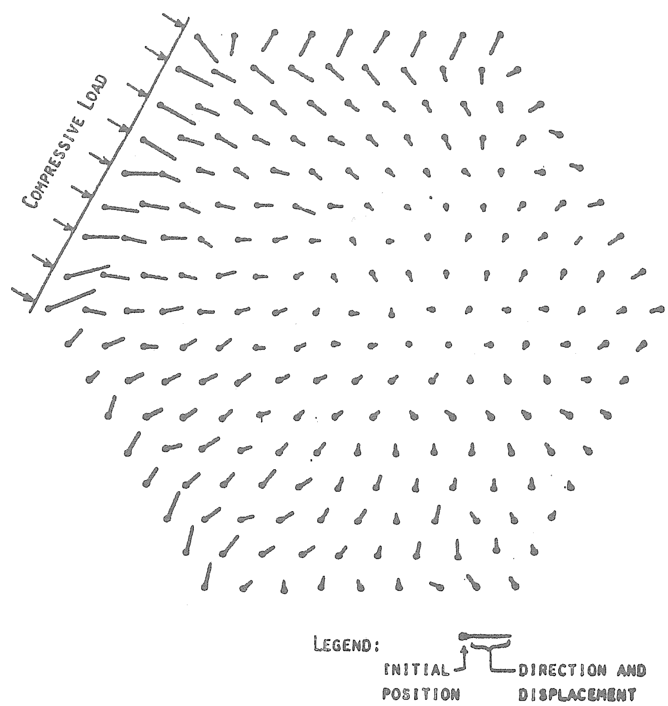

FIGURE 2.
PIN DISPLACEMENT MECHANICAL COMPONENT DATA FROM 217-PIN BUNDLE COMPRESSION TEST

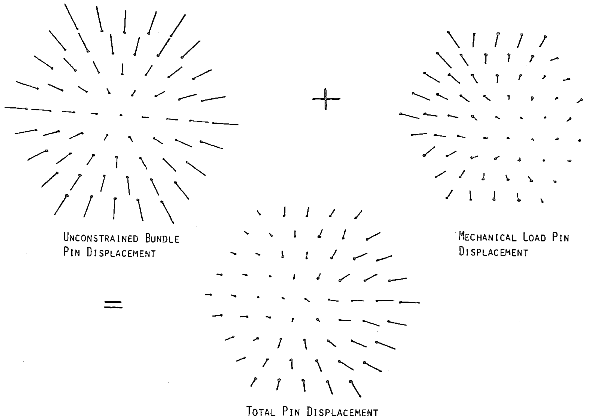

Figure 3. Superposition of Pin Displacement

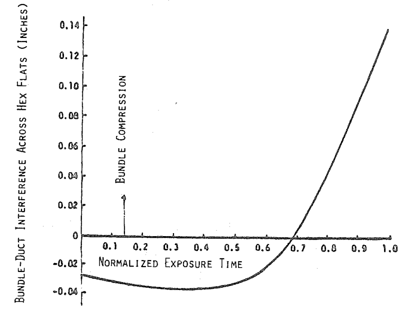

Figure 4
Bundle-Duct Interference History at the Mid-Core Elevation

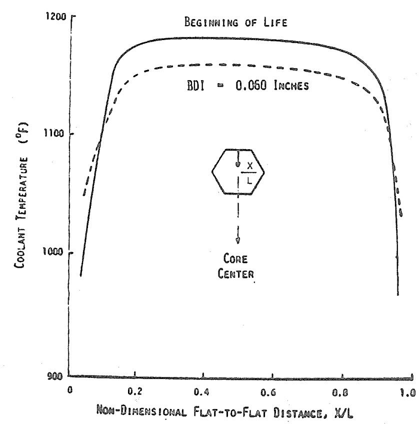

Figure 5.
Coolant Temperature Lateral Distribution for Different Values of BDI

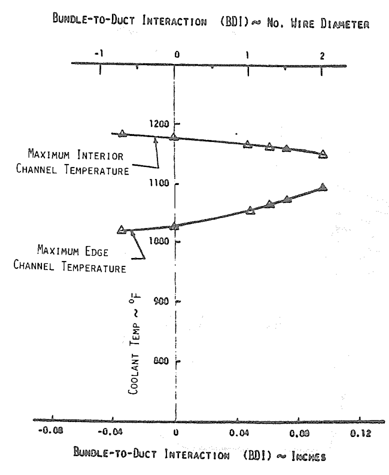

Figure 6.
XEBRA Analysis of 271-Pin Assembly on BDI Effect on Coolant Temperature