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DESIGN ANALYSIS FOR LMFBR CORE RESTRAINT*

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ABSTRACT

This study considers Liquid Metal Fast Breeder Reactor (LMFBR) core restraint concepts featuring both mechanical and hydraulic holddowns. It evaluates the wide range of support and restraint designs from the loose 'vase' type design to a highly restrained system with complex loading. The analysis includes consideration of both steady state and transient thermal response along with irradiation induced materials effects. Of the arrangements considered, systems featuring a high degree of restraint yield minimum end-of-life irradiation induced distortions but require higher loads on assembly structures. Systems which are loosely restrained yield lower loads but extremely high predicted thermal and irradiation induced distortions. All arrangements studied gave 'worst case' transient thermal bows which were satisfactory from the standpoint of positive nuclear reactivity input over the total operating range.

1. INTRODUCTION

The object of this study is to evaluate the various core restraint arrangements which may be applicable to a Liquid Metal Fast Breeder Reactor (LMFBR). Typical radial temperature profiles present in an LMFBR core would normally cause fuel assemblies to bow inward, towards the core centerline, upon increase in power level. To prevent a large positive contribution to the power coefficient of reactivity, this bowing must be minimized.

The primary requirement of a core restraint system is that the positioning of fuel assemblies must be predictable, that the design should exhibit a negative overall power reactivity coefficient, and that the restraint system must not interfere with the refueling process. The design of such a system is complicated by the effects of radiation induced swelling and creep, which are added to the effects of core assembly bowing due to uneven thermal gradients.

In the past, two general approaches have been used to provide adequate reactivity characteristics: 1) 'loose' cores featuring controlled free bowing of fuel assemblies and

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2) 'tight' cores which restrict bowing. Current LMFBRs have high fuel burnup goals leading to predicted irradiation induced swelling of up to 12% by volume in the core region. This eliminates from consideration, the use of restraint aids in that region. Thus, with the restraint system contact pads moved out of the core center to positions of minimal swelling, the restraint design involves determination of the form required and the degree of compliance required, in order to limit permanent core assembly bowing without damaging assemblies in the process.

This analysis considers different degrees of restraint, incorporating both mechanical and hydraulic core holddown designs. The mechanical holddown system with intermediate radial restraint is the most highly restrained design evaluated, while a 'vase' type hydraulic holddown system using only below core restraint is the least restrained design evaluated. An intermediate design is considered which applies a moderate degree of restraint above the core and a hydraulic holddown. A schematic of these three approaches is shown in Figure 1. It is important to note that the holddown designs selected are only approaches assumed to produce the desired degree of restraint and all the assumed loading patterns shown in Figure 1 could be achieved with either system.

2. DESIGN OBJECTIVES

Structural Reactivity Coefficient: For nuclear safety, the core design should have an overall negative power reactivity coefficient. The design analysis must determine the optimum spacing between fuel assemblies in order to obtain the desired negative structural reactivity coefficient without overstressing the core from the effects of irradiation induced swelling, creep, and thermal expansion. In this analysis a negative structural reactivity coefficient is sought, although depending on the magnitude of other reactivity effects, such as Doppler, sodium voiding, and material expansion coefficients, a zero or slightly positive structural reactivity coefficient might be tolerable if it is well defined.

Load/Temperature Sensitivity: In order to maintain a negative structural reactivity coefficient, the restraint system must be effective from low power levels to full power and must 'follow' the core through abnormal temperature conditions. This requires that the restraint be referenced to predictable and representative temperatures and geometries. The restraint must also have a certain amount of resilience in order to absorb abnormal displacements without mechanical damage.

Compensation for Swelling: Radiation induced swelling may be expected to produce linear swelling rates as high as four percent in some core locations. If intermittent contact pads are used for core radial restraint, these pads must be located in regions of minimal swelling so core spacing will be unchanged throughout life. Variations in radial and axial neutron flux profiles can be expected to produce core assembly bowing which could be more severe than that associated with thermal expansion if the assembly were unrestrained. The analysis considers the application of radial loads through the restraint system which increases radiation and thermally induced creep effects which, in turn, reduce the degree of permanent bowing of core assemblies.

Ease of Refueling: Radiation induced swelling and creep effects are expected to offer the greatest complication to the refueling process. No matter how sophisticated the restraint and swelling compensation, some of the fuel assemblies are going to become permanently bowed. The core, control and radial blanket assemblies, as well as the restraining system, must be designed with sufficient clearance at refueling temperatures that bowed assemblies can be removed and, if desired, be repositioned.

Restraint System Must Be Satisfactory for Large LMFBRs: Since the eventual application is in a large reactor, the principle of core restraint systems should be practical for plants in the 1000 to 2000 MWe size range. In addition, it is desirable that the support/restraint system be structurally compact and mechanically simple.

3. ARRANGEMENT AND ANALYSIS APPROACH

The sections of the fuel, radial blanket, control rod and reflector assemblies located between the upper and lower core support plates have similar envelope dimensions and are arranged in an array illustrated in Figure 2. The assemblies measure approximately 140 inches between the support Olates and are positioned on a cold pitch of 5.10 inches. The core was assumed to extend from 47 to 77 inches above the lower core support in all cases. Cold clearances assumed between contact pads ranged from 0.005 inches at below core locations to 0.015 or 0.020 inches at above core locations.

The core support/restraint concepts evaluated in this analysis used radial restraint simulations which were similar in definition but varied in point of application. In the case of the hydraulic holddown, the lower nozzles of the core assemblies are positioned not only radially, but axially in the lower core support structure as shown in Figure 1 B&C.

The lower nozzles are the primary alignment guides for the assemblies when inter-assembly contact pads are not touching because an above core structure, if it exists, is designed primarily to prevent the accidental ejection of fuel assemblies. Conversely, an above core mechanical holddown, Figure 1 A, provides relatively inflexible positioning of the core assembly outlet nozzles.

When the reactor is at refueling temperature, gaps are opened between the spacer pads, with the gap dimensions being a function of axial and radial position. The intent of the spacer gap design is to size the gaps so that they will be relatively open at refueling temperatures and closed, or nearly closed, by the time that the reactor reaches significant power levels. The refueling gap cannot be too large since the design must minimize the amount of inward bowing which can occur during reactor startup. In the case of fuel and radial blanket assemblies located far from the core center, which have more severe thermal gradients, the contact pad gap is also used to reduce the mechanical loads on the core due to the relatively greater bowing of these assemblies.

3.1 Temperature Distributions

Beginning from the core centerline and traversing outwards to the radial reflectors there is a large variation in the power generation. The radial variation is slight near the core center and becomes progressively greater as the outside of the radial blanket is approached. Within each assembly there is a radial power gradient as well as side and corner channel effects which gives rise to cross-duct thermal gradients. Coolant temperature distributions were calculated for assembly locations along a radial slice taken from the core centerline and extending to the periphery. The section was taken at a corner of the core array shown in Figure 2 with the assemblies positioned flat to flat. A typical coolant temperature distribution across individual assemblies is shown in Figure 3.

3.2 Mechanical Analysis Methods

The restraint system analysis was done using a finite element computer code to analyze five to ten assembly arrays positioned radially within the core region. The array was chosen to place the core assemblies 'flat to flat' on the hexagonal cans to simplify the geometric analysis and include two control rods with the changes in temperature profile common to their environs. A typical ten assembly array extends from the blanket periphery to the center fuel assembly and gives a complete picture of the fuel assembly interactions along this line. The code is a general purpose computer program developed for the solution of a large class of structural analysis problems. The program uses a direct solution for the system of simultaneous linear equations developed by the matrix displacement method.

In the case of the core restraint system, the code can handle the following type of problems:

a) The response of arrays of fuel assemblies to power changes, considering varying restraint conditions.

b) Determination of imposed loads, elastic and plastic deformations of fuel assembly groupings as a function of time, considering creep and irradiation induced swelling.

c) Detailed analysis of intra-assembly stresses due to mechanical loading, unloading, and differential rates of thermal expansion due to unsymmetrical temperature conditions.

General analytical methods employed in handling these conditions are described by Swanson and Patterson [1].

4. THERMAL BOW ANALYSIS

4.1 'Vase' Arrangement (Figure 1 C)

Fuel assembly displacement analyses were run with two restraint configurations applied to the hydraulic holddown. The first of these is essentially the 'vase' type design, with assembly positioning being dependent on the lower core support and on a radial restraint immediately below the core. This restraint was applied at the 40 inch elevation above the lower core plate assembly. Radial displacements from the cold to the full power condition are illustrated in Figure 4 for this case.

Lacking any above core restraint, the core assemblies have a large thermal bow, producing unacceptable radial displacements for the upper part of the core and the assembly outlet nozzles which, in turn, result in an excessively high negative structural reactivity coefficient. The superposition of the effects of radiation induced swelling, in the absence of any alleviation due to creep, compounds the problem and eliminates the type of restraint from consideration.

4.2 Hydraulic Holddown Design with Above and Below Core Restraint (Figure 1 B)

In order to reduce the 'vase' restraint fuel assembly fanning effect shown in Figure 4, additional radial restraint was applied at the core periphery at the 105 inch level where a row of contact pads was positioned. At the same time, peripheral radial restraint at the 40 inch level was retained in order to limit outward movement at that point. This movement would be due to intra-assembly reactions due to varying thermal gradients. The result of this restraint was a considerable increase in the compaction of the core, over that of the 'vase' design as shown in the reduction in outlet nozzle displacements in Figure 5. A comparison of the full power core assembly displacements with those for the 'vase' configuration shows a 40 percent reduction in upper nozzle displacement with the application of above core radial restraint. The increase in degree of restraint increased the contact pad loads. On-power loads are given below for a new core.

Assy. at Radius of	Type	Pad Load In Pounds At Elevation of: 40"	85"	105"
5.1	Fuel	1772	0	0
10.2	"	1464	0	0
15.3	Control	1222	0	0
20.4	Fuel	966	267	0
25.6	"	799	0	200
30.7	Control	635	0	0
35.8	Fuel	353	514	0
40.9	Blanket	285	536	0
46.1	"	87	618	0
51.2	"	0	526	97
	Restraint	0	0	511

The contact pad loads are not directly additive because of the divergences in bowing among assemblies, and the inlet nozzle reaction loads which are not given. The effect of assembly distortions due to irradiation induced swelling and creep would be to further increase these loads with time.

An analysis of sensitivity to thermal perturbations was made by superimposing a series of thermal transients equal to 10% of total rated power at various reactor power levels. The analysis was made of a five assembly radial array including the assemblies with centerlines radially located 15.3 to 35.8 inches from the core center. Three of these units are fuel assemblies and two are control rod positions. A perturbation of 10% occurring at a low power operating condition of 20% power and 40% circulation produced the following average displacements of the fuel assemblies in the core region.

Assembly at Radius of:	Displacement At 20% power	Displacement At 30% power	Δ
35.8	+ .020	+ .013	- .007
25.6	+ .003	- .005	- .008
20.4	+ .001	- .004	- .005

Negative signs indicate motion towards the core centerline. These motions produce relatively small positive contributions to the power coefficient of reactivity.

At higher power levels the coolant flow is proportional to the power level, producing core temperature differentials nearly equivalent to those at full power. The resulting thermal expansion and thermal bow of the assemblies closes the contact pad gaps, making the core assemblies relatively insensitive to thermal perturbations. The following table lists the displacements of the three representative assemblies for a thermal perturbation of 10% of full power occurring at 100% of rated power.

Assembly at Radius of:	Displacement At 100% power	Displacement At 110% power	Δ
35.8	.096	.095	- .001
25.6	.063	.062	- .001
20.4	.050	.049	- .001

The most restrictive radial restraint arrangement considered for concepts utilizing a hydraulic holddown featured load pads at the upper nozzle level in addition to the pad locations assumed in the case above. The thermal bow characteristics approach those for the mechanical holddown arrangement described below and, therefore, are not described here.

4.3 Mechanical Holddown (Figure 1 A)

The mechanical holddown eliminates random radial motion of the upper nozzles, resulting in the most highly restrained system considered. The assemblies simulated in the analysis were assumed to be fixed at the lower end and pinned at the upper end. The lateral contact pads are retained at the 40, 85 and 105 inch levels on each assembly. These used the same diametral clearances that were used in previous analysis in order to establish a direct comparison with the hydraulic holddown designs. Peripheral radial restraint was input at the 40, 85 and 105 inch levels.

The overall effect of the upper core plate and the additional radial restraint was a more compact and more highly loaded core configuration. This is shown in Figure 6. A compilation of beginning-of-life contact pad loads is given below.

Assy. at Radius of	Type	Pad Load In Pounds At Elevation of 41"	85"	105"
5.122	Fuel	0	685	1890
10.244	Fuel	102	657	1502
15.366	Control	182	614	1223
20.488	Fuel	0	738	1513
25.610	Fuel	182	701	897
30.732	Control	332	687	345
35.854	Fuel	0	912	916
40.976	Blanket	0	1095	287
46.098	Blanket	0	894	81
51.220	Blanket	0	543	0
	Restraint	0	0	0

The analysis shows that for this calculation of a new, undeformed core, the thermal bow of the assemblies is concave; and that there is no loading applied by the peripheral restraint system. As assemblies become deformed after irradiation, the peripheral restraint system becomes active and pad loads increase to values as high as 3050 pounds at end-of-life for the worst case combination of radiation induced materials effects.

The sensitivity to thermal perturbations was determined by using the typical thermal 'bumps'. Due to the relatively high degree of restraint caused by the mechanical holddown, the core displacement was less than for the previous cases considered. Values for the perturbation at 20 percent rated power are given below.

Assembly at Radius of	Displacement at 20% power	Displacement at 30% power	Net Change
35.8 in.	+ .016 in.	+ .010 in.	- .006 in.
25.6 in.	+ .003 in.	- .001 in.	- .004 in.
20.4 in.	+ .005 in.	+ .001 in.	- .004 in.

The response to a perturbation at full power is given below.

Assembly at Radius of	Displacement at 100% power	Displacement at 110% power	Net Change
35.8 in.	+ .098 in.	+ .097 in.	- .001 in.
25.6 in.	+ .071 in.	+ .071 in.	- .000 in.
20.4 in.	+ .057 in.	+ .057 in.	- .000 in.

The calculated movement at this power level is insignificant. Outlet nozzle restraint which is inherent in the mechanical holddown provides the greatest control of core assembly bowing.

In the example chosen, the location of fuel element restraint points and proper choice of inter-element gap dimensions gives the core an overall negative structural power coefficient of reactivity for all normal and off-normal operating conditions. Thermal bow of assemblies gives an extremely small and short-term positive contribution during severe power perturbations. It is assumed that coolant circulation is controlled to match power levels above 20% full rated power and there is sufficient thermal expansion of the fuel assemblies, so that most of the contact pads are touching by that time. This makes the core relatively rigid, and insensitive to perturbations occurring at higher power levels. The most severe core structural reaction identified would be caused by an excursion during startup when assemblies are still "free standing." An excursion of 10% of rated power occurring while the reactor was operating at 1% power and 20% circulation rate caused an average inward movement of 0.019 inch by the 'worst case' fuel assembly. All other situations considered cause movements of the order of 0.006 inch or less. The worst case situation represents a positive contribution to the power coefficient of reactivity of less than 10% of the power coefficient.

5. EFFECTS OF IRRADIATION INDUCED SWELLING AND CREEP

Reactor core components in regions of high fluence are subject to radiation induced effects which can produce significant dimensional changes. Fluences higher than 10^{22} n/cm^2 and energies greater than 0.1 mev may produce significant material volume increases. The effects of radiation induced swelling and creep were evaluated for the restraint configurations described above. In regions toward the core periphery, the sharp fluence gradients produce differential swelling effects which permanently bow core assemblies. This bow can exceed that expected from thermal expansion. Carried to an extreme example, fuel assemblies could become so distorted that they might not be individually removable. On the other hand, if an assembly can be predictably loaded, or prestrained, creep may be employed to limit the amount of permanent deformation. These studies showed that the most highly restrained arrangements minimized assembly distortion.

Creep and swelling rate estimates given by Swanson and Patterson [1] were used in the assembly distortion analysis. Irradiation induced creep was assumed to vary from + 100% to - 20% about the nominal and estimated irradiation induced swelling rates were assumed to vary from + 40% to - 30% about the nominal value. Since swelling and creep effects tend to counterbalance each other, two extremes in assumed material property values were used; 1) maximum swelling and minimum creep, and 2) minimum swelling and maximum creep.

The analysis results for outer core assembly number 17 (Figure 2) is shown in Figure 7 for the highly restrained mechanical holddown system. The curves represent radial assembly displacements at refueling temperature after the upper nozzles have been freed and all peripheral restraint loads have been removed. The significant outward motions of the upper end of the assembly are due to the combined interaction effects of other distorted assemblies. A 70% load factor is assumed and assembly distortions are shown at the end 6, 12 and 24 calendar months for the extremes in material property assumptions.

The combination of minimum swelling and maximum creep tends to give distortions that are inward toward the core centerline for most assemblies, particularly early in life. The other extreme yields generally outward distortions towards end-of-life conditions.

A third case is plotted, where creep effects have been suppressed reducing the minimum creep rate by a factor of a 100. The result clearly shows how severe distortions can become without the beneficial effects of creep. It also gives insight into the problems of loosely restrained systems.

6. CONCLUSIONS

Of the systems evaluated, those featuring a high degree of restraint yield minimum end-of-life assembly distortions but require higher loads on assembly structures. Systems that are nearly unrestrained have much more severe steady state thermal bows characteristics and irradiation induced distortions. All arrangements studied gave 'worst case' transient thermal bows which were acceptable over the total operating range.

REFERENCE

[1] SWANSON, J. A., and PATTERSON, J. F., "Applications of Finite Element Methods for the Analysis of Thermal Creep, Irradiation Induced Creep, and Swelling for LMFBR Design," Paper No. L 4/3, Bundesanstalt Für Materialprüfung, Berlin, September, 1971.

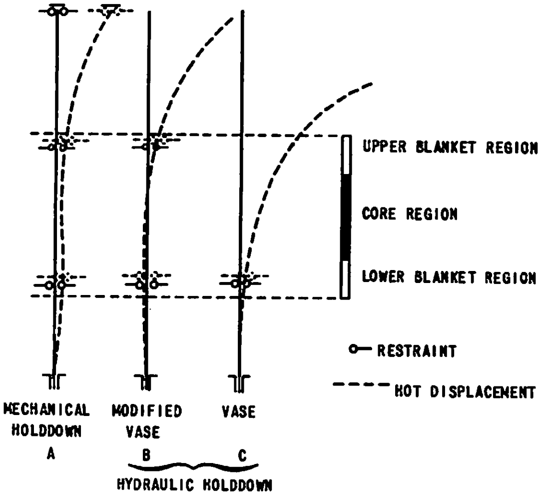
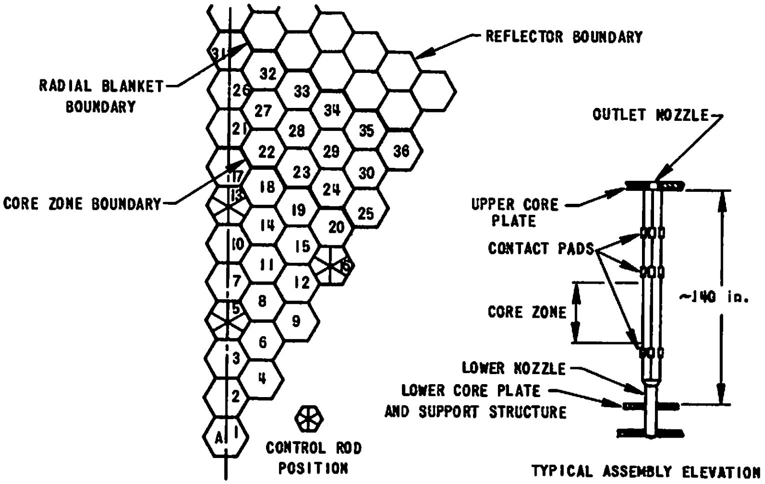


Figure 1. Core Support/Restraint Concepts



CORE ARRANGEMENT FOR 1/12 SECTOR

TYPICAL ASSEMBLY ELEVATION

Figure 2. Assembly Arrangement

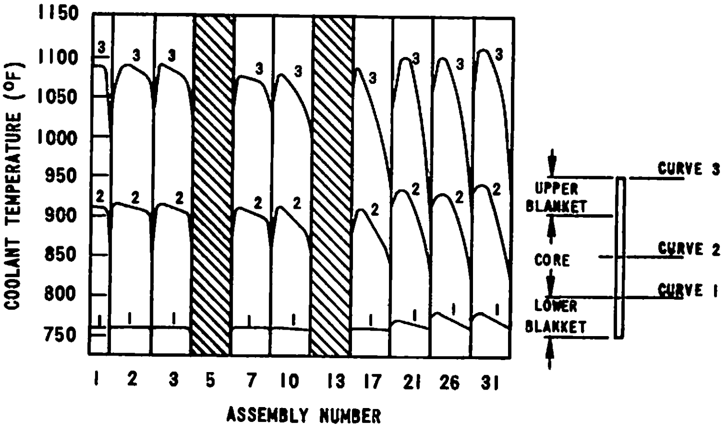


Figure 3. Coolant Temperature Profile Across Core Section

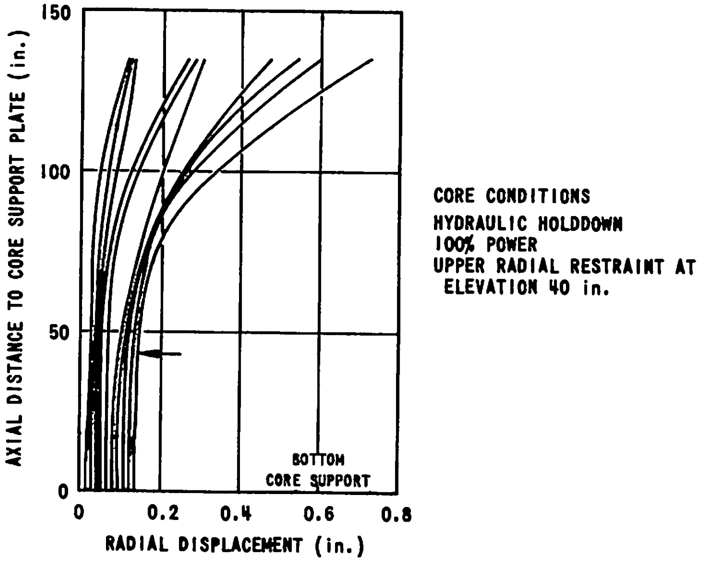
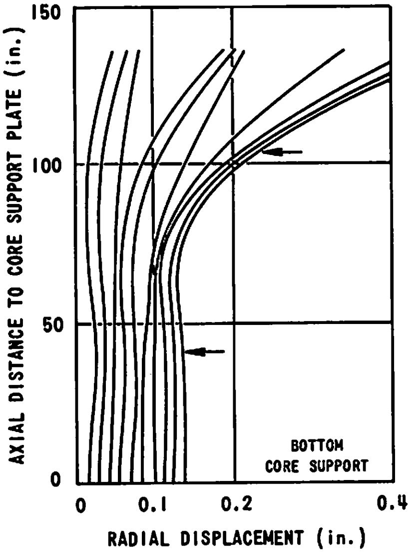
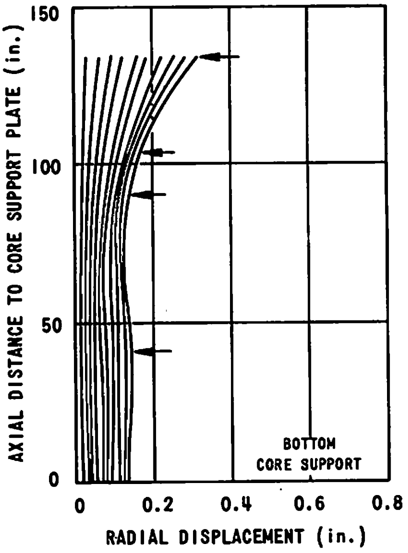


Figure 4. Assembly Displacements 'Vase' Arrangement



CORE CONDITIONS
HYDRAULIC HOLDDOWN
100% POWER
UPPER RADIAL RESTRAINT AT ELEVATIONS
40 & 105 in.

Figure 5. Assembly Displacements
Modified 'Vase' Arrangement



CORE CONDITIONS
MECHANICAL HOLDDOWN
100% POWER

Figure 6. Assembly Displacements
for Mechanical Holddown

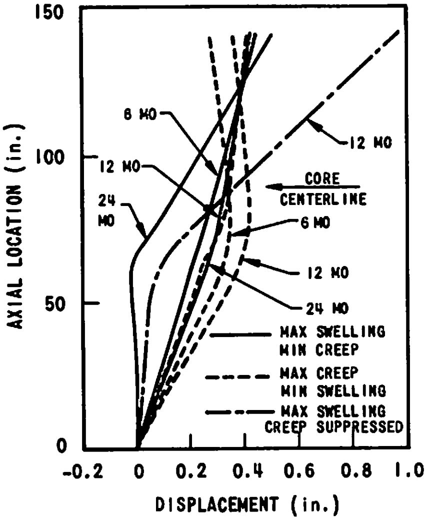


Figure 7. Distortion of Assembly 17 Versus Irradiation Time

DISCUSSION

Q M. BENDER, U. S. A.

With respect to deformation limits, are these sensitive to power level and core volume ? If so, what direction is the limit towards with changing power and volume parameters ?

A J. F. PATTERSON, U. S. A.

We found inward bow, due to increase in power more significant at lower power levels. We looked at two core sizes and found that the larger core displayed the smallest reactivity effect due to thermal bow.

Q G. K. SCHMIDT, Germany

Can you give us a figure - for your case of maximum creep in an outer row subassembly - of the maximum local value of creep strain occuring according to your calculation ?

A J. F. PATTERSON, U. S. A.

If we include both thermal creep and irradiation induced creep and then combine the effects of both lateral duct deformation and deformation due to differential pressure across the duct, local creep strains can be several percent. This is of course assuming the extremes in material property estimates. Irradiation induced creep is responsible for most of the total creep strain.

Q K. AKINO, Japan

If you adopt a mechanical hold down system, you have to provide upper core plate. During refueling this plate should be removed. Do you have a conceptual or practical design of the upper core plate ?

A J. F. PATTERSON, U. S. A.

We have developed a practical conceptual design for a mechanical hold down system. I would like to point out the fact that this concept is used in at least one operating breeder reactor, the Fermi Reactor.

Q S. CURIONI, Italy

Do you think that it is possible to have some problems during refuelling due to local deformations that can give very big loads to remove the fuel elements ?

A J. F. PATTERSON, U. S. A.

Fuel assembly distortions could be sufficiently large, using the extremes in predicted irradiation induced swelling and creep values, that high extraction loads would be required to remove fuel assemblies. That is unless the restraint imposed on the core were removed. As a consequence, we believe that a core restraint sytem design should provide a means to remove such restraint loads.

Q T. MALMBERG, Germany

Have you analysed the local strain pattern in the vicinity of the pads, and if so is there any appreciable strain at this point ?

A J. F. PATTERSON, U. S. A.

We have done a limited amount of analysis in the region of the load pads. The location of the load pads is in a region where no significant irradiation induced swelling and creep is expected. In addition, the assembly ducts are locally reinforced at these points. As a consequence, we have not found the strains to be appreciable at these locations.

Q V. S. BECKETT, U. K.

Is it not possible, with such a high degree of restraint used in a core where the swelling associated with the assemblies is as high as 12%, that the assemblies can interact to such a degree that very high extraction loads are necessary during refuelling ?

A J. F. PATTERSON, U. S. A.

High swelling levels will, no doubt, require the designer to provide space between assemblies in the core region for dimensional increases in the ducts. In all cases considered load pads for core restraint were placed above and below the core region where no significant swelling is expected. However, it may be necessary to release any restraint arrangement at the periphery of the core in order to remove assemblies with reasonable extraction loads.

Q V. S. BECKETT, U. K.

You talk of substituting a negative reactivity coefficient by a small positive value. Considering the safety aspects of fast reactors in general is it not better in principle to design for negative reactivity coefficients rather than positive ?

A J. F. PATTERSON, U. S. A.

As a ground rule, we require that the overall power coefficient of reactivity be negative. The positive reactivity effect I referred to in one of the cases we considered, was only a very small effect due to inward bow of fuel assemblies. In no case did this bow affect the total power coefficient by more than 20% in the positive direction.

In summary, we found both the structural reactivity coefficient and overall power coefficient of reactivity to be strongly negative over the total operating range for all cases we considered, thus the safety aspects, for which you were concerned should be adequately provided for.

Q G. R. WAYMIRE, U. S. A.

In your analysis did you assume that the restraint loads were constant load, variable displacement or constant load, no displacement ?

A J. F. PATTERSON, U. S. A.

We assumed neither constant load or constant displacement. The finite element code which we used for our analysis is capable of evaluating a group of assemblies simultaneously. The code even has the capability of modeling gaps between assembly load pads. Therefore, we can evaluate both loads and displacements which are variable with time.