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SODIUM FLOW DISTRIBUTION IN TEST FUEL ASSEMBLY P-23B

Hanford Engineering Development Laboratory

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J.P.S. Taylor

August 1978

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ABSTRACT

Relatively large cladding diametral increases in the exterior fuel pins of HEDL's test fuel subassembly P-23B were successfully explained by a thermal-hydraulic/solid mechanics analysis. This analysis indicates that while at power, the subassembly flow was less than planned and that the fuel pins were considerably displaced and bowed from their nominal position.

In accomplishing this analysis, a method was developed to estimate the sodium flow distribution and pin distortions in a fuel subassembly at power.

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SODIUM FLOW DISTRIBUTION
IN TEST FUEL ASSEMBLY P-23B (FF064, FF121)

1.0 INTRODUCTION AND SUMMARY

The Hanford Engineering Development Laboratory (HEDL) P-23B⁽¹⁾ test assembly was irradiated in the Experimental Breeder Reactor II (EBR-II). This test was part of an irradiation testing program being conducted by HEDL for the Department of Energy in support of the Liquid Metal Fast Breeder Reactor (LMFBR) Program. The P-23B test is designed to evaluate the behavior of Fast Test Reactor type mixed oxide fuel pins clad with AISI 316 20% cold-worked stainless steel at peak cladding temperatures of approximately 1400°F.

The P-23B test assembly was irradiated in EBR-II from July 1974 to the time of this report. The experimental assembly was a very successful part of an overall program designed to demonstrate the adequacy of the fast test reactor fuel pin design. The test assembly had been removed from the reactor for interim data collection on three occasions prior to the withdrawal that led to this analysis. After each withdrawal the assembly was reconstituted and placed back into the reactor. During its irradiation the test experienced three fuel pin failures, two of which have been analyzed and determined to be high temperature (~1500°F) failures. The test assembly was designed to operate in a temperature region (~1400°F at top of pin) in which there has been little experience. Unexpected large pin diameter growths in corner and edge pins indicated that this test may have operated under significantly different conditions than expected. This analytical project was performed to explain these anomalous deformations.

Postirradiation measurements performed on the P-23B pins after the fourth period of irradiation indicated larger diameter increases in corner and edge pins than predicted by material behavior models. Measured and predicted diameter increases were forced to agree by varying the cladding

temperatures. The sodium flow redistribution among subchannels was inferred from these temperatures. It was also determined that there was a 10-20% reduction in the total flow of sodium to the pin bundle. A flow rate reduction of this magnitude was potentially possible since substantial by-pass flow paths had been provided.

Using simplifying assumptions, the motions of the pins during irradiation were derived from the redistributed subchannel flow rate values. The method of analysis is shown in Figure 1.

2.0 DISCUSSION

The Hanford Engineering Development Laboratory's (HEDL's) P-23B 37-pin fuel subassembly was withdrawn from the Experimental Breeder Reactor II (EBR-II) after reactor Run 87A. The P-23B test was designed to evaluate the behavior of the Fast Test Reactor (FTR) type fuel pins with AISI Type 316 stainless steel cladding at peak cladding temperatures of $\sim 1400^{\circ}\text{F}$.

Routine diametral measurements were performed on 36 of the 37 pins in the test with a helical trace profilometer. This device measures the diametral increase of a fuel pin while following a helical course axially up the pin. Analysis of the diameter increases indicated that pins on the corners and edges of the hexagonal bundle had undergone larger increases than interior pins. This was unexpected, as generally the interior hotter pins deform more than colder pins. To check this behavior, a detailed thermal hydraulic structural mechanics analysis was performed. COBRA-IV,⁽²⁾ a thermal hydraulic code for pin bundles, was used to predict the sodium flow rate for each sub-channel of the P-23B bundle. COBRA is a code developed to solve for the coolant velocity, temperature and enthalpy distributions in typical fuel bundle geometry. The code determines these quantities by solving the continuity, momentum and energy equations for each computational cell or subchannel.

FIGURE 1. Analysis Method.

COBRA-II⁽³⁾ was also used to determine the coolant flow rates and temperature distribution, but its use was discontinued because COBRA-IV was determined to be more suitable for solving flows in distorted pin bundles. Much of the early work reported in this document was with COBRA-II results, so reference to both COBRA-II and COBRA-IV are frequent. COBRA-II solves the conservation equations through the initial value method. COBRA-IV solves these equations by the boundary value method. Table 1 lists the important constitutive relations, such as friction factor, that were input to the code.

TABLE 1

COBRA INPUT

CONSTITUTIVE EQUATIONS

FRICTION FACTOR

$$f = \text{maximum of } (.252 \text{ Re}^{-.226} \text{ or } 64 \text{ Re}^{-1.00})$$

Re = Reynolds number

FILM COEFFICIENT

$$h_{\text{film}} = K/D \ 0.025 \text{ Re}^{.80} \text{ Pr}^{.80} + 7.000$$

K = sodium thermal conductivity

D = channel hydraulic diameter

Re = Reynolds number

Pr = Prandtl number

MIXING FACTOR

$$\beta = 0.10 \text{ Re}^{0.00}$$

Re = Reynolds number

The COBRA-II analyses assumed that the pins remained in their nominal positions and there was nominal (as designed) coolant by-pass around the test bundle. The results of the COBRA II predictions are shown in Figure 2 as coolant temperatures. Exterior and corner flow channels of the bundle were predicted to have operated at lower temperatures than interior channels because of the unheated surrounding duct. Normally the exterior pins would

be expected to have smaller diameter increases than the interior pins if diameter change increases as cladding temperature increases.

To determine if the larger diameter increases in the edge and corner pins were anomalous, an analysis of the temperature dependence of 316 20% cold-worked stainless steel deformation was performed. It was of interest to determine if a lower operating temperature could induce larger diameter increases in fuel pins assuming equivalent irradiation conditions. Experimental correlations for swelling⁽⁴⁾ and for various types of creep including thermal creep⁽⁵⁾ were programmed into a computer code to determine their combined temperature dependence. Figure 3 shows the predicted axial position deformation plot for the irradiation conditions of three typical P-23B fuel pins: an interior pin, an inside row pin and a corner pin. The interior pin has two peaks in its axial position-deformation curve. The first is due to the combined effects of irradiation-induced creep and swelling and the second is due to thermally activated creep. These curves can be conceived as showing how the cladding deforms as the temperature increases up the fuel column. The nominally calculated top of the fuel column temperatures for the interior, inside row and corner pins are respectively: 1340°F, 1250°F and 1180°F.

The nominally-predicted time-averaged cladding temperatures at the top of the fuel column for all the pins are also shown in Figure 2 on the circular areas which represent fuel pins. These cladding temperatures indicate that the top of the interior pins were nominally calculated to have been operating in the region dominated by thermally activated creep, while the top of the exterior and corner pins operated in the temperature region between the swelling and thermally activated creep peaks. The nominal temperatures correspond to approximately 1340°F for the interior and 1180°F for the exterior pins. For these temperatures, Figure 3 shows that the interior pins should have experienced larger diameter changes than exterior pins. There is only a small region between $Z = 8.5$ and $Z = 11.4$ inches at which the corner pin is calculated to have a larger diameter increase than

FIGURE 3. Deformation vs Axial Position for 3 Typical P-23B Pins.

the interior pin. However, this behavior was noted all the way up the fuel column. Thus, based on this thermal hydraulic analysis and the temperature dependency of 316 20% cold-worked stainless steel, the behavior of the fuel pins in P-23B was anomolous.

SIFAIL*, a fuel pin thermomechanical performance computer code to calculate fuel pin deformation, was used to determine the difference between the measured and calculated diameters for the 36 pins. The code contains swelling and creep models like those used to construct Figure 3. The analysis using the code underpredicted diameters in the exterior pins and overpredicted diameters in the interior pins. Table 2 lists the major inputs required for the SIFAIL code for these analyses. The analysis used fission gas pressure as the only loading mechanism for cladding deformation. SIFAIL was used at an earlier date⁽⁷⁾ with the same type input values in Table 2 to predict the deformations of 88 other fuel pins with similar geometries and stress histories which had been irradiated in EBR-II. The code generally underpredicted diameter changes with an average error of 0.03% D/Do. The calculation error values for the P-23B subassembly were scattered randomly about zero with an order of magnitude greater than that for the 88 pins analyzed earlier. This result indicates that significant error was introduced through assumptions made in the irradiation environment, material properties, models or in the diameter measurements themselves for the P-23B assembly.

Previous comparisons have shown that helical postirradiation diameter measurements, like those performed on the pins from the P-23B subassembly, are on the average comparable to those from the HEDL profilometer which measured the 88 fuel pins in the prior study. The material properties for deformation used in the P-23B analysis are the same as those used for the

*A version of SIEX⁽⁶⁾ modified to compute cladding deformation based on a thin wall stress analysis using fission gas pressure as the loading mechanism.

TABLE 2

SIFAIL INPUT FOR TYPICAL P-23B PIN

Active Fuel Column Length	13.5 in.
Fuel Diameter	0.195 in.
Pin Diameter	0.230 in.
Cladding Thickness	0.015 in.
Pin Heating Rate	10.6 kW/ft
Coolant Mass Flow Rate	212 lbm/hr
Coolant Specific Heat	0.300 Btu/lbm-°F
Coolant-Cladding Film Coefficient	3.59×10^4 Btu/hr-ft ² -°F
Fuel Cladding Gap Coefficient	1.65×10^3 Btu/hr-ft ² -°F
Inlet Coolant Temperature	700°F
Fraction of Theoretical Density	90.3%
Fuel Theoretical Density	10.95 gm/cc
Fissile Metal Fractions	0.221 Pu/0.486 U ²³⁵
Peak Burnup	95,000 MWd/MTM
Effective Plenum Length	13.5 in.
External Pressure	35 psig

prior study of 88 pins. This leaves the modeling of pin deformation and the irradiation environment as candidates for the source of calculational inaccuracy.

The modeling used for each analysis was identical, but a recently proposed model⁽⁸⁾ of additional deformation has not been taken into account. The deformation rate resulting from a decrease in cladding operating temperature during irradiation has been observed to act as if the material were still at its original temperature. This phenomenon was initially thought to have some effect on the amount of deformation in the P-23B corner pins, since these pins were moved to their corner positions from relatively warmer edge locations during a reconstitution of the assembly. The COBRA-II calculated reduction in temperature was about 36°F which would not produce any significant amount of additional cladding deformation. Since the rest of the modeling of pin deformation in this analysis is similar to the 88 pin study, the most probable remaining source of calculational inaccuracy is the irradiation environment.

The modes of permanent deformation of a fuel pin, as modeled in SIFAIL, are creep and swelling. The environmental parameters which affect the creep and swelling rates are: neutron flux, fission gas generation rate, cladding thickness, time in reactor and the coolant flow rate. There is a good understanding of all these parameters as time varying quantities, except the coolant flow rate. The irregular pattern of residual diameters indicates a general flow pattern existed in the assembly unlike the one calculated with COBRA-II or COBRA-IV with nominal geometry.

At this point in the analysis, it was decided to infer the flow pattern from the fuel pin deformation measurements. The method to be used was to iteratively run SIFAIL with a varying assumed flow rate for a pin until the measurements and calculations were minimized for each of ten axial locations.

Figure 1 shows the schematic used to determine the cladding temperatures. Cladding temperatures were inferred with SIFAIL from measurements of pin deformation. The coolant temperature and flow rate distributions were then determined by averaging values from surrounding pins. By assuming constant velocity in a subchannel, the flow areas were determined and these areas were then used to determine the pin movement during irradiation. This distorted geometry was then used as input to COBRA-IV and the resultant coolant temperatures were reduced to pin temperatures and compared to SIFAIL calculated values.

In order to achieve 1400°F cladding temperature without exceeding the coolant outlet temperature limitation, this subassembly was irradiated in a by-pass flow duct which allows some portion of the inlet sodium to bypass the pin bundle and travel in a liner past the assembly. There is sufficient historical precedence, in terms of fuel pin failures, to question the reliability of COBRA-II calculated fuel pin temperatures in these by-pass flow assemblies. Most of the fuel pin failures experienced in EBR-II have shown some degree of local overheating⁽⁹⁾ in comparison to nominally calculated COBRA-II temperatures.

The flow distribution in P-23B was assumed to vary axially to account for the scatter in the measurements. The input coolant flow rate value for SIFAIL is a lumped or averaged number, since a number of channels surround a pin. Figure 4 shows a twelfth section model of a 37-pin subassembly. The flow rate for Pin 5, for example, would be:

$$\dot{m}_{P5} = \frac{1}{6}(\dot{m}_{C4} + \dot{m}_{C5} + \dot{m}_{C6}) + \frac{1}{4}(\dot{m}_{C7} + \dot{m}_{C8})$$

where subscript P5 refers to pin number 5 and subscript C4 refers to channel number 4. These lumped flow rates were used in SIFAIL and appropriate assumed values were iterated until the SIFAIL prediction for an axial location matched the measurement. The resultant SIFAIL calculated temperature

FIGURE 4. One-Twelfth Section of P-23B Subassembly.

distribution was then used to determine the coolant flow rate distribution. Figure 5 shows the axially variant flow rates for the six corner pins as ratios with respect to the COBRA-II lumped flow rate values. Figure 6 is a similar plot for six inside row pins and Figure 7 has the flow rate ratios plotted for six interior pins. Note that the corner and inside row pins required less flow than the nominal with the lower portion of the pins more flow starved than the top of the pins. The trend is opposite of that for the interior pins. Furthermore, the net result is that the analysis indicates that the total flow rate to the subassembly bundle is reduced by 10-20% from the nominal. Table 3 shows the average reduction in flow for the ten axial planes considered. The average reduction was calculated as one minus the sum of the SIFAIL flow values over the COBRA-II flow values divided by the number of subchannels or:

$$\text{Average flow reduction} = 1 - \frac{\sum \frac{\dot{m}_{\text{SIFAIL}}}{\dot{m}_{\text{COBRA}}}}{78} \quad \text{where 78 is the number of subchannels in a 37-pin bundle.}$$

The lumped flow rate values for a fuel pin as analyzed by SIFAIL were then reduced to subchannel flow rate values by the following method. The SIFAIL calculated mass flow rate in channel number 4, $\dot{m}_{C4}$, (see Figure 4) is calculated using a simple weighted average of the SIFAIL to COBRA flow rate ratios for the pins surrounding the channel:

$$\dot{m}_{C4 \text{ SIFAIL}} = \dot{m}_{C4 \text{ COBRA}} \left[\frac{1}{3} \frac{\dot{m}_{P3 \text{ SIFAIL}}}{\dot{m}_{P3 \text{ COBRA}}} + \frac{1}{3} \frac{\dot{m}_{P4 \text{ SIFAIL}}}{\dot{m}_{P4 \text{ COBRA}}} + \frac{1}{3} \frac{\dot{m}_{P5 \text{ SIFAIL}}}{\dot{m}_{P5 \text{ COBRA}}} \right].$$

A computer program was written to solve the resultant 78 equations for the 78 subchannels of the 37-pin subassembly. Figures A1-A10 in the Appendix show the SIFAIL/COBRA flow rate ratios for ten axial sections.

FIGURE 5. Ratio of SIFAIL to Cobra-II Flow Rates for P-23B Corner Pins.

FIGURE 6. Ratio of SIFAIL to Cobra-II Flow Rates for Six P-23B Inside Row Pins.

FIGURE 7. Ratio of SIFAIL to COBRA-II Flow Rates for Six P-23B Interior Pins.

TABLE 3
AVERAGE FLOW REDUCTION FOR P-23B ASSEMBLY

REDUCED FLOW RATES	
<u>Z/L</u>	<u>Average Flow Reduction (%)</u>
.056	19
.167	20
.278	17
.389	19
.500	14
.611	16
.722	13
.833	18
.944	13
1.000	12

OVERALL AVERAGE: 16% Reduction

To determine if the flow distribution derived from pin deformations was plausible and could be calculated by a thermal hydraulic computer code, the locations of the pin centers with respect to some fixed origin, was determined. The COBRA-II computer code uses the geometry of the pin assembly as input and it was obvious that the code would not calculate the SIFAIL flow distribution unless the pins had moved in the assembly relative to one another.

The mechanical reasons for this fuel pins movement were not addressed in this analysis, but a brief description of the forces involved and potential subsequent deformation mechanisms will be included for completeness. For a straight pin configuration typical of fresh fuel pins, the thermal stresses during heatup to operating temperature will cause the pins to attempt to bow toward the middle of the bundle creating a wheat sheaf effect. Since the pins are constrained, stresses develop. These thermal stresses are rapidly relieved by irradiation-induced creep and the result will be a straightening of the pins. However, the temperature gradient which caused the initial bow will still exist. Upon shutdown, the temperature gradient which caused the initial bowing tendency of the pin is removed and the originally hottest side of the pin will contract more than the cooler side. This will produce bow in the direction opposite that which occurred originally. The pins will then assume a barrel shape upon the shutdown of the reactor.

The swelling of the fuel pin cladding also affects the bow of the pin, but it is nonlinear in its temperature behavior. At core midplane where the neutron flux is highest, the interior hotter side of the cladding swells more than the cooler exterior side causing the pin to bow inward. Slightly above core midplane the peak swelling is reached at approximately 1075°F and the effect is reversed. Now, for the rest of the fuel column the hotter side of the pin swells less than the cooler side and the pins will attempt to bow outward under this phenomenon. This would cause the barreling out of the fuel pins at operating temperature which would lead to a flow reduction

in the exterior channels and an increased amount of flow in the interior channels.

Rigorous considerations of pin movement mechanisms were not included in this analysis. The complexity of coupling a thermal hydraulic and mechanical analysis was not considered at this time.

Assuming the fuel pins moved relative to their original locations, the subchannel areas were determined using some simplifying assumptions:

1. The mass velocity of the sodium in the subchannels did not change as a result of pin realignments.
2. Sodium density remains constant over the temperature range 1100-1500°F.

These assumptions permitted using the following expressions:

$$\dot{m}_{Co} = \rho_o A_{Co} V_o$$

$\dot{m}_{Co}$ = straight bundle subchannel mass flow rate

ρ_o = sodium density

A_{Co} = straight bundle subchannel flow area

V_o = sodium velocity

$\rho_o V_o$ = constant from above assumptions

so,

$$\dot{m}_{Cn} = \rho_o A_{Cn} V_o$$

where n refers to conditions after pin movement, and

$$\rho_o V_o = \frac{\dot{m}_{Cn}}{A_{Cn}} = \frac{\dot{m}_{Co}}{A_{Co}}$$

So, the new subchannel flow area after pins have deformed may be calculated as,

$$A_{Cn} = A_{Co} \frac{\dot{m}_{Cn}}{\dot{m}_{Co}}$$

The values show a consistent reduction with respect to COBRA-II input values.

These areas may be used to determine pin locations if one further assumption can be made. If the bundle remains hexagonal and the pins move relative to one another, while the assembly retains its shape, then the pins retain their triangular orientation although the triangles become enlarged or shrunk. The formula for a triangle in x-y space, is:

$$A = \frac{1}{2}(x_1y_2 + x_2y_3 + x_3y_1 - y_1x_2 - y_2x_3 - y_3x_1)$$

where the points of the triangle are located at (x_1, y_1) , (x_2, y_2) and (x_3, y_3) . Referring to Figure 8, this formula may be applied to the triangular areas between fuel pins. If we assume the origin of the x-y system is located on the center pin, then the formula for the triangular area designated as 3 between pins 1, 2 and 4 in Figure 8 is:

$$A_{Cn3} = A_{Co3} \frac{\dot{m}_{Cn}}{\dot{m}_{Co}} = \frac{1}{2} (x_1y_2 + x_2y_4 + x_4y_1 - y_1x_2 - y_2x_4 - y_4x_1)$$

A_{Cn3} = new area of subchannel 3

A_{Co3} = old area of subchannel 3

FIGURE 8. One-Sixth Section of P-23B Subassembly Showing Coordinate System.

Since the center pin's coordinates are assumed to be (0,0), there remain 72 unknowns ($x_1, x_2, x_3, \dots, x_{36}$) and ($y_1, y_2, y_3, \dots, y_{36}$) for a 37-pin bundle. There are 72 subchannels in the assembly when the six corner channels are disregarded. The resulting 72 equations for subchannel areas are in terms of the 72 unknowns. The equations are of a nonlinear nature, so a nonlinear equation solving routine on the Boeing Computer Services math-science library was chosen. The routine uses the general law of secants to locally linearize the equations to effect the solution. The method will minimize a set of 72 equations of the following form:

$$F_i = A_i - A_i^C$$

where: F_i = residual area

A_i = nominal area

$$A_i^C = \text{calculated area} \left[\text{i.e. } \frac{1}{2} (x_1 y_2 + x_2 y_4 + x_4 y_1 - y_1 x_2 - y_2 x_4 - y_4 x_1) \right]$$

The routine attempts to find the x and y values for A_i^C that will minimize the F_i 's. Convergence is reached when the equations are jointly satisfied to some suitable error criteria (i.e., F_i 's are a minimum value). If the error criteria cannot be met in a predescribed number of iterations, the code will return its best estimates of the unknowns.

The 72 equations were programmed into a computer code and the equation solving routine was applied to them. The results show, in general, that the pins moved away from the center of the assembly. Figure 9 shows a typical distorted plane. The deformed areas were geometrically possible within the confines of the assembly duct.

The deformed areas were then used as input to COBRA-IV to estimate the temperature distribution in the subassembly using the assumptions described earlier. The temperature distribution from a COBRA-IV run with deformed

FIGURE 9. Typical Distorted Geometry.

geometry was compared with the nominal temperature distribution using the SIFAIL calculated temperatures as a reference. Appendix B shows the SIFAIL calculated temperature distribution, Appendix C contains the nominal COBRA-IV temperatures based on a 15% flow reduction and Appendix D contains the COBRA-IV temperatures based on deformed geometry and a 15% flow reduction.

If the SIFAIL temperatures are assumed to be the correct temperatures in the subassembly, then comparing the COBRA-IV nominal and deformed results should indicate the benefit of inferring the flow rate distribution from the cladding dimensional changes. If the temperature difference between a COBRA-IV calculation and the temperature distribution actually experienced by the pins can be reduced by allowing the pins to move, then analysis of this type is valuable.

Figure 10 shows the average temperature differences for the 37 pins as a function of axial position for both the deformed and undeformed COBRA-IV cases. The results show that at the bottom of the core the COBRA-IV results for both the straight and deformed cases does not predict a high enough temperature. At the top of the core the effect is reversed and COBRA-IV for both cases overpredicts the temperature. The deformed COBRA-IV case is larger than the straight pin case at all axial planes considered, but it is closer to zero in all cases except the first four. The fuel pin deformation models used in SIFAIL may not be adequate at the bottom and top of the fuel column, so the results in the middle of the pin should be the most significant. At the bottom of the pin where the pin is coldest the cladding has thermally expanded less than at the top, while the fuel is at relatively the same temperature over its entire length so the possibility of any fuel-cladding mechanical interaction is greatest at the bottom of the pin. Since fuel-cladding mechanical interaction is not modeled in SIFAIL it could be the cause of the COBRA-IV underpredictions at the bottom of the pins. At the top of the fuel pins where thermally activated creep becomes important, the model for diameter change could be inadequate. Above 1300°F the model

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FIGURE 10. Temperature Discrepancies Between SIFAIL and COBRA-IV. Neg 7803364-1

for thermally activated creep is a steeply increasing function, however, large diameter increases predicted at the top of fuel pins from other assemblies operating up to 1400°F have never been observed. Therefore, the COBRA-IV overpredictions at the top of the fuel column could again be due to poor modeling in SIFAIL.

The results for the deformed COBRA-IV case show very good agreement in the region where SIFAIL and COBRA-IV predictions should be best, the region just above the core midplane. Temperature differences between subchannels due to different enthalpy rises in the subchannels are small at the bottom of the bundle, and thus comparison between straight and deformed cases is not as meaningful as in the top half of the bundle. The deformation models used in SIFAIL are considered to be adequate and the temperature profile predicted by COBRA-IV should be correct in this region. The straight pin COBRA-IV case is not as close to zero as is the deformed case, so on the basis of this region of the core, the deformed geometry bundle prediction is an improvement over the undeformed case.

Figure 11 shows the sum of the squares of the temperature differences for all the subchannels for each axial plane. This plot can be conceived as an indication of the scatter about zero of the temperature differences. The plot shows that the deformed bundle case is closer to zero for all but two axial planes. Again, this plot indicates the benefit of using a deformed bundle to calculate fuel pin temperatures.

FIGURE 11. Temperature Squared Difference Between SIFAIL and COBRA-IV. Neg 7803364-2

3.0 CONCLUSIONS

1. The apparent pin deformation abnormalities in the P-23B test can be explained by flow reduction and fuel pin redistribution.
2. Cladding deformation measurements indicate that sodium flow through the P-23B fuel pin bundle was reduced by 10-20% during its irradiation which contributed to higher than nominally calculated cladding temperatures, especially in corner and edge pins. The reduction could have been caused by more flow in the by-pass flow path than predicted.
3. In addition to the 10-20% decrease in assembly flow, a general realignment of the pins was indicated by the measurements. A model was developed and applied to calculate this realignment. In general, the pins bowed outward causing reduced internal temperatures and increased peripheral pin temperatures consistent with the deformation results.
4. Calculated subchannel coolant temperatures for the deformed (realigned) bundle showed that calculating the temperature distribution in an irradiated assembly from measurements of pin diameter changes is an improvement over straight pin COBRA-IV calculations. Improved modeling of fuel pin deformation may increase the improvement.

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APPENDIX A
SUBCHANNEL FLOW RATIOS

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FIGURE A4. Subchannel Ratios of SIFAIL to COBRA Flow Rates for $Z/L = .389$.

FIGURE A5. Subchannel Ratios of SIFAIL to COBRA Flow Rates for $Z/L = .500$.

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SIFAIL PIN TEMPERATURES

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COBRA-IV TEMPERATURES
(Straight Bundle)

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