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300 kwT Core Conceptual Model Thermal/Hydraulic
Characteristics

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The 300 kw, 199 element NASA-Lewis/AEC core conceptual model, has been analyzed to determine it's thermal-hydraulic characteristics using the GEOM-3 code. Stack ups of tolerances and fuel rod asymmetry patterns were used to ascertain cross element ΔT 's. Both zoned and uniform spacing were analyzed with a somewhat lower fuel temperature and cross element ΔT found for zoned spacing.

With the models considered, the core design appears adequate to limit thermal gradients to approximately 32°F. Bypass flow should be controlled to prevent excessive edge element ΔT 's.

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I. INTRODUCTION

A study has been made of a NaK cooled reactor containing 199 ZrH- UO_2 fuel elements to determine thermal hydraulic characteristics of the core bundle. The nominal operating power of the reactor is 300 kw with the NaK exiting from the core at 1200°F. Past analytical studies made on similar reactors provided the basis for using a two-zoned core to vary flow as necessary to attain a fairly uniform coolant outlet radial temperature profile. However, a study was made of a uniformly spaced core since this reactor has more benign thermal conditions than those previously considered. The effect of element bowing and fuel asymmetry was bounded by using extreme tolerance stackups to attain maximum cross element temperature gradients.

II. SUMMARY

From a thermal-hydraulic standpoint, the core design appears adequate to limit thermal gradients to acceptable levels under currently foreseeable operating conditions. Various severe cluster and asymmetry patterns were imposed on the core model with a maximum equivalent cross element ΔT of 35°F. The zone boundary, now set as close to circular as possible, does not exhibit high cross element ΔT 's as did the previously used hexagonal boundary.

The study indicates high bypass flows result in high gradients across edge elements necessitating positive control of core edge flows. The comparison between a zoned and uniformly spaced core indicated lower thermal gradients and lower fuel temperatures in the zoned core. Further fuel temperature reduction is possible by increasing inner zone spacing. Analytically, the scalloped fin did not show a marked advantage over the standard fin. However, testing is strongly recommended to ensure that full channel rather than stratified mixing is obtained in the core.

III. GENERAL REACTOR CHARACTERISTICS

The core is composed of a bundle of 199 fuel elements in a triangular lattice. The elements are spaced on a uniform 0.74 inch pitch. Flow area variation to match core flow to core power distribution is attained by the use of two clad diameters in two zones as shown in Figure 1. Positive spacing is attained by the use of three fins on approximately 2/3 of the elements in a right-left-neutral (RLN) configuration as shown in Figure 2.

FUEL ELEMENT IDENTIFICATION

(VIEW TOWARD INLET GRID PLATE)

FIG 1

FIN ORIENTATION
(VIEW TOWARD INLET GRID PLATE)

- NEUTRAL ELEMENT (61)
(91 INNER, 30 OUTER)
- L - LEFT HAND WRAP (69)
R - RIGHT HAND WRAP (69)
(33 INNER, 36 OUTER)

FIG 2

The reactor is controlled by eight void back drums as shown in Fig. 3. Because this non-symmetrical arrangement leads to power ripples in the fuel element bundle, the numbering system shown in Figure 1 has been keyed to one drum designated as drum No. 1. All identification has been set up in a clockwise rotation when viewing the core from inlet to outlet.

In order to avoid developing loads at element elevations other than the design support plane, the fins are relieved to avoid contact as shown in Figure 4.⁽¹⁾ This has the effect of reducing mixing capability because of the reduced fin height. In order to minimize the reduction, the fins are relieved only at the point of contact with adjacent elements. As shown in Figure 4, it is possible to overcome this loss of mixing action (indeed to increase it) by hobbing oversize fins and then relieving to attain required spacing. Both configurations are analyzed later in this report.

The core edge currently consists of clad BeO internal reflector segments which fill the spaces between the core pressure vessel and the outer row of elements. The configuration of the resultant coolant channels is shown in Figure 5. There are six unfinned elements on the core periphery. At these points, positive spacing will be provided by pads on the internal reflector segments.

The axial power distribution in the core is assumed to have a chopped cosine shape with a minimum local to average power ratio of 0.347 at the ends of the fuel rods and 1.35 at the rod centers. The radial power distribution is as shown in Figure 6. The discontinuity in the power at the zone boundary is caused by the use of larger fuel diameters in the outer zone. Figure 7 shows the effect of the aforementioned zoned flow control in conjunction with the radial power shape resulting in a fairly flat coolant temperature profile.

IV. ANALYTICAL METHODS AND DATA

The major analytical tool used for this report was the GEOM 3 code.⁽²⁾ Thermal coupling to the reflector can be accomplished by iteration with a TAP model of the reflector using the pressure vessel outer surface as the interface or assuming an adiabatic wall at the pressure vessel.

OVERALL REACTOR LAYOUT
(VIEW TOWARD INLET GRID PLATE)

FIG 3

FIN ENVELOPE DIMENSIONS

NOTE: VALUES IN ()
ARE FOR IT"
IN COLLOID CLAD.

STANDARD FINS						
	INNER ZONE			OUTER ZONE		
	A	B	C	A	B	C
h_f	0.02675	0.02675	0.02675	0.01125	0.01125	0.01125
h_u	0.005	0.000	0.008	0.005	0.000	0.008
h'_f	0.857	0.892	0.922	0.714	0.783	0.843

SCALLOPED FINS						
	INNER ZONE			OUTER ZONE		
	A	B	C	A	B	C
h ₅	0.055	0.055	0.065	0.050	0.050	0.050
h _u	0.0733	0.0283	0.0363	0.0433	0.0333	0.0463
h _f	1.260	1.386	1.159	1.626	1.918	1.488

NOTE: $h_f' = \text{EFF. FIN HT.} / \text{NOM. FIN HT.}$
 $\eta_m = \text{RATIO OF ACTUAL/COMPUTED MIXING}$
 FIN HEIGHT = SPACING

FIG 4

CORE EDGE AREAS

$$\textcircled{\bullet} A_{2/3} = .433(.74)^2 - \frac{\pi}{12}(.725)^2 - .5774(.3625)^2$$

$$A_{2/3} = 0.08363$$

$$\textcircled{\bullet} A_{1/3} = .5774(.3775)^2 - \frac{\pi}{24}(.725)^2$$

$$A_{1/3} = 0.01948$$

NOTE: INTERNAL REFLECTORS ASSUMED
TANGENT TO EXCLUDED ELEMENTS

FIG 5

POWER PROFILES

FIG 6

CORE RADIAL PROFILES

FIG. 7

Since heat transfer test data was not yet available, coolant film coefficients were derived from correlations developed from detailed TAP models with respect to spacing, clad thickness, and mixing effects.^(3,4) Some test data is available from water testing of finned tube bundles using the RLN fin configuration.^(5,6) This data correlates mixing rates and friction factors to analytical results. The range of parameterization, however, was quite limited. Two fin heights and pitches were the only variables, thus a good deal of extrapolation was necessary to arrive at the predictions reported herein. Tests are either in progress or planned to reduce this extrapolation.

Aside from the positive spacing afforded by the fins, the single most important feature of the core from a thermal-hydraulic viewpoint is the ability of the induced mixing to alleviate thermal gradients caused by element clustering, fuel rod movement away from the element center (asymmetry), and a bypass flow around the core periphery.

A. Mixing Analysis

The right-left-neutral approach to attaining mixing results in a cross flow pattern which varies according to channel location in the core. Each full channel has one inlet and two outlets or one outlet and two inlets. Figure 2 shows the fin orientation used throughout the core. Note that each full channel is bounded by a right, a left, and a neutral element. The total cross flow passes through the space between the right and left elements. A portion of this cross flow passes through the space between the right and neutral elements and the remainder passes between the left and neutral elements. If the fins are of equal height and the surrounding channel flows are equal, the latter two portions are each half of the first. In any case, the total cross flow into a channel must be equal to the total flow out to attain a mass balance.

It is assumed that no change in axial flow is caused by cross flow and that cross flow varies axially only due to fin height changes, not because of fin position. The validity of this assumption is illustrated in Figure 8 which shows the effect of axial location on fin position. The current design uses three fins having an axial pitch of 5.66 inches. Thus, at every ~ 1.88 inch interval along a channel, the fins are in identical positions. In the

AXIAL EFFECT ON CHANNEL FIN POSITION

FIG 8

axial interval between these nodes, it can be seen that two fins acting in series are practically performing the same function as the single fin in the initial position. While there probably is some variation in mixing rates across the 1.88 inch node, the variation should be quite small. Considering the low heat fluxes, the effect of assuming constant cross flow should make a negligible difference between predicted and actual coolant temperatures.

One further variation exists in computing mixing. This is the effect of varying element diameter, channel areas due to element bowing, and channel area variation at the core edge. Since a cross flow balance must exist in each channel, an average channel area, and flow is computed for each element at each node. For example, as shown in Figure 9, the average flow and area for element 21 is the average of channels 33, 34, 40, 41, 48, and 49. The mixing factors computed are based on total flow across a channel, thus 1/2 the cross flow of each element is used as shown by the flow values given. This method ensures a cross flow balance and also accounts for the effect of large fin height in small channels as well as small fin height in large channels.

B. Bypass Flow Analysis

In order to fill in the space between the truncated hexagonal core bundle and the cylindrical pressure vessel, stainless steel or clad BeO filler pieces are used as an added reflector segment. Some clearance is necessary to permit assembly of the core bundle. This results in an area open to coolant flow which bypasses the power producing fuel elements. Sealing devices are used to limit this flow to the minimum attainable. However, since these reflector segments must be free to expand when heated, they are also free to bow within the tolerances used, thus bypass flow can become a significant performance factor.

The reactor enclosure wall temperature can be regulated to govern the control drum temperature level. Therefore, for conceptual design purposes, it has been assumed that the heat radiated to the walls will be limited to that generated in the reflector. Thus, all heat which is conducted from the core through the internal reflectors to the pressure vessel is absorbed by bypass flow and an adiabatic wall is assumed to exist between the pressure vessel and the outer reflector. The analytical technique used is fully described in Ref. 2.

MIXING FLOW MODEL

NOTE:
32.7 = Direction & Magnitude
of Cross Flow in
lb/hr-in

MIXING PARAMETERS

Element	14	17	18	21	24	25	29
Avg Flow	247.23	227.29	227.29	198.32	188.53	188.53	170.26
Mixing Factor	27.3	0.00	0.00	15.7	15.7	15.7	0.00

NOTE: Data Given At Maximum Fin Height

FIG 9

C. Hydraulic Analysis

It has been found that channel friction factor test results may reasonably be correlated⁽⁶⁾ by an equation of the form:

$$f = \frac{k_B}{Re^n} YZk'_n$$

where:

- f = friction factor
- k_B = constant
- Re = Reynolds number
- n = pressure exponent
- Y = correction for pitch/diameter ratio
- Z = correction for fin pitch/diameter ratio
- k'_n = correction for number of fins

In order to attain the total bundle pressure drop, average values are determined for the above parameters as well as average velocities which account for fin height variations.

Flow distribution is computed by assuming radial uniformity of pressure which permits the flow to be computed by:

$$\dot{w}_2 = \dot{w}_1 \left(\frac{A_2}{A_1} \right)^{\frac{3}{2-n}} \left(\frac{Y_1}{Y_2} \right)^{\frac{1}{2-n}} \left(\frac{P_{w1}}{P_{w2}} \right)^{\frac{1+n}{2-n}}$$

where:

- $\dot{w}$ = channel flow, lb/hr
- A = channel area, in²
- P_w = channel wetted perimeter, in

The k_B , Z, and k'_N factors do not enter into the equation since they are constant throughout the core. The method permits two dimensional solution of a three-dimensional problem quite accurately by the nodal approach to axial position.

D. Gas Gap Conductance

Operation at low temperatures and low H/Zr ratios results in relatively low gap pressure.⁽⁷⁾ The free molecular effects become stronger and thermal conductance is lowered. Figure 10 shows the conductance used for design studies.

E. Cross Element Temperature Gradients

Temperature gradients in the clad induce stresses. Two factors are involved - the equivalent temperature which causes bending stress, and the 60 ripple superimposed which causes alternate compressive and tensile stresses circumferentially around the cladding. Of the two, the bending stress component is normally of prime interest. Therefore, cross element ΔT 's reported herein are those causing bending stress.

Figure 11 illustrates the temperature gradient patterns. The equivalent temperature is obtained by fitting a 2π sine wave to the actual temperature. This represents the circumferential temperature of the cladding surface unwrapped. The equivalent ΔT is the difference of maximum-minimum on this curve. The ripple inducing temperatures are also noted. It is of interest to note that the ripple is quite dependent on axial location because of the axial power shape. At the ends of the element, the temperature variation is more highly controlled by channel temperature differences. For the data shown, at $Z/L = .53$, there are six swings from tension to compression around the clad. At $Z/L = 1.0$, there is only a single swing and at a much lower magnitude. Thus, the total stress at both points may be about the same even though ΔT differs by 80%.

V. TRADE STUDIES & NOMINAL OPERATING CHARACTERISTICS

Many trade studies of spacing and zone boundary location have been made on reactors similar to the CST reactor. As a result, a two-zoned configuration with 30 and 15 mil spacing has been selected as the zoned model. The purpose of zoning is, of course, to attain a relatively flat radial temperature profile with a minimum number of different elements required. For a high power, high outlet temperature reactor, this technique is mandatory to limit peak fuel temperatures. For this application, however, a single zone core was felt to be practical, therefore a trade study was conducted to evaluate the merits of each.

FIG 11

Figure 12 shows the basic 60° sector model used for the thermal hydraulic analysis. Fin wrap directions are not specified, however, it can be seen that there are six neutral elements abutting the internal reflectors. Figure 13 shows an enlargement of this region. Two factors become apparent:

- a) There can be no cross coolant flow on the outer portion of the neutral element
- b) The coolant flow areas on the outer portion of the neutral element are larger than those of corresponding coolant channels elsewhere on the periphery due to the lack of fins.

The lack of cross flow cannot be overcome. The area, however, must be adjusted by shaping the internal reflector segments to suit. This factor has been accounted for in the analysis by simply decreasing area a small amount. Tailoring of channel area will be needed in the final design.

The original concept of the RLN finned system was simply a hobbled fin of full height completely around the cladding. Stress analyses, however, indicated that full length contact would set up secondary contact points and that it would be necessary to undercut the fins to avoid this situation.⁽¹⁾ This undercut seriously reduces mixing which has the undesirable result of increasing thermal gradients. To minimize this effect, the concept of simply shaving the fins at the six circumferential contact surfaces was developed. This in turn led naturally to the idea of hobbing oversize fins and shaving them to the required spacing to provide a maximum amount of mixing. This type fin has been termed "scalped."

Figure 14 shows a comparison of the two fin types. To date, only the standard fin has been tested. The technique used to measure mixing, a conductivity probe measuring saline solution concentration, takes an average value across the total channel. This could mean that the salt is actually well distributed in the channel or that a highly concentrated solution is following the fin contour and a very weak solution is flowing axially down the channel unperturbed by the fins. With the scalped fins, the latter condition cannot possibly exist because the fins extend to the center of the channel. Because of this much more pronounced axial flow disturbance, it is theorized that a higher friction factor will be attained resulting in a higher pressure drop.

BASIC 60° SECTOR MODEL

FIG 12

CORE EDGE FIN CONFIGURATION

NOTE: 61/70 HAS NO FINS VS 12/79

62/69 HAS $\frac{1}{2}$ THE FINS VS 13/78

FIG 12

SCALLOPED/STANDARD FIN COMPARISON

NOTE: STANDARD FINS PERMIT LARGE
PORTION OF CHANNEL FOR
UNPERTURBED AXIAL FLOW

FIG 14

However, manufacturing and assembly of scalloped fins is more complex than standard fins although only if the standard fins are not shaved. A second trade study was conducted to evaluate the merits of the two fin configurations.

Four symmetric configurations were examined to determine the trade-offs between zoning and uniformity of spacing and between scalloped and standard fins. All four cases considered a 0.5% bypass flow and also the proper fin areas for the configuration under study. Table I gives the case numbering nomenclature, and Table II lists the pertinent characteristics of each configuration at the 300 kw power level using a 17" Incolloy 800 clad fuel rod. All data herein is B.O.L.

It should be noted at this point that edge areas are fixed by the assumption that the inner reflector filler blocks are made as shown in Figure 5. This results in excessive coolant flow at the core periphery leading to higher cross element ΔT 's than should occur. This can be overcome by tailoring edge areas to suit. However, this entails some manufacturing problems and is a design area that requires further investigation. The reader should bear in mind that core edge temperatures can be increased if necessary.

A. Zoned vs Uniform Spacing

As would be expected, the uniform spacing results in a higher peak fuel temperature than does the zoned spacing. Since the peak occurs at a Z/L of approximately 0.6, the differential is not quite as great as is indicated by the outlet coolant temperature differential. Figure 15 compares the fuel temperatures for the standard fin configurations. In general, the cross over point of the two curves occurs at the zone boundary location as would be expected.

The maximum differential of 24°F is not extreme but is significant in swelling calculations. If sufficient reactivity exists, the zoned peak fuel temperature can be further reduced by increasing inner zone spacing. This cannot be accomplished with uniform spacing. Thus, from a fuel temperature standpoint, the zoned core exhibits lower peak temperatures, a flatter radial profile, and is flexible in attaining still lower temperatures.

TABLE I

Case Condition Numbering

1.	Symmetric core	
2.	Inward cluster	)
3.	Inward cluster with asymmetry	) See Figure 17
4.	Row cluster	)
5.	Row cluster with asymmetry	) See Figure 18
6.	Random cluster	)
7.	Random cluster with asymmetry	) See Figure 19

- N Standard undercut fins
- S Scalloped fins
- U Uniform (1 zone) spacing
- X No mixing accounted for

TABLE II

Symmetric Core Comparison

Parameter	IS	IN	ISU	INU
Pressure drop, psi	1.28	0.99	1,206	0.96
Peak fuel temperature, °F	1366	1368	1388	1392
Bypass temperature rise, °F	58.6 (1.2 kwt)	55.2 (1.1 kwt)	49.8 (1.0kwt)	48.2 (.95 kwt)
Maximum channel out temperature, °F	1210.8	1212.6	1231.0	1231.7
Minimum channel outlet temperature, °F	1180.7	1175.4	1167.9*	1164.0*
Maximum cross element, ΔT , °F	16.9	18.4	17.0*	18.6*
Element having maximum ΔT	No. 28	No. 28	No. 30*	No. 30*
Average Reynolds number	15360	15750	15440	15780
Peak mixing factor, %/in	38.7	24.7	36.2	19.3
Fuel area, in ²	62.373	62.373	62.365	62.365
Coolant area, in ²	13.49	13.49	13.090	13.090

Note: Nominal flow and power, 0.5% bypass

* Edge elements with very cold edge channels ignored.

COMPARISON OF ZONED/UNZONED PEAK FUEL TEMPERATURE

FIG. 15

Figure 16 shows the bulk coolant temperature at the plane of peak fuel temperatures. The cross over is fairly well defined and it is seen that channel temperature differences decrease toward the core edge. This accounts in part for the lower fuel temperature differences. The remaining differences result from the fact that resistance is inversely proportional to radius and four resistances are seen by the heat flux. Additionally, the non-uniform heat flux caused by varying channel temperatures effectively changes radius as the peak fuel temperature is not necessarily centered. It should be noted that the temperatures are not plotted versus radius but rather by channel for direct comparison. In most instances, the general trend is the same. In a few channels (25, 31, 42, 60), the trend is in opposite directions. This is probably caused by the difference in mixing rates. The large variation in 61, 62, 69, and 70 is caused by the excessive flow in channels 61 and 70.

The power into the bypass is somewhat lower for uniform spacing since less power is generated at the core edge and coolant temperatures are lower. The difference is quite small and is not considered a factor in the trace-off.

Figure 17 compares the cross element ΔT profile of the two configurations. Ignoring elements 27 and 31, (which are affected by channels 61 and 70) it can be seen that in general the uniform spacing suffers larger cross element ΔT 's than does the zoned spacing. This shows quite well the effectiveness of matching flow to power. At the core edge, ΔT 's are not greatly different. With tailored edge areas, these ΔT 's could be significantly lowered. This would not affect the center of the core to a great extent, however, and the zoned spacing would still show an advantage over the uniform spacing.

While cluster and asymmetry runs were not made with the uniformly spaced core, there is no reason to believe the performance would differ greatly in kind or amount from that of the zoned core. Since the uniform core starts symmetrically at a higher average ΔT (10.8°F ignoring 27 and 31 vs. 8.0°F) than the zoned core, similar characteristics would be expected for cluster and asymmetry.

Therefore, from both thermal gradient and fuel temperature standpoints, the zoned core must be considered the preferred choice.

COMPARISON OF ZONED/UNZONED BULK COOLANT TEMPERATURE

(AT $Z/H = 0.6$)

FIG 14

FIG. 17

B. Scalloped versus Standard Fins

Table II shows a small decrease in both coolant outlet temperature variation (30.1 vs 37.2) and cross element ΔT ($\sim 9\%$) for the zoned spacing. This, of course, is due to the increase in mixing. The 28% increase in pressure drop is due in part to the decrease in channel volume caused by the oversize fins and in part to the increased friction factor. In all other respects, there is very little difference in the two configurations.

Without test data to deny or confirm the aforementioned stratification problems of standard fins, a judgement on the trade-off between scalloped and standard fins must be subjective. The small temperature differences shown in Table II are not sufficient to override an increase in manufacturing cost or complexity, should it exist. Therefore, all studies made regarding clustering and asymmetry have considered standard fins. However, it is the author's strong recommendation that a final decision not be made without full recognition of the scalloped fin destratification capability.

VI. EFFECTS OF ELEMENT BOW & FUEL ASYMMETRY

A series of GEOM3 runs have been made to determine the effect of postulated cluster and fuel asymmetry patterns. Cluster patterns can be predicted from the temperature profiles computed for symmetric cases. However, manufacturing tolerances must, of necessity, allow some residual bow in the cladding tube. Unless the exact location of this bow is known, it can offset or override natural temperature effects so that predictions are meaningless. Fuel asymmetry cannot be predicted under any circumstances. Segmentation of the fuel further complicates the randomness in that the fuel slug orientation can vary axially as well as radially.

Thus, it has been necessary to select clad and fuel orientation patterns which arbitrarily cause severe channel to channel temperature gradients to determine an upper bound on cross element temperature gradients. For these studies, it is assumed that bowing occurs in a circular arc with no movement at the ends and the maximum bow occurring at the core midplane. Fuel rod asymmetry is assumed to occur with the rod touching the glass for the full length of the element. The latter is an extremely severe assumption and has an extremely low probability of occurring. There will, of course, be

a temperature gradient on the fuel which will cause the free standing fuel slug to bow, thus forcing some portion away from the glass and reducing the asymmetry effect.

Figures 18 through 20 show the three patterns selected for study. The total inward cluster model was selected to determine the effect of internal reflectors bowing inward. This opens the bypass area and a 5% bypass is assumed (8). The row cluster model examines the effect of extremely hot and extremely cold channels on a few elements along the zone boundary. A lesser amount of reflector bow occurs and the bypass is assumed to be 1%. A data location index value was input incorrectly in the row asymmetry resulting in elements 15-20 having asymmetry in different directions than the bow. Since these models are simply worst case assumptions, it was not felt reviewing the cases was warranted at this time. The random model is basically the orientation which would occur from temperature induced bowing as indicated by symmetric data. The asymmetry is selected to reinforce the bow. Internal reflector movement is between the row and inward cluster models and the bypass is assumed to be 3%.

Figures 21 through 23 show the peak cross element equivalent ΔT 's engendered for each element. For each configuration, the effect of cluster only and cluster plus asymmetry is shown with mixing accounted for and also the latter without mixing. The figures show only the equivalent ΔT which causes bending stress. However, it must be remembered that mixing also reduces the 60 ripple which cause alternate compressive and tensile stresses in the clad. For example, mixing reduces the 60 ripple on the center element by approximately 50%. Thus, Figures 21-23 only show part of the advantages of mixing.

A. General Observations

In most instances, mixing effectiveness is somewhat in proportion to the magnitude of the unmixed cross element ΔT . This is of course due to the fact that a larger driving force exists from channel to channel to have caused the temperature variation initially. Zone boundary effects seen in earlier studies are quite small in this reactor. This is due in part to the low temperature rise in the core (75° vs 135° in the 600 kw core), the low power density and

TOTAL INWARD CLUSTER & ASYMMETRY MODEL

FIG. 18

ROW CLUSTER & ASYMMETRY MODEL

FIG. 19

RANDOM CLUSTER & ASYMMETRY MODEL

FIG 20

CROSS ELEMENT ΔT - INWARD CLUSTER

○ CONFIGURATION 2N
(CLUSTER ONLY)
BYPASS $\Delta T = 29^\circ F$

● CONFIGURATION 3N
(CLUSTER & ASYMMETRY)
BYPASS $\Delta T = 25^\circ F$

* CONFIGURATION 3N X (NO MAXIMA)
(CLUSTER & ASYMMETRY)
BYPASS $\Delta T = 20.4^\circ F$

NOTE: BYPASS FLOW = 5%

CROSS ELEMENT EQUIVALENT $\Delta T, ^\circ F$

50
40
30
20
10
0

0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40

ELEMENT NUMBER

MINIMUM
 $\Delta T = 32^\circ F$

— CONFIGURATION 1N

* DENOTES EDGE ELEMENT

FIG 21

CROSS ELEMENT ΔT - ROW CLUSTER

CROSS ELEMENT ΔT - RANDOM CLUSTER

FIG 123

the small step in the radial power curve discontinuity. It is also due to the relocation of the zone boundary to more closely approach concentric rings.

It is also vividly shown that the location of channel area variation and rod asymmetry is quite important. In a few instances, it is seen that asymmetry and/or clustering and/or no mixing reduce rather than increase cross element ΔT . However, as a general rule, any variation from the symmetric core results in increased ΔT .

The effect of asymmetry in these models is the maximum that could possibly occur. The probability that asymmetry and bow will coincide in all cases is extremely low. In addition (as noted before), fuel rod bow must occur if there is a gradient across the fuel. Therefore, it is impossible for the fuel to be fully asymmetric along its full length. In light of these factors, it is felt the models used will probably encompass the worst cladding gradients that will be experienced in the actual core.

B. Inward Cluster Model

Figure 21 shows that clustering alone has a very small effect on the central portion of the core. This is expected since effectively the channels have been reduced in area only and the flow ratios from channel to channel are not changed significantly. In the outer portion of the core, the same area relation exists, however, the effect of the large bypass is now seen. Approximately five times the symmetric power loss is felt in this model and as can be seen, the effect shows up in the two rows of elements adjacent to the internal reflectors. This model then shows that fully uniform clustering and/or asymmetry is quite tolerable, however, bypass flow limiting is very necessary.

C. Row Cluster Model

Figure 22 again shows that the cluster effect alone on cross element ΔT is quite small. It is of particular interest that the elements in the tight cluster at the zone boundary were affected less than those in the inner zone (8-12) subjected to large and small areas. This is due primarily to the power jump in the outer zone working advantageously for this particular cluster. The asymmetry effect around the cluster is seen to be severe as

anticipated but the mixing effect reduces the ΔT 's to a great degree. The asymmetry on the outer elements is seen to greatly reduce the cross element ΔT because it adds more heat to the otherwise cold edge channels. As can be seen, it does so at the expense of increased power loss to the bypass. If the edge channels had been tailored to suit symmetric operation, this type of asymmetry would have caused an increased ΔT because the outer channels would run hot.

D. Random Cluster Model

In this model, the effect of clustering is more severe since alternate hot and cold sections of the core are set up. However, the increase in ΔT is still not great. Because the cluster effect is stronger, the added asymmetry also has a stronger effect than in the other two models. Again, it is seen that mixing attenuates ΔT in proportion to the unmixed ΔT . The effect of asymmetry toward a cold channel on the edge can be seen strongly in elements 33-35.

VII. OFF NOMINAL OPERATING CHARACTERISTICS

Applying the logic of operating tolerances of Ref. 9 to the criteria of Refs. 10 and 11, the core outlet temperature can vary $\pm 20^\circ\text{F}$ and the power ± 15 kw. The power swing could increase the core ΔT 3.75°F . The temperature swing could result from measurement tolerances or flow rate control or a combination. From these criteria, the maximum core ΔT should be on the order of 85°F .

Since cross element ΔT (maximum) found in this study was less than 50% of the axial ΔT , off nominal operation at 85°F ΔT should not increase the cross element ΔT more than 5°F and probably less. It was not felt at this early design stage, that additional GEOM runs were warranted since past experience has indicated the axial ΔT to be a fair indication of cross element ΔT . When the design has proceeded to a more firm stage, off nominal operation will be analyzed in more detail.

Transients must also be considered, however, they are beyond the scope of this study.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The two zone core has been shown to exhibit better thermal performance than a uniformly spaced core. While the differences are not great, S8DR experience dictates that the most thermally benign core design possible is the correct choice.

Fuel asymmetry has again been shown to be the greatest driving force to high cross element ΔT 's. Although mixing has been shown to greatly attenuate this effect, there is sufficient indication that fuel centering is desirable but probably not mandatory from a thermal standpoint.

Bypass has been shown to be a potential source of problems at the core edge. The design of the internal reflector segments must consider:

- (1) Edge area tailoring.
- (2) Flow access between the outer bypass area and the edge channels.
- (3) Bowing tendencies of the structure.

A detailed analysis of the entire core edge including heat loss through the reflector appears to be the next major effort needed to more accurately determine core performance.

With the current spacing and standard fins, a design cross element ΔT of 32°F appears reasonable. While scram power peaks could reach 350 kwt resulting in higher cross element ΔT 's than shown herein, it is felt that the assumptions of full length asymmetry and complete cluster and asymmetry reinforcement are so improbable that the safety margin implied is sufficient to account for the overpower. This design gradient could be reduced to approximately 28°F by using scalloped rather than standard fins.

A hydraulic test comparison of scalloped and standard fins is necessary to ensure that the final core design provides true full channel mixing since all GEOM results are predicated on this assumption. Simultaneously, an objective study of the assembly and manufacturing penalties assumed to be associated with scalloped fins should be made to permit sound design decisions.

Finally, a nuclear-thermal study should be made to determine the inner zone spacing limit to minimize fuel temperature.

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