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CORE RESTRAINT SYSTEM TESTS AND ANALYSIS

PHASE I: PLANAR EXTERNALLY CLAMPED CORE

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PHASE I: PLANAR EXTERNALLY CLAMPED CORE**

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ABSTRACT

Tests of a core restraint system employing external yokes to load and compact the reactor core were conducted using the Planar Clamping Model (PCM) test facility at HEDL. The operation of the FTR core restraint mechanisms, core component stiffness, load and friction characteristics, and the dimensions and tolerances were simulated to the extent possible in a planar mock-up. Important characteristics of hex channel arrays when subjected to inward-directed restraint loads were observed, photographed, and measured.

All tests were conducted using an array of 199 aluminum alloy channels, each 4.719 ± 0.001 inches across flats, 0.270 inch in wall thickness, and 4 inches long. Each channel was flame-sprayed with a coating of alumina (Al_2O_3) 0.0025 inch thick to increase the interchannel coefficient of friction to a value between 0.7 and 0.76.

Three series of tests were run:

- *Load Distribution Tests—These tests were designed to determine experimentally the interchannel force levels in a 60-degree pie-shaped segment of the core and to determine the effect of an oversized channel on that distribution.*
- *Dependence of Core Compaction on Yoke Load Sequencing—The ability of several different yoke actuation procedures to compact the core was evaluated using yoke position data.*
- *Effects of Lateral Forces on Compaction—The difficulty of compacting the core with one lateral force channel was experimentally assessed.*

1. INTRODUCTION

The function of a core restraint system is to maintain the correct positions of fuel, control, and blanket assemblies in an LMFBR core during both routine and abnormal reactor operation, while permitting removal and replacement of these assemblies during refueling. The design of the core restraint system must take into account the effects of distortion caused by thermal differential expansion as well as irradiation-induced swelling and creep. Because of the complexity of the core component interactions, rigorous analytical techniques are not yet available for predicting assembly movements during compaction operations (after refueling) and component loads and distortions during reactor operation. Consequently, experimental tests are required to evaluate candidate core restraint systems.

Tests of a core restraint system employing external yokes to load and compact the reactor core have been completed using the Planar Clamping Model (PCM) test facility at Hanford Engineering & Development Laboratory (HEDL) and are summarized in this report. This test series is the first in a three-phase planar test program being conducted by GE-BRD under Task 11, Subtask 4, Core Restraint Engineering.

All objectives set forth in the development specification¹ for these tests of an externally clamped array of 199 high-friction channels were met. The core compaction data and the interchannel force distribution data obtained in these tests have proven useful in understanding the important characteristics of this core restraint system.

2. SUMMARY AND CONCLUSIONS

2.1 SUMMARY

Tests of a core restraint system using external yokes (i.e., Phase I tests) were conducted using the HEDL PCM in an unmodified form (see Figure 1). The operation of the fast test reactor (FTR) core restraint mechanisms, the core component stiffness, the load and friction characteristics, and the dimensions and tolerances were simulated to the extent possible in a planar mock-up. Important characteristics of hex channel arrays when subjected to inward-directed restraint loads were observed, photographed, and measured.

All tests were conducted using an array of 199 aluminum alloy channels, each 4.719 ± 0.001 inches across flats, 0.270 inch in wall thickness, and 4 inches long. Each channel was flame sprayed with a coating of alumina (Al_2O_3) 0.0025 inch thick to increase the interchannel coefficient of friction to a value between 0.68 and 0.75.

Three series of tests were run:

- a. *Load Distribution Tests* – These tests were designed to determine experimentally the interchannel force levels in a 60-degree pie-shaped segment of the core and to determine the effect of an oversized channel on that distribution.
- b. *Dependence of Core Compaction on Yoke Load Sequencing* – The ability of several different yoke actuation procedures to compact the core was evaluated, using yoke position data.
- c. *Effects of Lateral Forces on Compaction* – The difficulty of compacting the core with one lateral force channel (simulating a bowed core assembly) was experimentally assessed.

2.2 CONCLUSIONS

Significant conclusions from the test program are the following:

- Comparison with previous HEDL PCM tests shows that, in general, less core compaction is obtained with high-friction (friction coefficient, $f = 0.68\text{--}0.75$) surfaces on load pads than with low friction ($f = 0.25\text{--}0.33$) surfaces. However, the tests show that even cores with high friction load pads can be adequately compacted by proper selection of the compaction sequence.
- The optimum method for compacting the disarrayed core was found to be sequential loading of opposite yoke pairs. In this scheme, equal loads are applied to two opposite yokes while the remaining four are retracted. The two loaded yokes are then retracted and another pair loaded. This sequence is repeated six times before all six yokes are loaded simultaneously. It was observed that channels between the two opposite loaded yokes formed into columns that had little or no lateral interaction; formation of the columns caused rotation of the channels into their proper orientations. This compaction technique should be equally effective for larger cores.
- Statistical analysis of the average pad forces shows the load distribution to be hydrostatic (i.e., equal forces on all pad faces) except for the outermost row of channels in contact with the yokes. Row-to-row load bridging varies from a high of 72% near core center to 7% near the edge and is independent of load level. The empirical curve determined in the tests agrees very well with the theoretical one for hydrostatic loading.
- An oversized channel produced only a localized effect on the core, producing $\sim 100\%$ increase in load in hex forces next to the channel, but does not significantly affect bridging or transmission of load to the centermost channel.

Figure 1. Planar Clamping Model

- A disarrayed core with channel rotations is significantly more difficult to compact than one with only channel translations. However, the optimum core compaction sequence fully compacted all disarrayed cores (maximum diametral gap of 9.8 mils at 10,000 pounds yoke load).
- The instrumented channel was found to have several deficiencies. Because of its construction, it does not distort in the same manner as a standard channel. The across-flats compliance does not match that of a standard channel and is not consistent for the three pairs of load pads. Interchannel forces are best determined by averaging data taken with the instrumented channel rotated to each of its six axial positions. The nontypical compliance of the instrumented channel results in the total measured load on the hexes in contact with a yoke being about 30% less than the applied yoke load. However, excellent force balances are obtained within the core array (where all measurements are made with the instrumented channel).

3. EXPERIMENTAL DETERMINATION OF INTERCHANNEL FORCES

The interchannel forces in each of 33 locations in a 1/6-pie-shaped (60 degrees) segment of the core were measured for uniformly applied yoke loads of 2,500, 5,000, and 10,000 pounds. The measurements were made by sequentially positioning an instrumented channel (only one was available) to each monitored location. For all measurements, every channel was in its correct position in the compacted core.

3.1 INSTRUMENTED CHANNEL

3.1.1 Description

The instrumented channel, illustrated in Figure 2, was designed by HEDL to measure independently the inward forces from each of the six surrounding channels. It consists of a central hexagonal support; six load cells, each instrumented by four strain gages forming a Wheatstone Bridge; and six load pads. For these tests, a B&F integrating, digital-voltmeter-type data acquisition system was used to record on paper and punch-tape the load cell responses as well as the yoke load and yoke position data.

3.1.2 Calibration

The response of the instrumented channel was correlated to the loading through use of a standard load cell traceable to an N.B.S. standard. For this calibration, the instrumented channel was positioned in the peripheral channel locations adjacent to the center of the yoke. The standard load cell was positioned in the neighboring location toward the center of the PCM. A single row of solid hex "channels" was used to transfer the reaction load to the opposite yoke. The force level was controlled by adjusting the yoke hydraulic pressure.

The data acquisition system zero and span (amplifier gain) were adjusted for each load cell (two opposite cells were monitored at the same time) so that readings at the zero load and 1500-pound load corresponded to the standard cell response. Subsequently, D.A.S. readings were recorded for intermediate loads. This calibration data, in the form of a polynomial curve fit, were used to interpret the instrumented channel data for the interchannel force tests.

3.1.3 Deficiencies of the Instrumented Channel

Several deficiencies in the instrumented channel were found which affect the data to some extent. The deficiencies include the following:

- The instrumented channel does not distort in the same manner as does a standard channel; the Poisson effect is not duplicated. In a standard channel, the inward movement of one side due to a force is strongly dependent on the inward forces on the other five sides. This is not true of the instrumented channels

Figure 2. Top View of Instrumented Channel

because the compliant members are the load cells which distort independently of each other. This characteristic has influence on the interchannel force data, particularly in locations where the six forces are not equal (i.e., peripheral row of channels). In addition, the across-flats compliance is not the same as for a standard channel. (These effects are discussed in more detail in Subsection 3.2, Evaluation of Interchannel Force Test Results.)

- The response of the instrumented channel was found to have a weak dependence on the height at which the inward force is applied. This is due to the vertical positioning of the strain gages in the load cell. The inaccuracies due to this appear to be important only at the periphery since the 4-inch-high yokes are positioned 5/8 inch above the grid plate. The channels, which are 4 inches high, are thus loaded 5/8 inch above their centers.
- The load pads are structurally weak and do not extend to the edges of the channel sides. Because of this, the instrumented channel loads neighboring channels at the center of their sides. This is in contrast to the loading between standard channels, which is at their edges. This atypical loading causes the neighboring channels to be slightly more compliant than those which are remote from the instrumented channel. The effect of this on the measured interchannel forces is probably slight.
- The compliance across three pairs of load pads is not the same. The spring constants across pads 1 and 4, 2 and 5, and 3 and 6 are 228 lb/mil, 282 lb/mil, and 288 lb/mil, respectively, for loads between 0 and 1000 pounds.

3.1.4 Test Procedure

The propagation of inward-directed yoke loads throughout the loaded core was determined by sequentially positioning the instrumented channel at all 33 locations in a 1/6-pie-shaped repeating segment of the core. After removing the yoke loads, the instrumented channel was carefully slid into a monitored location after that channel had been removed. Before loading the core, any displaced channels were manually nested together to remove any interchannel spaces still present. The compacted core (every channel was in its correct position) was compressed with the yokes loaded simultaneously up to 2,500, 5,000, and 10,000 pounds as indicated, using the D.A.S. Data from the instrumented channel and the yoke position transducers were recorded at each yoke load level.

3.2 MEASUREMENT OF INTERCHANNEL FORCES

Preliminary tests using three different measurement techniques were performed in an attempt to reduce the variation between corresponding interface load measurements (a single interface load measured with the instrumented channel at two neighboring locations). HEDL had used the instrumented channel in previous tests and found large variations. On the average, the variations were greater than 40% of the load. The poor correspondence of measured loads is probably caused by a combination of several facts, including

- Tolerances in neighboring channels
- Tolerances in instrumented channel
- Different compliant characteristics of the six load cells
- Imperfect compaction with small interchannel spaces present
- Statistical variations in inward directed core restraint loads for the different loadings

3.2.1 Uniform Instrumented Channel Orientations

In this test, the No. 1 cell of the instrumented channel was always oriented toward yoke No. 1 (north) which is also the yoke which loaded the monitored 1/6-pie-shaped segment of the core. A single series of measurements

(at 2,500-, 5,000-, and 10,000-pound yoke loads) was made for the instrumented channel at a single location. Interchannel forces were measured at all 33 locations, using this technique. The average variation between corresponding interface loads was found to be 40.3% of the load. The large variation can probably be attributed to all the foregoing factors. Interface data for the 33 locations with a 5000-pound yoke load level are presented in Figure 3.

3.2.2 Preservation of Seven-Channel Kernel

The effect of channel dimensional tolerances on measured channel loads was assessed by moving the instrumented channel and its six surrounding channels as a unit to five neighboring locations in the monitored segment of the core. It was evident that the differences between corresponding interface loads were not decreased by this technique. It was also evident that azimuthal dependence of the interface loads measured at each of the five locations is in a pattern which reproduces, as the "kernel" was moved, to a much greater extent than was evident in data measured using the first technique. The interchannel forces measured at these five locations for a 5000-pound yoke load level are presented in Figure 4.

3.2.3 Instrumented Channel Rotated to Six Azimuthal Orientations

The effect of the instrumented channel tolerances and the repeat loading nonuniform responses on the measured interface loads was assessed by rotating the device to each of its six azimuthal orientations at each of five locations. For each orientation, the core was loaded up to 2,500, 5,000, and 10,000 pounds. The experimental interface force was the average of six measured loads, each measured with a different instrumented channel load cell. Using this technique, the differences between corresponding interface loads was, on the average, much less than for the two techniques described previously. It was decided to continue measuring interface loads, using this technique, until all 33 locations had been monitored. The results of these measurements are shown in Figures 5, 6, and 7 for yoke loads of 2,500, 5,000, and 10,000 pounds, respectively. The average variation between corresponding interface loads is 16.0% of the load, using this technique.

3.2.4 Near an Oversize Channel

A channel which had been flame-sprayed with enough alumina to increase its across-flat dimension 0.013 inch over that of a standard channel was positioned three rows in from the yoke. Interchannel force measurements were made in 12 neighboring locations, using the rotation technique described previously. The data are presented in Figures 8, 9, and 10 for yoke loads of 2,500, 5,000, and 10,000 pounds, respectively.

3.3 EVALUATION OF INTERCHANNEL FORCE TEST RESULTS

3.3.1 Boundary Force Balance

Force balances on the boundaries of a 1/6 segment were calculated from the diagrams of "average pad forces for each channel interface," which are Figures 11, 12, and 13. These pad forces (the compressive contact loads between hexes) are the result of a double-averaging technique. They are obtained by taking an average of the six readings in one hex location (obtained by rotating the instrumented hex) and then averaging the two values at each face between neighboring hexes. The results showed excellent balance of forces over a segment (Figure 14) but total measured load on the hexes in contact with the yoke was much less than the applied yoke loads. The measured loads averaged about 70% of the applied loads in the three tests, as seen in Table 1.

Table 1
COMPARISON OF APPLIED YOKE LOADS
AND TOTAL MEASURED LOAD ON HEXES

Applied Yoke Load, Pounds	2,500	5,000	10,000
Measured Load on Peripheral Channels, Pounds	1,945	3,480	6,224
Measured, as a Percentage of Applied	77.8	69.6	62.2

When these values are plotted (Figure 15), it may be seen that a smooth curve can be generated, showing a definite improvement at lower loads in the correlation of measured load and applied yoke load.

The reason for the discrepancy between the measured load and applied loads and the reduction in the discrepancy at lower loads is the "low" spring constant of the instrumented channel. The configuration of the instrumented channel (steel construction) and a normal channel (made of aluminum) is shown in Figure 16. Even though tests of the two channels, loaded across flats (two-sided loading), showed they have the following spring constants:

Instrumented channel — $K = 2.62 \times 10^5 \text{ lb/in.}$,

Normal channel — $K = 0.86 \times 10^5 \text{ lb/in.}$,

the design of the instrumented channel is such that adjacent sides are structurally decoupled, so its K cannot be taken at face value. A normal channel inherently has structural coupling, a sort of Poisson's effect. In fact, Reference 2 has shown that a channel loaded equally on all six faces is about 100 times stiffer than the same channel loaded only on two adjacent sides. Accordingly, when the instrumented channel and normal channels are placed in the core array, the K of the normal channel would be expected to increase to $8.60 \times 10^6 \text{ lb/in.}$, but the instrumented channel (since it is decoupled) would remain at $0.26 \times 10^6 \text{ lb/in.}$ Thus, the instrumented channel forms a soft spot in the hexagonal array and load transfers to the neighboring channels. All the channels in a given area tend to deflect equally, but since it takes less load to deflect the instrumented channel a given amount, the channel registers a lower load than would a stiffer normal channel if in its place. The larger the deflections (with greater loads), the more discrepancy is introduced.

3.3.2 Internal Force Balance

The contact forces between hexes in a 1/6 segment at three yoke load levels were analyzed to

- Determine the amount of bridging — which is defined as the ratio of load diverted or lost in transmission through a row of hexes to the applied load on the outside of that row.
- Characterize the contact loads statistically.
- Determine the applicability of the test data to analytical techniques for clamping analysis.

The analysis was based on diagrams in Figures 11, 12, and 13, unless otherwise indicated in this subsection.

Figure 4. Measured Interchannel Forces for a Yoke Load of 5,000 Pounds Instrumented Channel and Six Surrounding Channels Moved as a Unit

Figure 5. Measured Interchannel Forces for a Yoke Load of 2,500 Pounds

Figure 6. Measured Interchannel Forces for a Yoke Load of 5,000 Pounds

Figure 7. Measured Interchannel Forces for a Yoke Load of 10,000 Pounds

Figure 8. Measured Interchannel Forces at 12 Locations Surrounding an Oversize Channel for Yoke Load of 2,500 Pounds

Figure 9. Measured Interchannel Forces at 12 Locations Surrounding an Oversize Channel for Yoke Load of 5,000 Pounds

Figure 10. Measured Interchannel Forces at 12 Locations Surrounding an Oversize Channel for Yoke Load of 10,000 Pounds

Figure 11. Average Interchannel Forces for Yoke Load of 2,500 Pounds

Figure 12. Average Interchannel Forces for Yoke Load of 5,000 Pounds

Figure 13. Average Interchannel Forces for Yoke Load of 10,000 Pounds

Figure 14. Boundary Force Balance for the Different Levels of Applied Yoke Load

Figure 15. Correlation of Measured Yoke Load and Applied Yoke Load

Figure 16. Channel Cross Sections Used in the Phase I Core Restraint Tests at HEDL

The results of the analysis of percent bridging versus row for any load level are shown in Figure 17. The values vary from about 72% near core center to about 7% near the core periphery. This is close to what would be expected for hydrostatic loading of the hexes. The bridging is not dependent on load level, as seen in Table 2 (average levels in last column were used to plot Figure 17).

Table 2
BRIDGING CALCULATED FROM AVERAGED TEST DATA

Row	Percent Bridging			Average
	2,500 Pounds on Yoke	5,000 Pounds on Yoke	10,000 Pounds on Yoke	
2	72.4	71.4	70.8	71.5
3	35.2	32.5	30.3	32.7
4	36.9	37.9	36.8	37.2
5	28.2	29.4	28.9	28.8
6	15.4	12.3	21.1	16.3
7	13.6	18.7	18.0	16.8
8	3.0	7.6	10.7	7.1

The method used for the calculation of bridging in, say, row 6 for a 10,000-pound yoke load in Table 2 can be illustrated by the use of Figure 13 and the following calculations:

$$\begin{aligned}\text{Load on inside of row 6} &= \cos 30^\circ (446 + 427 + 325 + 411 + 378/2 + 378/2 + 357 \\ &\quad + 409 + 361 + 398) \\ &= 0.866 \times 3512\end{aligned}$$

$$\begin{aligned}\text{Load in outside of row 6} &= \cos 30^\circ (462 + 357 + 440 + 406 + 377 + 466/2 + 406/2 \\ &\quad + 300 + 412 + 426 + 359 + 444) \\ &= 0.866 \times 4449\end{aligned}$$

$$\text{Radial transmission, } \alpha = \frac{\text{load acting on inside of row}}{\text{applied load on outside of row}}$$

$$\alpha = \frac{0.866 \times 3512}{0.866 \times 4449} = 0.789$$

$$\% \text{ Bridging, } \beta = 1000 (1.0 - \alpha)$$

$$\beta = 100 (1.0 - 0.789)$$

$$\beta = 21.1$$

An analysis of bridging was also conducted with the data of Figures 5, 6, and 7 in order to examine the effects of using data taken from direct measurements by the instrumented channel without double averaging techniques. The results are shown in Table 3 and plotted in Figure 18. Comparison of Figures 17 and 18 shows that the curve based on direct data conforms more closely to the theoretical curve.

Table 3
BRIDGING CALCULATED FROM DIRECT TEST DATA

Percent Bridging
from Direct Measurements

Row	2,500 Pounds on Yoke	5,000 Pounds on Yoke	10,000 Pounds on Yoke	Average
2	75.5	72.7	72.0	73.4
3	44.6	41.0	39.0	41.5
4	32.4	32.2	33.7	33.1
5	24.0	26.0	22.7	24.2
6	14.0	17.6	19.4	17.0
7	13.8	17.7	20.4	17.3
8	10.5	12.9	14.8	12.7

The contact loads for the three loading cases were analyzed statistically, row by row, to determine how closely the contact loads conformed to a hydrostatic situation. The results are shown in Tables 4 and 5. A special row designation scheme was employed to separate the outermost row from the remaining rows, as shown in the following sketch.

Table 4
ROW-BY-ROW STATISTICAL ANALYSIS OF CONTACT LOADS

Statistical	2,500-Pound Yoke Load			5,000-Pound Yoke Load		10,000-Pound Yoke Load	
	Number of Loads	Arithmetic Mean	Standard Deviation	Arithmetic Mean	Standard Deviation	Arithmetic Mean	Standard Deviation
Outermost	17	183.5	67.1	316.1	113.5	554.5	208.4
8	14	150.6	74.2	256.1	103.5	418.6	140.4
7	19	144.4	42.9	243.9	60.5	398.7	91.9
6	17	160.2	30.0	254.4	48.0	407.2	52.0
5	13	154.9	24.3	255.8	33.8	379.8	41.3
4	11	159.0	30.7	239.2	38.5	366.8	53.8
3	7	136.9	18.1	215.4	21.7	232.9	27.6
2	5	145.4	19.5	238.2	28.9	370.4	38.1
Overall	87	151.0	42.3	246.0	59.7	388.2	83.8

Table 5
COMPARISON OF ARITHMETIC MEANS OF CONTACT LOADS
IN ROWS TO THE OVERALL MEAN LOAD

Statistical	Percent Difference of Arithmetic Means for Row from Overall Mean			
Row	2,500 Pounds on Yoke	5,000 Pounds on Yoke	10,000 Pounds on Yoke	Average
Outermost	+21.5	+28.3	+42.5	+30.8
8	− 0.3	+ 4.0	+ 7.6	+ 3.8
7	− 4.4	− 1.0	+ 2.5	− 1.0
6	+ 6.1	+ 3.2	+ 4.7	+ 4.7
5	+ 2.5	+ 3.9	− 2.4	+ 1.3
4	+ 5.3	− 2.9	− 5.7	− 1.1
3	− 9.4	−12.6	−16.8	−12.9
2	− 3.7	− 3.3	− 4.8	− 3.9

The outermost row, being adjacent to the yoke, experiences concentrated loading, and hexes are not loaded uniformly on all six sides.

In most cases, due to gaps at the yoke, one to two sides are not loaded at all on the outermost row. Although the standard deviations are rather large in Tables 4 and 5, inspection of the arithmetic means shows that hydrostatic loading does exist in rows 2 through 8. The arithmetic means in those runs are on the average within +5% and -13% of the overall mean contact load, as seen in Table 5. The overall mean contact load does not include the outermost row.

Figure 17. Percent Bridging Calculated from Averaged Test Data and Compared with Theory

Figure 18. Percent Bridging Calculated from Direct Test Data

The reasons for the high standard deviations, which read as high as 45% of the mean, are ascribed to the following:

- Inaccuracy of instrumented channel. According to Reference 3, an accuracy of ± 30 pounds is expected. Based on different mean loads, this gives errors on the means of 20, 12, and 8% in the above table that could be expected.
- Tolerance differences between hexes could constitute additional error.
- The low spring constant on the instrumented hex would cause it to deform differently from what a normal hex would do and tend to unbalance the load readings on the faces.
- Shear loads may be present at the contact surfaces, and these could either distort the instrumented channel gages or the load pattern itself.

For the outermost row, the great difference in mean value from overall mean of rows 1 to 8, averaging 30%, shows why this row is not considered part of the hydrostatically loaded area. Indeed, an inspection of this part of the array shows that many of these hexes tend to experience four-sided or five-sided loading, as explained in Subsection 3.2.1, and thus concentration of loads on the hex faces in this row is produced.

3.3.3 Oversize Channel

A diagram of the load distribution measurements associated with the oversize channel is given in Figure 9. It represents the effects of a yoke load of 5000 pounds. The oversize channel is located in hexagon No. 14. Comparable numbers for load distributions when a normal channel was in place are found in Figure 6. Comparison of the numbers leads us to conclude:

- Load increases only locally. Three out of four of the channels at left and right of No. 14 experience a 100% increase in load on the faces next to the oversize channel. Matching faces on the top and bottom adjacent channels register a 50% increase in load.
- Bridging (measurements available for only one row) is not appreciably changed by adding the oversize channel.
- Load transmitted to the center is practically unchanged by adding the oversize channel. Only a 4% increase is calculated.

A typical one of the adjacent channels to right and left, which experiences an increase in load on one face, is No. 21 (channels 8, 9, 20, and 21 are the channels principally affected) and it sees a change in loading as shown in Table 6.

Table 6
EFFECTS OF OVERSIZE CHANNEL ON CONTACT LOADS
IN A TYPICAL CHANNEL

It can be seen that side A, next to the oversize channel, increases greatly in load (93%), as does side E (86% increase) which feels the effects of both oversize No. 14 and the yoke load. Sides C and D increase just a moderate amount, about 35%. Load at B goes practically to zero, and load at F decreases 25% due to the tendency of the oversize channel to force all six adjacent channels apart. This effect is illustrated in the following sketch.

If the loads are compared on the arch that has channel No 14 as its center, little change is found in the load when the oversize channel is installed. Referring to Figures 6 and 9, if we calculate vertical components for the contact loads along the darkened line, we obtain

$$\begin{aligned}
 \text{Load} &= 0.5 (309 + 253 + 302 + 81 + 280 + 299) + 220 + 235 + 265 + 258 + 251 \\
 \text{Normal} & \\
 \text{No 14} &= 2041 \text{ pounds} \\
 \\
 \text{Load} &= 0.5 (304 + 289 + 512 + 350 + 382 + 410) + 336 + 56 + 494 + 29 + 300 \\
 \text{Oversize} & \\
 \text{No 14} &= 2339 \text{ pounds}
 \end{aligned}$$

The oversize hex thus increases the inward directed load by about 15%, indicating that load transmission toward the center is not altered appreciably. Thus, an oversize channel must have only a small effect in bridging.

4. EXPERIMENTAL DETERMINATION OF COMPACTED CORE COMPRESSIBILITY

4.1 DESCRIPTION OF TESTS

The dependence of the core diameter on the yoke loading was experimentally determined for the compacted core (no interchannel spaces) during the interchannel force distribution tests. The data were in the form of yoke load and yoke position data recorded for 1,000-, 2,500-, 5,000-, 7,000-, and 10,000-pound yoke loads (all yokes equally loaded). Figure 19 illustrates experimental dependence of the core diameter on the yoke loading for the compacted core. The theoretical core diameter based on measured dimensions of the alumina coated channels was 70.794 inches.

4.2 EVALUATION OF CORE COMPRESSIBILITY

4.2.1 Discussion of Compressibility Curve

The compressibility curve (Figure 19) has two distinct sections. The first section from 0 to 4000 pounds yoke load represents the takeup of clearances and reduction of high spots. The second section, which is practically a straight-line relation between 4,000 pounds and 10,000 pounds, is representative of elastic deformation of the hexagonal shapes. It has a slope or, in other words, gives a measured core radial spring constant K_{core} of

$$\begin{aligned}
 K_{\text{core}} &= \frac{10,000 - 4000}{0.0170 - 0.0135} \\
 \text{measured} & \\
 &= 1.714 \times 10^6 \text{ lb/in}
 \end{aligned}$$

Inspection of the core action under compression reveals that only the edge hexes are the contributors to the core spring constant — the second section of the curve. These edge hexes are Nos 0, 1, 3, 7, 12, 19, 25, 30, and 33 in Figure 3. The other interior hexes in a segment are virtually incompressible due to their hydrostatic loading. As previously shown (Subsection 2.4.2), the contact loads in these interior hexes are essentially equivalent — the arithmetic means being, on the average, no greater than ~ 13 of the mean value for yoke applied loads above ~ 4000 pounds, thus demonstrating hydrostatic loading.

Of the nine edge hexes, three (Nos 3, 12, and 25) have four-sided loading, two have five-sided loading (Nos 1 and 30), and four have six-sided loading (unequal loading on each side). This comes about from the clearances allowed in the yoke, as seen in the following sketch.

It can be seen that hexes 3, 12, and 25 each have clearance on two sides to produce four-sided loading. Hexes 1 and 30 each have one-sided-clearance to produce five-sided loading. As for hexes 7 and 19, their sides a, b, c, and d are lightly loaded (see Figures 11, 12, and 13), with the remaining sides experiencing loads some 60, 90, or 125% greater, to form a hexagon unequally loaded on six sides. Hexagons Nos 0 and 33 are in six-sided loading but its nature has not been ascertained so they will be assumed to act as Nos 7 and 19 do, for analysis purposes. The residual error between calculations and experiment thus may be partially based on this assumption.

Spring constants for the two types of loading were evaluated by the use of time-share program HEXDEF 1, described in Reference 3, and produced the following:

Hex with four-sided loading

$$K = 0.157 \times 10^6 \text{ lb/inch}$$

Hex with five-sided loading

$$K = 0.115 \times 10^6 \text{ lb/inch}$$

Hex with six-sided loading

$$K = 0.269 \times 10^6 \text{ lb/inch}$$

The models used for these calculations were:

Inside across flats	= 4.175
Wall thickness	= 0.270
Depth	= 4.0
Elastic Modulus	= 10.1×10^6

Figure 19. Radial Dependence of Core Compression on Yoke Loading, Phase I PCM Tests at HEDL

If the spring constants are combined for springs in parallel, we obtain the calculated core radial spring constant. We will assume that hexes 0 and 33 have a spring constant the same as that calculated for the six-sided loading model shown previously.

$$\begin{aligned} K_{\text{core}} &= (3 \times 0.157 + 2 \times 0.115 + 4 \times 0.269) 10^6 \\ \text{calculated} &1.777 \times 10^6 \text{ lb/in.} \end{aligned}$$

This is only about 4% higher than the measured value of 1.714×10^6 lb/in., found in the test.

4.2.2 Significance to Core Design

In the GE reference design core of 361 subassemblies (Figure 20), on the edge of each 1/6 segment there will be four hexes with four-sided loading, four with five-sided loading, and three with unequal six-sided loading. These hexes were analyzed on HEXDEF 1, with the following results obtained:

$$\text{Inside across flats} = 4.335$$

$$\text{Wall thickness} = 0.225$$

$$\text{Depth} = 8.0$$

$$\text{Elastic Modulus} = 21 \times 10^6$$

$$\text{Hex with four-sided loading} \dots\dots\dots K = 0.350 \times 10^6$$

$$\text{Hex with five-sided loading} \dots\dots\dots K = 0.255 \times 10^6$$

$$\text{Hex with six-sided loading} \dots\dots\dots K = 0.599 \times 10^6$$

The predicted radial core spring constant is therefore:

$$\begin{aligned} K_{\text{predicted}} &= (4 \times 0.35 + 4 \times 0.255 + 3 \times 0.599) 10^6 \\ &= 4.22 \times 10^6 \text{ lb/in.} \end{aligned}$$

This is predicated, of course, on loading of the interior hexes on all six sides and thus does not accommodate an internally clamped core where over 80% of the internal hexes experience four-sided loading.

Figure 20 Plan View of 1/6-Segment General Electric Reference Core Design

5. CORE COMPACTION TESTS

The ability of several different yoke actuation sequences to compact the core was evaluated experimentally. The degree of compaction or the diametral gap was measured after each experiment by monitoring the position of each yoke, using the yoke linear potentiometers when each yoke was applying an inward load of 10,000 pounds to the core. The diametral gap is defined as the diameter difference between the resultant core and the compacted core (no interchannel spaces), both measured at the same yoke loading.

5.1 TEST DESCRIPTION

The core for these tests consisted of 199 aluminum alloy channels, 4.79 ± 0.001 inch across flats and 0.270 inch in wall thickness. Each channel had been flame-sprayed with alumina (Al_2O_3) to increase the interchannel coefficient of friction to a measured value greater than 0.68. This value is well above that which allows channel rotations to be removed by inward forced from surrounding channels. Previous HEDL testing using the PCM had used low friction (coefficient equal to approximately 0.25) channels which simplified the compaction problem.

The six yokes were independently actuated hydraulically. Each was instrumented with a 0- to 25,000-pound load cell and a linear position transducer. Yoke load and position data from the transducers were recorded using the data acquisition system. The yokes were not constrained to move along a track, they could shift laterally and could rotate slightly about their vertical axis under certain conditions. The hydraulic servo system which had been used in previous HEDL tests was not used in Phase I. This system had permitted position control of the yokes in addition to the load control inherent in controlling hydraulic pressures. In the absence of the servo system for Phase I, hydraulic orifice valves were carefully adjusted to equalize the inward velocities of all the yokes from the retraction stops, which were one inch radially out from the periphery of the compacted core. The major disadvantage of the load control system used in Phase I was that the velocity and position of each yoke depended on the resistance it encountered during its inward movement.

The yoke position and load transducers were carefully calibrated prior to the compaction tests, using micrometers and a standard load cell. The calibrations were periodically checked during the course of the testing.

Photographs were taken of the core before, during, and after compaction tests, using a Hasselblad camera mounted from the ceiling. Interchannel spaces, channel rotations, etc., are clearly visible in the photographs.

5.2 TEST PROCEDURE

Prior to each compaction test, all six yokes were moved radially out to the yoke stops. At their fully retracted position, the yokes were exactly 1 inch out from the core periphery established by individual channel measurements. Two initial channel positions patterns were tested. The first one, which proved to be the easier one to compact, contained random interchannel spaces up to 3/8 inch. Care was taken to maintain the correct azimuth alignment of each channel. The second pattern not only contained interchannel spaces, but also had random azimuth misalignments up to a maximum of 10 degrees.

The yokes were moved inward from their stops either simultaneously or sequentially, depending on the test, in an effort to compact the core. Subsequently, the loading on each yoke was simultaneously increased to 10,000 pounds, at which time yoke loads and yoke positions were recorded. The compacted core diameter was determined by averaging the position of all six yokes. Comparison of this diameter with the diameter of the compacted core (all channels in their correct positions) measured at 10,000 pounds yielded the diametral gap.

5.3 RESULTS OF CORE COMPACTION TESTS

Two series of tests were run. The BB series started with a disarrayed core in which random interchannel spaces were present. The CC series started with a disarrayed core which had not only random spaces but random channel rotations. The following is a summary of the tests and the results.

5.3.1 Simultaneous Loading by All Six Yokes (Tests BB-1 and CC-1)

All six yokes were moved inward simultaneously from their stops at the same velocity until 1,000 pounds were applied to each yoke. The load on each yoke was then simultaneously increased up to 10,000 pounds over a period of 30 seconds. Several small interchannel spaces remained in test BB-1, even at the 10,000-pound-load level. For test CC-1, the channels were found to "lock" into their initial positions as the yoke loads were increased up to 1,000 pounds during the initial clamp-up. Increasing the yoke load to 10,000 pounds did not remove any of the locked-in spaces and rotations. Numerous large spaces were observed at 10,000 pounds. The resultant diametral gap for tests BB-1 and CC-1 was 28.2 mils and 106.2 mils, respectively. Figures 21 and 22 are photographs taken before and after test CC-1. Figure 22 clearly shows interchannel spaces and rotations present even though there is a load of 10,000 pounds on each yoke.

5.3.2 Simultaneous Loading by All Six Yokes with Oversize Channel Present (Tests BB-2 and CC-2)

These tests were repeats of BB-1 and CC-1, except that a 0.010-inch oversize channel (4.729 inches across flats) was positioned three rows in from the No. 1 yoke (north). The presence of the oversize channel did not seem to alter the way in which channels moved during the initial clamp-up. The resultant diametral gaps were 40.0 mils and 104.8 mils for tests BB-2 and CC-2, respectively.

5.3.3 Simultaneous Loading by Two Opposite Yokes (Tests BB-3 and CC-3)

In these tests, the two opposite yokes were moved inward simultaneously until 1,000 pounds were applied to the core; the four other yokes were kept retracted. The yokes were then withdrawn. The second and third pairs of yokes were then actuated in the same manner sequentially. The loading pattern was repeated twice. The second loading was up to a maximum yoke load of 2,000 pounds and the third was up to a maximum of 3,000 pounds. Subsequently, the load on each yoke was simultaneously increased up to 10,000 pounds over a period of 30 seconds. This technique was found to be a remarkable improvement over simultaneous yoke actuation for compacting the core. The channels between the two loaded yokes formed non-interacting columns. Interchannel spaces were removed, and any channel rotations present were also removed. No interchannel spaces were observed. The resultant diametral gaps were 5.2 mils and 9.8 mils for tests BB-3 and CC-3, respectively. Figure 23 is a photograph of the core subsequent to test CC-3. No significant interchannel spaces remain.

Figure 21. Photograph of Channel Orientations Prior to Test CC-1

Figure 22. Photograph of Channel Orientations Subsequent to Test CC-1

Figure 23. Photograph of Channel Orientations Subsequent to Test CC-3

5.3.4 Simultaneous Loading by Three Non-Neighboring Yokes (Tests BB-4 and CC-4)

In these tests, three non-neighboring yokes were moved inward simultaneously until 1,000 pounds were applied to the core. The yokes were then withdrawn. This loading was repeated using the second triad of yokes. This loading pattern was repeated up to a maximum of 2,000 pounds, and then 3,000 pounds. The load on each yoke was then simultaneously increased up to 10,000 pounds over a period of 30 seconds. This technique was not found to be significantly better than that used for BB-1 and CC-1. Several small interchannel spaces were observed at the 10,000-pound yoke load level. The diametral gaps were 24.2 mils and 33.4 mils for tests BB-4 and CC-4, respectively.

5.3.5 Opposite Yokes Shifted in Same Direction (Tests BB-5 and CC-5)

In these two tests, the six yokes were moved inward until 1,000 pounds were applied to the core. The load was released without withdrawing the yokes. All yokes were retracted 0.030 inch. Two pairs of opposite yokes were maintained in fixed positions while the two yokes of the third pair were moved in the same direction. One yoke was moved toward the core center, while the opposite was moved away from center. This manipulation using one pair of yokes was repeated (in opposite directions) four times. Subsequently, this series of manipulations was repeated with the other pairs of yokes. The load on each yoke was then simultaneously increased up to 10,000 pounds over a period of 30 seconds. The initial channel pattern was identical to BB-1. Subsequent to this experiment, only a few interchannel spaces were observed. The resultant diametral gaps were 10.4 mils and 17.2 mils for tests BB-5 and CC-5, respectively.

5.3.6 Simultaneous Rapid Loading by All Six Yokes (Tests BB-6 and CC-6)

These tests were identical to BB-1 and CC-1, with the exception that the load was increased from 1,000 pounds to 10,000 pounds over a period of 8 seconds instead of 30 seconds. No change in diametral gap attributable to this loading rate change was observed. The diameters were 48.4 and 264.2 mils for tests BB-6 and CC-6, respectively.

5.3.7 Simultaneous Rapid Loading by Two Opposite Yokes (Tests BB-7 and CC-7)

These two tests were identical to BB-3 and CC-3, with the exception that the load was increased from 3,000 pounds to 10,000 pounds over a period of 8 seconds instead of 30 seconds. The resultant diametral gaps were 4.2 mils and 7.2 mils for tests BB-7 and CC-7, respectively.

5.3.8 Ratchet Loading of All Six Yokes (Test EE-1)

In this test, the six yokes were moved inward simultaneously until 1,000 pounds were applied to the core by each yoke. The load on each yoke was then simultaneously increased to 2,000 pounds. After application of 2,000 pounds was achieved, the loading was simultaneously reduced to zero as rapidly as possible. The loading on each yoke was again increased up to a maximum of 4,000 pounds, after which it was reduced to zero. This ratchet loading was repeated in 2,000-pound increments up to a maximum of 10,000 pounds. The initial channel pattern was identical to CC-1. The resultant gap using this technique was 88.8 mils.

5.3.9 Ratchet Loading of Two Diametral Opposite Yokes (Test EE-2)

In this test, the two opposite yokes were moved inward simultaneously until 2,000 pounds were applied to the core. The yokes were unloaded as rapidly as possible, and then withdrawn. The second and third pairs were actuated in the same manner sequentially. This loading pattern was repeated twice. This ratchet loading sequence was repeated at 4,000 and 6,000 pounds. The loads on all yokes were then simultaneously increased up to 10,000 pounds. The initial channel pattern was identical to CC-1. The resultant diametral gap using this technique was 7.0 mils.

5.3.10 Simultaneous Loading by Two Opposite Yokes of a Swelling Dominated Core (Test WGM-1)

Prior to this test, the channels were positioned so that there were spaces of approximately 3/16 inch surrounding those channels at the control rod locations; no channel rotations were introduced. This configuration simulates the

lower clamping plane of the reactor core subsequent to unclamping. It is assumed that all distortions in this swelling dominated core are caused by the heat sink characteristics of the control rods during operation. Figure 24 illustrates the channel orientation prior to compaction. Other than the initial channel orientation, this test was identical to tests BB-3 and CC-3. The resultant diametral gap was 24.2 mils.

5.4 RESULTS OF CORE COMPACTION TESTS WITH A SPECIAL CHANNEL SIMULATING A WARPED FUEL ASSEMBLY

A special channel designed to impart lateral forces on neighboring channels was tested in two compaction attempts. This channel was fixed to the base plate and simulated to the effect of a warped or bowed channel. The device was found to have a lateral spring constant of 1000 pounds per 30 mils displacement.

Compaction attempts with this device located four rows in from the periphery of the core were not successful due to the effect of load on yoke movement. For example, when the six yokes were moved inward from their stops simultaneously, they were always the same radial distance from the core center unless one of them met resistance, which was the case when the lateral force device was present. When this happened, the affected yoke stopped while the other five continued to move inward. No significant movement of the affected yoke occurred until the other five were loading the core. By this time, the core was "locked up" in a distorted shape by the inward forces on five yokes. Movement of the sixth yoke then did not promote any significant compaction.

It should be noted that the Phase I tests were set up for load control; that is, the loading of the yoke was controlled by the hydraulic pressure. Previous HEDL tests had been made using a relatively complicated servo system which permitted load and position control. Had this system been used in Phase I, the lateral force channel might have been satisfactory since the yoke position would not have been affected by the resistance it encountered.

5.5 SUMMARY OF CORE COMPACTION TEST RESULTS

Based on the radial gap data presented above and summarized in Table 7, it is apparent that

- Uniform application of clamping forces caused the high friction channels to lock up, preventing the relative motions between channels required for good compaction. This lock-up occurs at yoke load levels less than 1000 pounds. High force levels have no observable effect in eliminating interchannel spaces. See results of BB-1 and CC-1.
- Increasing the rate of yoke load application after the 1000-pound level is reached has little apparent effect on the resultant radial gap. See results of BB-6 versus BB-1, BB-7 versus BB-3, CC-6 versus CC-1, and CC-7 versus CC-3.
- Presence of an oversize channel did not appear to help or hinder core compaction. See results of BB-2 versus BB-1, and CC-2 versus CC-1.
- The best method for compacting the core was the opposite loading sequence described in BB-3 and CC-3. It was observed that channels between two opposite loaded yokes formed into columns which had little or no lateral interactions. It is noted that these lateral interactions are the probable cause of the lock-up observed in BB-1 and CC-1. The individual channels in the columns rotated or moved to eliminate the interchannel space between their loaded faces. Subsequent loadings from the two other directions were effective in eliminating all spaces and rotations. See results of BB-3 versus BB-1, CC-3 versus CC-1, BB-7 versus BB-6, and CC-7 versus CC-6.
- As expected, a disarrayed core with both rotations and spaces was much more difficult to compact than one with just spaces. See results of CC series compared with BB series.
- The complex compaction schemes used for tests BB-5 and CC-5, and EE-1 and EE-2, were not as successful in compacting the core as the simpler scheme used in BB-3, CC-3, BB-7, and CC-7.

- Loading three non-neighboring yokes (BB-4, CC-4) simultaneously was not too successful for compacting the core. Unlike the opposite yoke loading approach (BB-3, CC-3, BB-7, and CC-7), non-interacting columns were not allowed to form and there was much lateral interaction. A lock-up was observed which was similar to that observed for tests BB-1, BB-6, CC-1, and CC-6.
- Compaction tests using the lateral force channel were unsuccessful due to the unavailability of yoke position control.

Table 7
SUMMARY OF CORE COMPACTION TESTS

Test	Disarrayed Core Configuration	Yoke Actuation Sequence (Loading Ratio)	Core Diameter Across Yokes 1&4/2&5/3&6 (in.)	Diametral Gap at 10,000-Pound Yoke Load (mils)
BB-1	Spaced	Simultaneous (300 lb/sec)	70.776/70.798/70.791	28.2
CC-1	Spaced and Rotated	Simultaneous (300 lb/sec)	70.876/70.893/70.834	106.2
BB-2	Spaced	Simultaneous (300 lb/sec)	70.791/70.810/70.800	40.0
CC-2	Spaced and Rotated	Simultaneous (300 lb/sec)	70.854/70.896/70.845	104.8
BB-3	Spaced	Opposite (300 lb/sec)	70.769/70.766/70.761	5.2
CC-3	Spaced and Rotated	Opposite (300 lb/sec)	70.776/70.768/70.763	9.8
BB-4	Spaced	3 non-neighboring (300 lb/sec)	70.786/70.779/70.782	24.2
CC-4	Spaced and Rotated	3 non-neighboring (300 lb/sec)	70.801/70.787/70.793	33.4
BB-5	Spaced	Opposites shifted (300 lb/sec) same direction	70.767/70.776/70.761	10.4
CC-5	Spaced and Rotated	Opposites shifted (300 lb/sec) same direction	70.784/70.778/70.770	17.2
BB-6	Spaced	Simultaneous (1200 lb/sec)	70.797/70.814/70.815	48.4
CC-6	Spaced and Rotated	Simultaneous (1200 lb/sec)	71.004/71.047/71.020	264.2
BB-7	Spaced	Opposite (1200 lb/sec)	70.765/70.762/70.766	4.2
CC-7	Spaced and Rotated	Opposite (1200 lb/sec)	70.771/70.771/70.760	7.2
EE-1	Spaced and Rotated	Simultaneous-Ratchet (300 lb/sec)	70.860/70.846/70.889	88.8
EE-2	Spaced and Rotated	Opposites-Ratchet (300 lb/sec)	70.773/70.781/70.749	7.0
WGM-1	Simulate swelling dominated core	Opposite (300 lb/sec)	70.801/70.807/70.745	24.2

Figure 24. Photograph of Channel Orientations Prior to Test WGM-1

REFERENCES

1. Marian, V. R., "General Electric Core Restraint Testing Using the Planar Clamping Mockup (PCM) at HEDL — Phase I, 199 Channel Core," Development Specification, September 7, 1972.
2. *Project Definition Phase Follow-On II Final Report, Task CBC 3 Core Restraint System*, December 28, 1971 (GEAP-13806).
3. Soderlund, R. J., "Test Plan for the Planar Clamping Model," document from HEDL dated January 3, 1972.

APPENDIX A. THEORETICAL BASIS FOR BRIDGING UNDER HYDROSTATIC LOADING

Figure A-1 illustrates the geometry of the bridging model which is a segment of channel (contact pad) row n .* Here, the assumption is made that six-face loading is present and the load on *each* face of a given row is the same. The surface loads, indicated intensity Q_n , are depicted as point loads; normal to the surface, however, they just as well could be uniformly distributed loads. Hence, the surface loads can be thought of as net normal surface forces. Inherent in the assumption of uniform normal surface loads on each face of a given row of channels is that the shear stresses (or forces parallel to the surfaces) are identically zero regardless of the coefficient of friction. Thus, the model applies for all friction coefficients.

Referring again to Figure A-1 and summing the vertical components (components normal to bridging line) of the surface forces from right to left on the upper and lower surfaces** yields, respectively,

$$T_n = \sqrt{\frac{3}{2}} \left[Q_n/2 + Q_n + 2(n-2) Q_n + Q_n + Q_n/2 \right] \quad (1)$$

and

$$B_n = \sqrt{\frac{3}{2}} \left[Q_n/2 + 2(n-2) Q_n + Q_n/2 \right], \quad (2)$$

where

T_n = Vertical component of the sum of forces acting on the upper (outboard) surfaces of row n , and

B_n = Vertical component of the sum of forces acting on the bottom (inboard) surfaces of row n .

Independently summing terms in Equations (1) and (2) gives

$$T_n = \sqrt{\frac{3}{2}} Q_n (2n - 1) \quad (3)$$

and

$$B_n = \sqrt{\frac{3}{2}} Q_n (2n - 3). \quad (4)$$

Defining the radial transmission coefficient, γ_n , equal to the ratio of B_n to T_n , then

$$\gamma_n = \frac{2n - 3}{2n - 1} \quad (n \geq 2). \quad (5)$$

For the central channel (i.e., $n = 1$) Equation (5) does not apply. The coefficient, however, is easily determined by observing that any load entering row 1 by definition is not transmitted radially inward; thus, for $n = 1$ the radial transmission coefficient is zero and the bridging coefficient is unity.

*Refer to Figure A-2 for channel row numbering

**Not including the forces parallel to the bridging line or normal to the symmetry boundary

Figure A-1. Simplified Bridging Model

Figure A-2. Channel Row Numbering and Radial Line-of-Channels

The radial bridging coefficient, β_n , is identically equal to $1 - \gamma_n$, hence

$$\beta_n = 1 - \frac{2n-3}{2n-1},$$

or

$$\beta_n = \frac{2}{2n-1}.$$

(6)

Figure A-3 is a plot of Equations (5) and (6) as a function of channel row n . In the development of Equations (5) and (6), it was assumed that the load intensity on each face of a given row is identical; however, because of compatibility considerations (i.e., each channel must deform an equal amount regardless of row number to maintain channel "nesting"), the load intensity normal to each channel face must be equal in a complete array of channels. Thus, when an array of channels is loaded equally on the outer row of channels, hydrostatic loading is in effect.

Figure A-3. Bridging and Radial Transmission Coefficients

APPENDIX B. EVALUATION OF FTR CORE RESTRAINT TESTS

This appendix presents an evaluation of tests on the Planar Clamping Model (PCM) and the Simulated Core Model (SCM) conducted at HEDL insofar as the results apply to the GE Phase I core restraint tests. The evaluation is based upon the interim data analyses presented in the references listed at the end of this appendix.

Specific results from the PCM and SCM test programs, as reported in the various HEDL references (B.1 through B.7), are quoted, followed by a paragraph of discussion and comment on each.

- a. *Less core compaction is obtained with high friction (friction coefficient, $f = 0.33$) surfaces on load pads than with low ($f = 0.25$) in the PCM.*

This statement is based on HEDL tests P83 and P84 which had an average diametral gap of 84 mils for $f = 0.33$, and tests P19 and P22 which had an average gap of 28 mils for $f = 0.25$. All four tests employed a core array of compliant channels, solid hexes in the reflector region, some rotated hexes, and all yokes loaded simultaneously.

The stated conclusion, based on only the HEDL data, is premature as friction coefficients of 0.33 and 0.25 are very similar, with both being less than the critical value of 0.57. A comparison of core compaction at different friction levels has greater validity and usefulness for LMFBR applications when friction values above and below critical are used. Preliminary inspection of the GE Phase I tests with $f = 0.68$ to 0.75 suggests that test CC-1 with a diametral gap of 106 mils is most comparable with the foregoing HEDL tests. The GE tests used an array of all compliant channels, while the HEDL tests in question used solid channels in the reflector region. However, compaction was generally better in the PCM study for an all-compliant core than for a mixed (compliant plus solid) core. It is concluded that the HEDL statement is correct and is confirmed by the GE high friction tests.

- b. *Position control of the PCM yokes (yokes moved simultaneously toward the core center in equal positional increments until an average load of 10,000 lbs is reached) was more effective in compacting the array than load control (yoke loads increased simultaneously).*

As examples of the benefit of position control over load control, the average residual diametral gaps for a number of HEDL tests are shown in the following table:

Friction Coefficient		Gap (mils)	
0.33	Mixed	82	10
0.25	Mixed	28	24
0.25	All compliant	29	1

The difference is probably attributable to the prevention of lock-up of the hexes. With position control, the hexes have more opportunity to become aligned while loads are relatively low. At some amount of loading, the hexes lock up and further compaction is impossible.

- c. *Use of an oversize central load pad in the PCM high friction array improved core compaction, but did not provide significant improvement in either the PCM or SCM low friction arrays.*

The reason for this may be the same as that attributed to position control. Providing space in the high friction array for the hexes to realign themselves may have prevented them from locking up in skewed position and thus improved the compaction. However, it should be noted that the oversized central load pad was effective only for a mixed array and not for an all-compliant array. It is possible that the array configuration is of more importance than the friction level in this case.

- d. *Removal of the 36 corner reflector pads in the PCM high friction array improved the core compaction but did not help in the SCM or PCM low friction arrays.*

Inspection of the PCM data shows this conclusion to be incorrect. Removal of corner reflector pads improved compaction in every case, for low as well as high friction and for all-complaint arrays as well as for mixed arrays. The method effectively results in clamping a smaller core; the remaining reflector pads act almost as extensions of the yokes. However, this fact is of little usefulness to the LMFBR core designer.

- e. *The average contact loads on the hexes in the PCM tests varied somewhat throughout the core but tended toward hydrostatic for both high friction and low friction arrays. However, maximum contact loads for the high friction core were higher and more variable in magnitude.*

This question has been resolved by the GE Phase I tests. Loads in an externally clamped array are essentially hydrostatic. The difficulty in the PCM tests was the relatively poor quality of load distribution data obtained.

- f. *The PCM compacts at lower loads than the SCM.*

The difference is attributable to the friction present at the nosepiece-to-support plate interface and to the interactions between the two clamping planes in the SCM. It is concluded that the nosepiece-to-support plate interface should be designed to have low resistance to azimuthal rotation and should at least approximate a ball-socket joint.

- g. *In the SCM tests (low friction surfaces), the withdrawal forces for removing 14 swelling-dominated assemblies (test 198) and 31 creep-dominated assemblies (test 208) were:*

Type of Core	ACLP Yoke Removal Distance	Average Withdrawal Pounds and Range
Swelling dominated (maximum swelling, minimum creep)	0.090	+ 134* 275 to 47
Creep dominated (maximum creep, minimum swelling)	0.067	+ 678 597 to 537

* High value for one duct which was adjacent to a closed loop was thrown out.

These empirical results do not agree very well with the latest analytical results in Reference B.7. If the Reference B-7 results are corrected to the $f = 0.2$ that was effective in tests 198 and 208, maximum forces are obtained as follows:

Swelling dominatedcalculated force = 343 lb

Creep dominated.....calculated force = 157 lb

Thus, it is seen that the ratio of 2:1 is preserved but, analytically, swelling-dominated is the higher load and, empirically, the reverse happens. The average load (250 pounds) of the two cases in the analysis is also 60% of the average empirical load (436 pounds).

The tests and analysis are not obviously connected, so the correctness of comparing withdrawal values for the two may be open to question. However, the tests and analysis were both based on the floating collar design, compliant load pads, and approximately the same duct dimensions, so they should be closely related.

- h. *Initial load pad orientation had no significant effect on compaction in the PCM low-friction array.*

In the Phase I tests, skewing of the hexes did have an effect when a simultaneous yoke loading pattern was used. By use of preplanned sequencing of yokes, good compactions could be achieved even with the skewed hexes present.

- i. *An improvement in compaction is indicated when compliant hexes are used in both the PCM and SCM.*

The fact that the compliant hexes when compressed in one direction tend to expand in the crosswise direction explains this improvement. A local jostling or massaging is produced by this action (or "Poisson's effect") which tends to reduce gaps between hexes. This fact justifies the additional expense required in 2D or 3D tests to provide prototypical load pad dimensions, rather than solid block hexes.

- j. *It is possible, as seen from the SCM test data, to obtain a well-compacted dimensionally stable core, even in the case of a severely misaligned initial array, by repetitively loading and massaging the yokes. However, neither the exact sequence nor the time or number of steps required can be predicted in advance.*

The first part of the HEDL conclusion agrees with GE experience, but the note that the successful loading sequence cannot be predicted is contrary to Phase I test results. Perhaps the problem is that the SCM loadings were in 2000-pound increments which were too high, since lock-up occurs at about 1000 to 1500 pounds. It is important that the hexes be able to rotate before array lock-up, and the higher the friction coefficient, the lower the load at which locking occurs.

REFERENCES FOR APPENDIX B

- B.1 Munro, G. A., et al., "Interim Report, Simulated Core Model Test Results," preliminary draft of HEDL report, November 13, 1971.
- B.2 Werle, J. E., "Reduced Simulated Core Model and Planar Clamping Model Data," letter WADCO/FFTF 715400 of November 30, 1971.
- B.3 Soderland, R. J., "Interim Report for the Planar Clamping Model Test Program Tests P-27 Through P-82," undated report of about January 1972.
- B.4 Besel, L. R., "Interim Report on Simulated Core Model, Tests No. 166 through No. 182," HEDL report of April 28, 1972.
- B.5 Ballard, D. L., "Interim Report for the Simulated Core Model Test Program SCM Tests Nos. 183 through 208," WADCO letter W/FFTF-724907 of August 24, 1972.
- B.6 Besel, L. R., "Interim Report for the Planar Clamping Model Test Program Tests P-83 through P-92," forwarded by WADCO letter W/FFTF-723880, undated.
- B.7 Brown and Yant, *Comparative Performance of Three Candidate LMFBR Core Restraint Systems Considering Uncertainties in Irradiated Material Effects*, October 1972 (WARD-3045T2B-4).

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