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OVERVIEW OF CORE DESIGNS AND REQUIREMENTS/CRITERIA FOR CORE RESTRAINT SYSTEMS

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ABSTRACT

The requirements and lifetime criteria for the design of a Liquid Metal Fast Breeder Reactor (LMFBR) Core Restraint System is presented. A discussion of the three types of core restraint systems used in LMFBR core design is given. Details of the core restraint system selected for FFTF are presented and the reasons for this selection given. Structural analysis procedures being used to manage the FFTF assembly irradiations are discussed. Efforts that are ongoing to validate the calculational methods and lifetime criteria are presented.

1.0 INTRODUCTION

The design of Liquid Metal Fast Breeder Reactor (LMFBR) Cores requires the exact positioning of core assemblies in close proximity to each other. Furthermore, during the operational history of the reactor it is necessary that motion of these assemblies be minimized so as to not jeopardize the safe and reliable operation of the reactor. Environmental conditions within the reactor core; high temperatures and temperature gradients, high neutron flux and flux gradients, cause the assemblies to expand and to bow in direct contradiction to the requirement for minimum core motion. Thus, it became necessary to design some type of core restraint system that would provide adequate dimensional stability during the operation of the reactor but allow the assemblies to be removed upon reactor shut down. This design of an adequate core restraint system was further complicated by the confirmation that the proposed materials for core components fabrication swell significantly when exposed to a high fast flux environment. This volumetric growth called irradiation swelling does not reverse itself upon reactor shutdown as do thermal expansions. Thus, the advent and confirmation of the phenomenon of material swelling required the design of a core restraint system which could accommodate high levels of irradiation swelling. This paper describes the development of a core restraint concept designed to satisfy the set of requirements and lifetime criteria associated with a high swelling core component material.

2.0 REQUIREMENTS

Design of a Liquid Metal Fast Breeder Reactor (LMFBR) core restraint system requires the satisfaction of both functional requirements and performance requirements. The performance requirements vary with the specific objectives of the breeder program and will not be addressed here. The functional requirements are aimed at assuring the safe and reliable operation of the reactor core and its associated interfacing systems and are thus, generic, to any LMFBR core system. The functional requirements can be broken down into four major categories: 1) Reactivity Control, 2) Refueling Requirements, 3) Interface Requirements and 4) Design Life. These requirements generally turn out to be in direct conflict with each other as is the case with reactivity control and refueling. To satisfy the reactivity requirements all interassembly gaps would be set at a minimum value but these small gaps would result in excessive forces being required to remove the irradiated assemblies from the core. Thus, an acceptable core design requires trade-offs between conflicting functional requirements. A brief summary of typical core restraint system functional requirements is given in Figure 1.

The reactivity controls are imposed to assure the safe and predictable operation of the reactor and to insure that the fuel pin damage limits are not exceeded. The fuel pin damage limits are defined by the core step reactivity insertion which would bring the fuel to its limiting condition. The maximum step reactivity insertion may be determined by the permissable core motion allowed by the core restraint system design. The refueling

REACTIVITY CONTROL

- MAINTAIN A NEGATIVE POWER COEFFICIENT AT ALL CORE POWER LEVELS
- LIMIT STEP REACTIVITY INSERTIONS SUCH THAT THE FUEL NORMAL PLUS UPSET DESIGN CONDITION DAMAGE LIMITS ARE NOT EXCEEDED

REFUELING REQUIREMENTS

- CORE COMPONENT INSERTION AND WITHDRAWAL LOADS NOT TO EXCEED DESIGN LIMITS
- CORE COMPONENT HANDLING SOCKET TO BE POSITIONED WITHIN REFUELING GRAPPLE RANGE

INTERFACE REQUIREMENTS

- MAINTAIN ALIGNMENT OF THE CONTROL ASSEMBLY DUCTS WITH THE UPPER INTERNALS STRUCTURE
- ALIGN DUCT NOZZLE EFFLUENT WITH UPPER INTERNALS FLOW COLLECTORS
- LIMIT BOWING OF THE CONTROL ASSEMBLY DUCTS
- PREVENT EXCESSIVE CONTACT OF DUCTS IN THE ACTIVE CORE REGION

DESIGN LIFE

- NUMBER OF YEARS TARGET LIFE AT A SPECIFIED LOAD FACTOR FOR CORE COMPONENTS
- NUMBER OF YEARS FOR PERMANENT CORE RESTRAINT HARDWARE
- REFUELING FREQUENCY

FIGURE 1. Typical Core Restraint System Functional Requirements.

requirements are derived from the desire to keep the assembly insertion and withdrawal loads to an acceptably low value. Furthermore, bowing of the assemblies must be sufficiently restricted to allow the refueling grapple to locate the assembly handling socket. The interface requirements are concerned primarily with insuring the operability of the control assemblies which imposes a limit on allowable misalignment and interactions with neighboring assemblies. The design life of the assemblies is controlled by the objectives of the irradiation program and has a significant impact upon the acceptability of a particular core restraint system design.

3.0 CORE RESTRAINT SYSTEM DESIGNS

Three types of core restraint system designs(1) have been used in LMFBR core design. The leaning post concept is exemplified by the British PFR core restraint system design depicted in Figure 2. The essential features of this design are the location of transverse support pads in the lower axial blanket region of the fuel assembly and the forced contact of the support pads with the leaning post by means of a cantilever beam spring in the fuel assembly nozzle. The fuel assemblies are clustered in groups of six with the center leaning post housing the control rods. All thermal and irradiation induced bowing of the fuel assemblies takes place above the leaning post contact point in a region where the fuel assembly is free standing. This design concept does not allow the use of irradiation creep to offset the effect of bow due to differential swelling. The permanent residual bow due to swelling will continue to increase with increasing fluence and eventually the assembly lifetime will be limited by the fuel handling machines capability to locate the handling socket of the assembly to be removed. An increase in assembly lifetime with this design concept can be accomplished by either rotating the assemblies frequently to straighten them or developing a satisfactory low swelling alloy.

EBR-II, Rapsodie and Phenix have used a free standing core restraint concept depicted in Figure 3. In this concept the long close fitting nozzles provide cantilever support for the free standing core and radial shield assemblies. Pressed dimple type spacer pads are located either in or just above the active core region. The fuel assemblies are free to bow outward at the top until they interact with the shield assemblies at the core periphery. The large number of shield assemblies act as soft springs and absorb and diffuse the loads produced by the bowing of the fuel assemblies due to differential swelling. High bending stresses in the fuel assemblies are prevented by irradiation creep. Lower stresses are produced in the shield assemblies, however, these are not relaxed out because of the much lower flux values in this region. Assembly lifetime limits with this concept are associated with the spacer button indentation load limit and the difficulty of maintaining tolerances and alignments in a large reactor core with a spring type boundary.

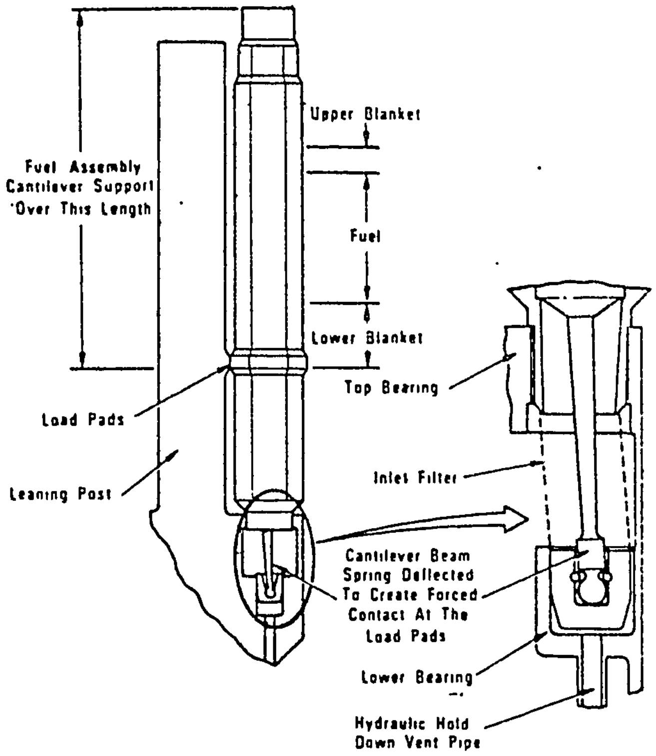

FIGURE 2. PFR Leaning Post Concept.

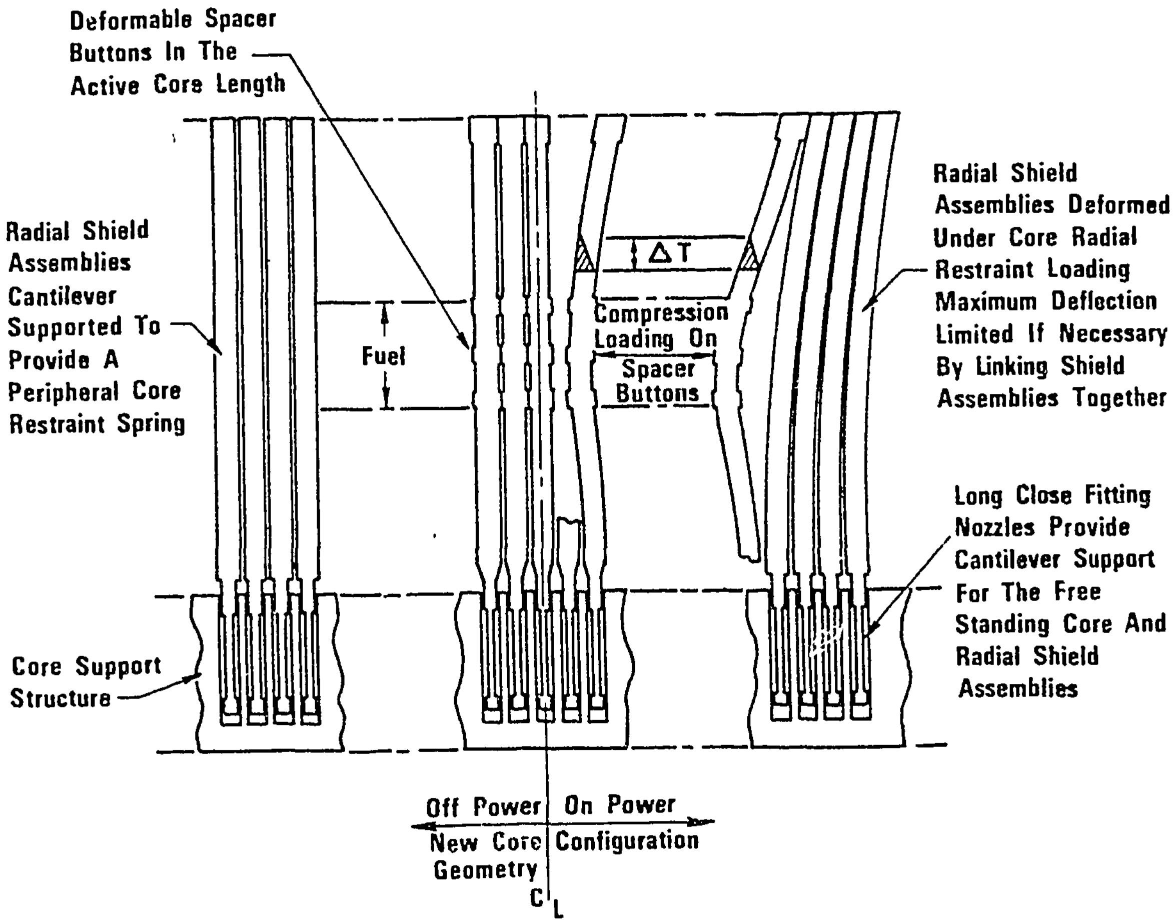

FIGURE 3. Free Standing Core Restraint Concept.

4.0 FFTF CORE RESTRAINT DESIGNS

The core restraint concept employed in the design of the FFTF core restraint system was specifically designed to accommodate the high levels of swelling associated with the reference duct structural material (Austenitic Stainless Steel - 20% CW AISI 316). This concept defined as the limited free bow core restraint concept is shown in Figure 4. Essential feature of this concept is the use of core formers on the exterior boundary to limit the bowing of the fuel assemblies. The core formers are attached to the core barrel and thermally expand and contract depending upon the relative temperature distributions. Lateral restraint of the fuel assemblies is provided at three locations, top and bottom of the assembly and at a location just above the top of the active core. This middle restraint is located at this position so that the fuel assemblies will bow radially outward from the core center in response to temperature gradients generated across the ducts. This also eliminates the need for a mid-core spacer button system to control the reactivity response of the core. The nozzle-receptacle interface is designed to allow free in-plane rotation of the nozzle resulting in a pinned rather than a cantilever structural support. Free bow of the fuel assemblies is controlled by setting the gaps between the core formers and the radial shield assemblies. The radial shield assemblies are designed to have low flexural bending stiffness so that the core restraint loads are transmitted directly to the core formers. The core former gap settings restrict the amount of duct bowing which can occur due to differential swelling and thermal expansion. The stresses which would result from differential swelling and thermal expansion are either eliminated or relaxed by irradiation creep resulting in relatively low on-power core former restraint forces. Shut down of the reactor eliminates the temperature gradients across the ducts and the ducts deform elastically through their limited free travel. This results in significant duct straightening upon reactor shutdown. Furthermore, the differential thermal contraction results in the tendency to reopen the core former gaps.

The optimum restraint system from the refueling point of view would have been core formers actuated by hydraulic rams which could be withdrawn to facilitate the withdrawal of fuel assemblies. Major problem with the activated core former design was the inability to guarantee the initial compaction of the core within required limits. Thus, it was necessary to design not only a mechanically activated device to move the core formers but a measuring system had to be designed to locate accurately the core former position. In addition, compaction testing in core mechanical mockups were never able to demonstrate that repeatable compaction of the core could be achieved within the allowable dimensional tolerances. Because of these unresolved design considerations the core former gaps were set statically. The static gap values chosen were set to allow adequate restraint load reduction for refueling and at the same time limit free core motion such that the potential step reactivity insertion limit would not be exceeded.

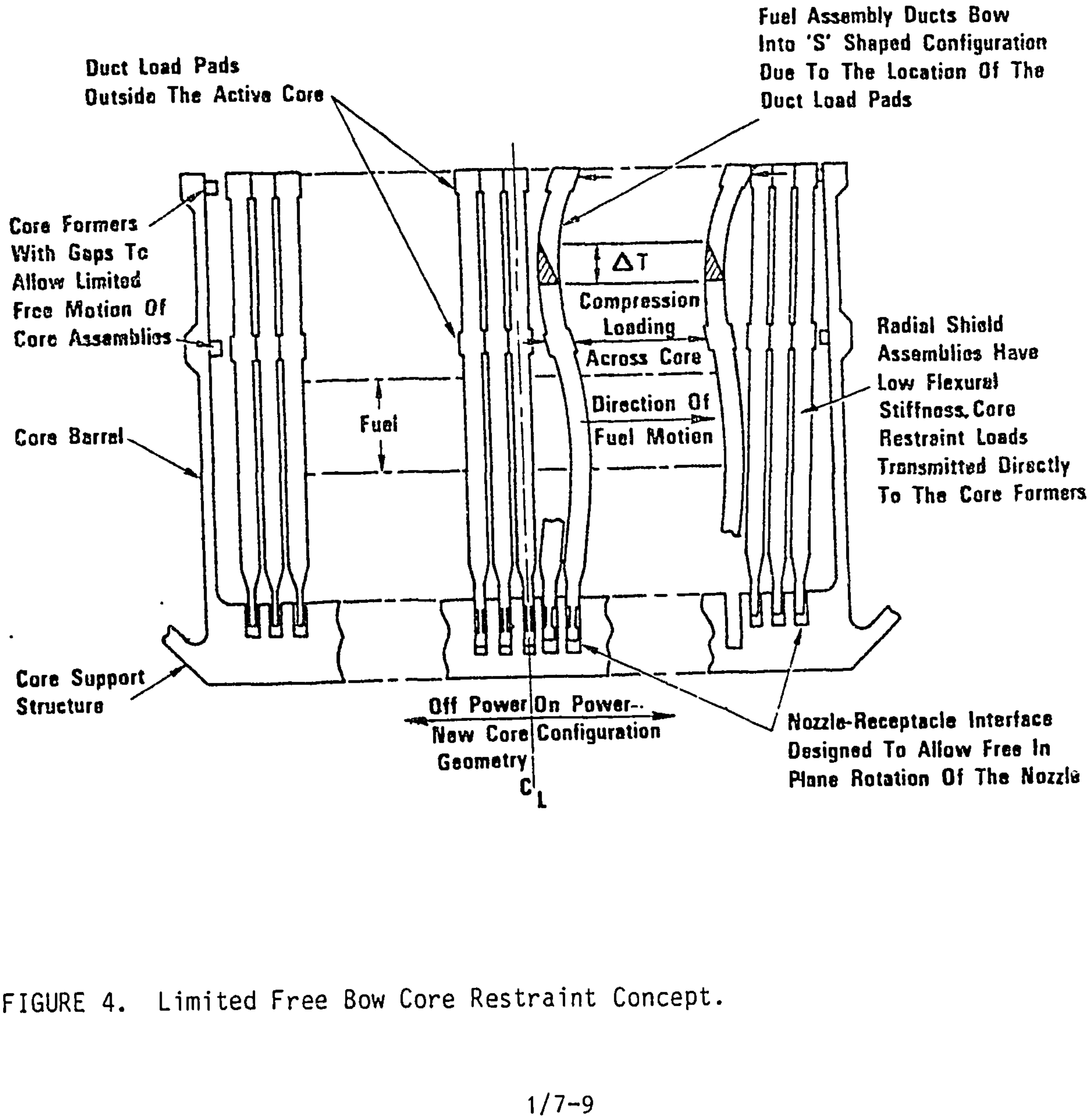

FIGURE 4. Limited Free Bow Core Restraint Concept.

The limited free bow core restraint concept used in the FFTF core design is expected to have high burnup potential even with a high swelling duct material.

5.0 FFTF CORE RESTRAINT DESIGN LIFETIME CRITERIA

The core restraint system concept used in the FFTF core design has resulted in duct deformations being calculated to be assembly lifetime limiting when the reference material (20% CW AISI 316) is used. The duct deformations which may be lifetime limiting are shown in Figure 5. The three limiting deformation mechanisms are duct bowing, duct length change and duct dilation. The duct dilation and duct bowing results are combined to create the ultimate duct lifetime limit which is duct withdrawal force. Satisfactory operation of the FFTF reactor has required that an operational limit be placed upon each of the duct lifetime limiting variables.

The limit on duct length change(2) is 0.65 to 0.75 in. depending upon the core sector and is based on the capability of the fuel handling and in-reactor storage system. If this limit is exceeded, the In-Vessel Handling Machine cannot, in a reliable and automatic mode, remove core subassemblies and then deposit them in In-Vessel Storage. A secondary length change limit of 1.0 in. is imposed to prevent a subassembly from contacting the bottom of an Instrument Tree (a reactor upper internal device for making core temperature and flow measurement and providing secondary hold down).

The unrestrained residual duct bow is limited to a maximum value of 0.9 in. which assures that the assembly will fit in the In-Vessel Storage pot. Assembly bow also has an effect upon the withdrawal loads, but the limited free bow core restraint concept results in a saturation value for residual bow at a value significantly below 0.9 in. This bow saturation value is a direct result of the interactions between irradiation creep and swelling in a constrained system.

Permanent duct dilation occurs as a result of two effects. One effect is the uniform volumetric growth due to isotopic swelling. The second effect is the cross-sectional irradiation creep deformation due to the internal pressure loading. A great deal of uncertainty exists as to how restrictive these limits should be to assure the structural integrity of the ducts and the ability to refuel the core. Major concern with refueling is the problem of pulling the dilated core region through the spatial envelope created by the above core load pads of the adjacent assemblies. This envelope does not form a rigid boundary but rather a spring supported boundary with the spring constants defined by the interactions with the remainder of the core. Because of the uncertainty involved with the duct dilation limit, the residence time of a duct is carefully examined any time its radial dilation exceeds 0.070 in. This value corresponds to the radial clearance in the load pad envelope when the dilated section first interferes with the load pad. Whether this 0.070 in. dilation constitutes

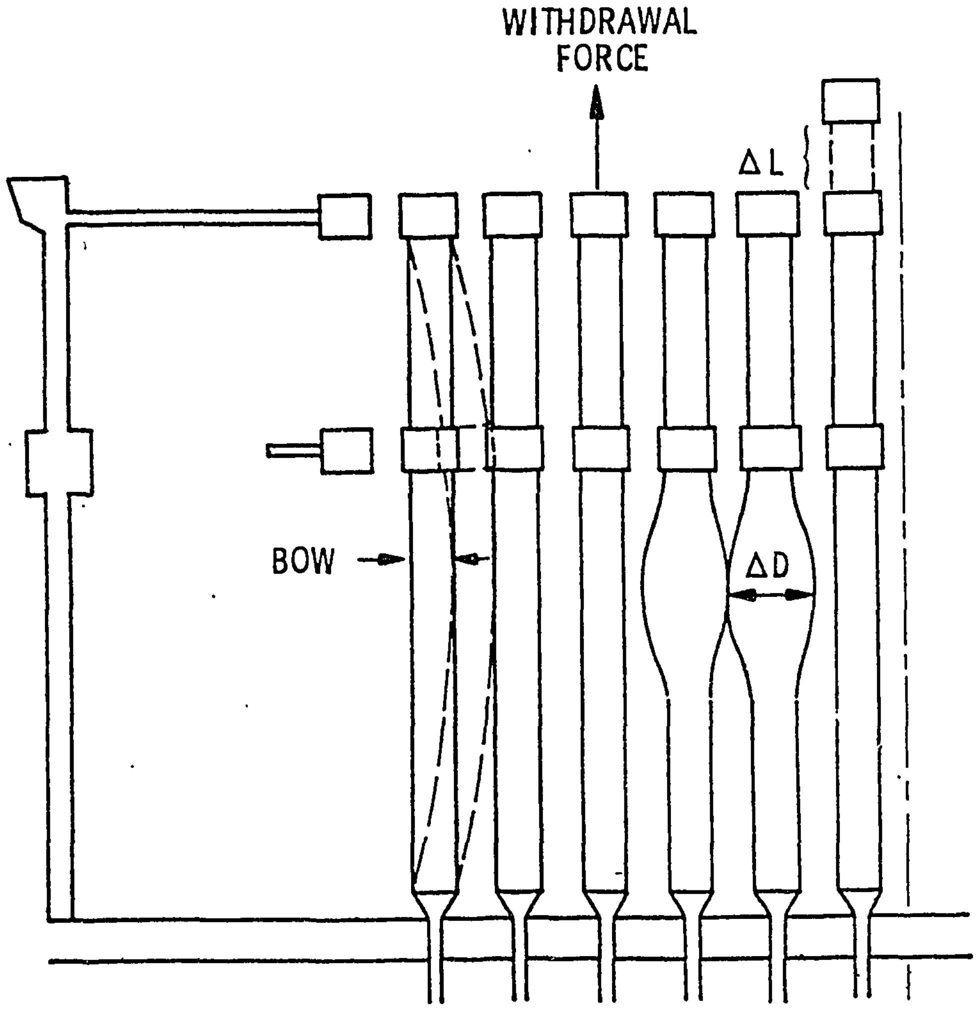

FIGURE 5. Duct Lifetime Limit Variables.

a hard limit for that particular assembly depends upon the dilation history of all ducts adjacent to that assembly. If most of the adjacent assemblies have short residence times in the reactor, then the allowable radial dilation may be raised to a value as high as 0.130 in.

The withdrawal loads limits imposed on the fuel handling machine are a 4000 lb hardware limit and a 2000 lb software limit. The automatic software limit can be over ridden manually.

6.0 ANALYSIS PROCEDURE TO MANAGE FFTF ASSEMBLY IRRADIATIONS

Lifetimes for the reference material FFTF subassemblies are expected to be dictated by the duct lifetimes. Two types of structural analyses(3) are performed on each reactor operating cycle to determine the duct lifetime limits. These are core-wide single assembly analyses and core-restraint system analyses. These analyses require updated values for the fast neutron flux, temperatures, and pressures for each reactor cycle consistent with the modified core loading for each cycle. Core reload simulation is accomplished by modification of component history data bases and can simulate reload of assemblies with new or previously irradiated assemblies as well as assembly shuffling and rotation.

Core-wide single assembly analyses involve the calculations of decoupled duct dilation and axial growth on an assembly by assembly basis for the entire fueled region of the FFTF core. The resulting duct dilation calculations represent upper bound values since duct-to-duct contact is not considered. Reducing the conservatism in the calculations requires a core-restraint system analysis where the interaction between assemblies is assumed.

The core-restraint system analysis includes the effect of power and time dependent structural response with respect to subassembly interactions and external core former boundaries. Core subassembly deformations, interaction loads, and reactivity effects are calculated at each time or power step. Deformations include in-reactor bows (restrained), permanent residual bows, and duct dilations. Withdrawal loads are calculated from the normal loads on subassemblies interfaces times the appropriate coefficient of friction at refueling conditions.

Results from both sets of analyses are used to determine the core refueling scheme based on duct lifetime for the next reactor cycle.

7.0 VALIDATION OF CALCULATION METHODS AND LIFETIME CRITERIA

FFTF represents the first attempt to utilize the limited free bow concept for core restraint design. Therefore, it is not only necessary to validate the computer codes used to predict the subassembly lifetimes but it is necessary to establish that the lifetime criteria are realistic and consistent with observations.

Code validation involves two concepts; verification and qualification. Verification is defined as the demonstration that a computer program actually does correctly what it is supposed to do; that is, it solves correctly the model that was programmed, regardless of whether the model is a valid representation of any particular physically realistic system. Qualification is concerned with the use of computer programs for solving real problems and relating the solutions to experimentally measured results. Verification of the structural computer codes for core restraint calculations does not present any unique difficulties, but the same is not true for qualification. Two types of data from FFTF exist to assist in the qualification of core-restraint codes: 1) operational data consisting of withdrawal loads and In-Vessel Handling Machine length changes, and 2) Postirradiation duct dimensional characterization consisting of length change, residual bow, and cross-sectional dilation. The use of these types of data for qualification has the obvious disadvantage of lumping all of the uncertanties; environmental conditions, material properties, geometrical discretization, and boundary conditions, into the measured response characteristic. Thus, the correlation of analytical predictions with experimental results is by no means a straightforward procedure. It can be expected that there will be differences between predicted and measured values and qualitative agreement, not quantitative agreement, should be sought.

Major effort is also involved in establishing the proven duct lifetime criteria. Considerable conservatism has been purposely built into the duct lifetime criteria. Fuel assembly economics dictates that the fuel be used to its maximum limit. Thus, the incentive is high to remove as much conservatism in the duct lifetime criteria without placing the refueling of the core in jeopardy. Careful examination of all available reactor data will be required to establish optimum duct lifetime criteria.

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