CONF-810625--21

The Effect of Irradiation Induced Structural Material

Deformations on Core Restraint Design

J. E. Kalinowski

MASTER

Westinghouse Advanced Reactors Division
Madison, PA

DISCLAIMER

This document contains information which is proprietary to Westinghouse Electric Corporation. It is to be controlled and its use restricted in accordance with the provisions of the Atomic Energy Act of 1954, as amended, and the regulations promulgated thereunder. It is to be controlled and its use restricted in accordance with the provisions of the Atomic Energy Act of 1954, as amended, and the regulations promulgated thereunder. It is to be controlled and its use restricted in accordance with the provisions of the Atomic Energy Act of 1954, as amended, and the regulations promulgated thereunder.

ABSTRACT

A summary of the major considerations in the design of LMFBR core restraint systems is presented. A discussion of these considerations is given using the design features and environment of the Clinch River Breeder Reactor Plant core restraint system design. A comparison of core restraint performance with an alternate concept is provided. Conclusions are drawn on the direction of current and future core restraint system designs.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EHB

INTRODUCTION

In the design of fast reactor cores, the position of the core assemblies and their mechanical interactions with other core assemblies and the core supporting structures must be controlled in order to assure adequate core safety and performance. This gives rise to the definition and selection of mechanical features on the core assemblies and at core assembly--core support structure interfaces which permit core performance, safety and interfacing component functions to be achieved. The composite of core assembly and core support structure mechanical features which affect core assembly positions and mechanical interactions defines the core restraint system. Core restraint system design is complicated by reactor core and external environmental considerations. These include: high temperatures and temperature gradients; high fast neutron flux and flux gradients; the potential for seismic events during the life of the plant. This presentation illustrates how these environmental considerations affect the design of the Clinch River Breeder Reactor Plant (CRBRP) core restraint system with the focus of attention placed on the design problems introduced by the irradiation of core structural materials.

REACTOR SYSTEM DESIGN FEATURES

Figure 1 illustrates the relative location of the components which comprise the CRBRP reactor system.⁽¹⁾ The reactor core assemblies are supported from below and laterally by the core support structure whose main structural components are the core support plate and the core barrel. Direct vertical support of the core assemblies is provided by the lower inlet modules and the bypass flow modules. The lower inlet modules are seated on inlet module liners which extend through penetrations in the core support plate. The bypass flow modules which support the low flow core assemblies are supported by the core support plate between the lower inlet modules and the core barrel. Peripheral support of the core assemblies is provided at two elevations: the above core load plane (ACLP) and the top load plane (TLP). At these elevations the core former structure, which limits the outward radial motion of the core assemblies, is supported by the core barrel.

The upper internals structure is located above the core assemblies and promotes mixing for the flows of differing temperatures which exit the core assemblies. Instrumentation posts which are located directly above the core assembly outlet nozzles provide support for core outlet thermocouples and provide backup holddown of the core assemblies.

During refueling, the upper internals is lifted 229 mm and rotated out of its operational position over the core. This allows the in-vessel transfer machine (IVTM) access to the core assemblies for replacement or relocation within the core. Assembly replacement is accomplished by the straight pull or push of assemblies out of or into their in-core positions.

The CRBRP core map is illustrated in Figure 2. Fuel and inner blanket assemblies are interspersed in a heterogeneous configuration which provides improved breeding ratio and a reduced sodium void effect. The fuel region is surrounded by two rows of radial blanket assemblies and four rows of removable shielding assemblies. The main control and safety function is provided by nine primary control assemblies. The six secondary control assemblies provide alternate shutdown capability in the extremely unlikely event that the primary control system fails to shutdown the reactor.

The fuel assembly schematic is illustrated in Figure 3A. The fuel assembly provides support and a coolant flow path for the power generating fuel pins. The main fuel assembly structural members are the inlet nozzle, shield block, duct and handling socket. Raised circumferential load pads are located at the above core and outlet nozzle elevations corresponding to the ACLP and TLP elevations of the core former structure. The external features of the blanket and control assemblies are similar to the fuel assemblies. The removable radial shielding assemblies differ in that the inlet nozzle extends to the base of the duct in the absence of a shield block region.

CORE ENVIRONMENT

Liquid metal fast breeder reactor (LMFBR) core temperature environments are characterized by a large temperature rise from core inlet to core outlet. In CRBRP at full power conditions sodium enters the core at a temperature of 388°C and leaves the reactor vessel at 535°C. Typical core assembly duct axial and radial temperature profiles are shown in Figure 3. The axial temperature change is shown in Figure 3A. The increase in temperature and temperature gradient occurs in the fuel region. Radially, the duct temperatures vary with assembly type. In a fresh core, the fuel assemblies run "hot" while the blanket assemblies run "cold." As fissionable plutonium builds up in the blanket assemblies power generation and temperatures increase. At end-of-life conditions the blanket assemblies run as "hot" as the fuel assemblies. Assembly to assembly temperature gradients are due to interassembly heat transfer. At start-of-life, the steepest interassembly temperature gradients occur at the fuel-radial blanket interface. At end-of-life, the steepest temperature gradients occur in ducts adjacent to the control assemblies.

The radial distribution of the fast flux is shown in Figure 4 at the core mid-plane elevation. Because of the heterogeneous configuration of the core, the neutron flux peaks in the outer fuel rows and is depressed in the center of the core. As plutonium builds up in the blanket regions, the flux shifts toward the core center and the peaking in the outer fuel region diminishes.

The reactor plant is designed to accommodate the effects of seismic events during the plant lifetime. Seismic motion is applied to the core at the inlet nozzle and load plane elevations by the core support structure. The magnitude of design seismic motions is sufficient to displace the entire core against the core support structure. The inertia loads generated within the core assemblies are reacted at the core formers and the inlet nozzle receptacles. At the ACLP and TLP, inertia loads are transmitted from assembly to assembly prior to being reacted against the core former rings. Consequently, duct seismic loads are maximum in those assemblies adjacent to the core formers.

CORE RESTRAINT DESIGN CONSIDERATIONS

The mechanical features of the CRBRP core restraint system and significant interface parameters are shown in Figure 5. The reactor assemblies are laterally supported at three elevations: inlet nozzle, ACLP and the TLP. The core assemblies are provided with circumferential load pads at the ACLP and TLP. Small interassembly gaps at the ACLP and TLP allow accommodation of limited assembly bowing motions and differential thermal expansion between the core and core support structures. Small clearance gaps at the inlet nozzle permit a limited degree of pivoting motion at the inlet nozzle. Gaps at the shield block level and between ducts are sized to limit the degree of inter assembly contact at non load plane elevations. Peripheral restraint of the core array is provided by core formers at the ACLP and TLP. The location and sizing of the core restraint system mechanical features are determined by the following core restraint system requirements.

Reactivity

In a fast reactor core small motions of the fuel region give rise to changes in the core reactivity. Positive reactivity is added when the core assemblies displace radially inward. Core assembly motions are most likely during reactor startup when power is being increased at constant reactor flow. Core assembly temperatures and temperature gradients buildup from an isothermal state to the level shown in Figure 3. Transverse duct temperature gradients cause the assemblies to bow and the resultant motion changes the core reactivity level.

The ACLP gaps (interassembly and peripheral) are chosen to limit assembly motions which would add positive reactivity. Likewise, locating the central of the three load planes above the core promotes negative assembly motion reactivity feedback when the reactor is at power. This occurs because at-power, the ACLP gaps in the fuel region assemblies are closed and the active core zone of the high worth outer fuel region assemblies are forced to bow outward for an increase in power.

In addition to limiting assembly motions due to thermal bowing, the lower core former ring serves as a safeguard against any spurious reactivity insertions due to assembly sticking and slipping at the two load planes. Furthermore, the load pads are coated with a hard surface, low friction chromium carbide coating to minimize the occurrence of a stick-slip phenomenon.

Interassembly Loads

Contact loads between adjacent assemblies arise due to the three environmental sources discussed in the Introduction: thermal, neutron flux and seismic. Figure 6 illustrates the interassembly contact and load pattern established at the ACLP and TLP due to the start-of-life duct temperatures of Figure 3. Utilizing the symmetry in the core arrangement and environment, core restraint evaluations are performed for a 30° sector using the NUBOW-3D computer program⁽²⁾ and employing the analysis techniques discussed in Reference 3. Figure 6 shows that the temperature gradients at the fuel radial blanket interface play a dominant role in establishing interassembly load and contact patterns. Assemblies inboard of the fuel-radial blanket interface are compacted inward toward the reactor centerline. The radial blanket and radial shielding assemblies are displaced outward against the lower and upper core former rings. Interassembly contact loads tend to concentrate in a ring of assemblies extending from the sixth to the tenth radial rows at the ACLP. Outboard of row 10, the interassembly loads are generally radial in nature out to the core former rings. With irradiation (the action of neutron flux over time), the interassembly contact pattern remains generally the same, however, the level of the local pattern is predicted to decrease or increase depending on the dominant irradiation deformation mechanism (creep or swelling). This is discussed further in Section 4.4. The ACLP load pad is the critical elevation for design against core restraint loads. Circumferential load pads are sized to provide adequate structural margin against a combination of normal and design transient core restraint loads, secondary loading due to design transient temperatures and seismic interassembly loads.

When the reactor is brought off-power for refueling the core assemblies retain a residual bowing shape due to on-power irradiation structural effects. Restraint provided by the core former rings results in off-power interassembly

load plane contact loads. The magnitude of the contact loads must be assessed in defining the push/pull capability of the core assembly refueling equipment. Likewise, interassembly loads must be limited to prevent galling at the load plane surfaces. Refueling loads are limited by making the interassembly load plane gaps sufficiently large to avoid exceeding conflicting requirements: reactivity at the ACLP, alignment at the TLP.

Alignment

Misalignment of the assembly top ends from their theoretical pitch positions is limited in order to permit the refueling equipment to locate the assemblies at refueling and to limit side loads on the control assembly driveline which could adversely affect reactor shutdown. The main parameters which determine that alignment considerations are satisfied are the interassembly and peripheral gaps at the TLP.

Irradiation Effects

Stainless steel is the typical structural material for fast reactor core assemblies. In CRBRP, the core assembly ducts will be fabricated from 20% cold worked AISI 316 stainless steel. Extensive small sample and full size component tests have shown that this material exhibits swelling and creep during irradiation. Swelling of 20% CW 316 stainless steel initiates following an incubation period in the core flux environment. For duct temperatures in the range of Figure 3, the swelling rate increases with temperature. The overall swelling at any location is nearly proportional to the product of the swelling rate and the difference between the actual fast fluence (flux X time) and the incubation fluence. The irradiation creep strain at a given location depends on the local temperature, neutron flux and stress state. A more detailed discussion of irradiation creep and swelling on core assembly ducts is presented in Reference 4. The overall effects of these phenomena on core restraint performance are examined below.

Figure 7 illustrates the primary deformation effects of swelling and creep on a core assembly. Duct dilation refers to the duct bulging at the active core elevation under the combined action of creep and swelling. Primary loading of

the duct due to the coolant pressure as well as high temperature and flux are the active factors for this effect. Duct bowing occurs as a result of the differential swelling gradient across the duct. This gradient is especially pronounced in assemblies at the fuel-radial blanket interface where temperature and flux gradients are steepest. Axial growth of the duct is primarily due to the axial swelling strains. In the CKBRP core, limited amounts of each deformation type can be accommodated during core assembly lifetimes without impeding the functions of the core restraint and interfacing systems. This is accomplished by providing adequate gaps between ducts and above the assemblies to accommodate duct bowing dilation and axial growth. The provision of three load planes at the elevations selected (inlet nozzle, ACLP and TLP) permits irradiation creep to be utilized to offset the effects of swelling induced duct bowing. The ACLP is located at an elevation sufficiently above the active core where dilation effects are negligible.

CORE WIDE IRRADIATION EFFECTS

Figure 8 illustrates the change in the on-power assembly bowing pattern during equilibrium fuel assembly life along a radial spoke extending from the core centerline to the core former structure. The dotted lines are shown for selected assemblies to illustrate the pattern of irradiation induced bowing deformation. Irradiation induced bowing is worst in the outer fuel region as a result of peak temperature and flux levels and gradients.

Off power loading effects due to irradiation induced bowing at the core formers are illustrated in Figure 9. The initial load buildup is due to the relaxation of thermal bowing stresses by irradiation creep which produces the initial bowing distortion in the core assemblies. Beyond 125 days, the ACLP core former loads diminish and the TLP core former loads increase slightly as swelling bows the assemblies in a direction opposite to that caused by irradiation creep. Another illustration of core wide effects is shown in Figure 10 where the assembly motion reactivity at power changes with fuel assembly life. The pattern is primarily associated with the motion of the high worth outer fuel assemblies. The initial reactivity drop is due to irradiation creep relaxation of the thermally induced bow. However, as the ducts begin to swell and bow inward, reactivity is added to the core. At approximately 300 days, mid-core duct contact due to dilation initiates between the outer fuel assemblies impeding their further inward displacement and assembly motion reactivity change.

From the core wide standpoint, studies to date show that irradiation induced effects can be accommodated. Reactivity effects are minor. Loads are self limiting as creep and swelling act to offset each other. Duct dilation effects are limited as neighboring ducts come into contact cancelling the primary load driven creep bulge. Work is continuing on the refueling and seismic consequences of duct to duct contact patterns which may develop.

The CRBRP core restraint system is derived from the FFTF core restraint design. With operation of the FFTF reactor now in progress operational data on duct performance, core reactivity and refueling loads will be used to confirm the conclusions drawn on the adequacy of the CRBRP core restraint system design.

ALTERNATE CORE RESTRAINT CONCEPTS

In smaller sized fast reactor cores there is a greater sensitivity of core reactivity to assembly displacements. Consequently, earlier fast reactor designs emphasized control of assembly motion. In EBR-11 and Phenix^(5,6) this was achieved by providing a greater degree of assembly restraint at the inlet nozzle but permitting more freedom to bow at the assembly top end. This concept is sometimes referred to as the "free standing" or "free bow" concept. In this concept the reactor assembly inlet nozzle consists of a lengthy stalk which is closely supported by a core support grid near the bottom and top of the stalk. Because of this, the lower end of the assembly is not free to pivot as in the limited free bow concept. In EBR-11, spacer buttons are located at the mid-core elevation while in Phenix the buttons are located immediately above the core. During a rise to power, interassembly contact at the spacer button plane is established and the assemblies are displaced outward adding negative reactivity. Top load pads are not provided in this concept and theoretically no contact at the top end occurs between assemblies due to thermal bowing. In practice, however, irradiation induced bowing will cause the top ends of the assemblies to contact at specific locations. Peripheral support of the core is provided by several rows of reflector or shielding assemblies whose inlet nozzles are restrained similar to the fuel assemblies. On the periphery at the elevation of the assembly top ends, a ring mounted to the core barrel acts as a stop for core seismic motions.

A disadvantage of the free standing concept is that the locations of the assembly support points do not permit irradiation creep to be utilized to offset swelling induced bowing. Consequently, this concept is bowing limited especially at the outer fuel boundary where the temperature and flux gradients are the steepest. This can be illustrated using the results of a single assembly analysis of the free bow and limited free bow concepts at a fuel radial blanket interface. Figure 11⁽⁷⁾ shows the sum of the lateral forces acting on the assemblies at refueling conditions as a function of time in life. Initially, loads build up due to irradiation creep in the limited free bow concept. However, when swelling initiates, the refueling load reduces as swelling causes the irradiation bow to reverse. The load increases again but

stabilizes at a relatively low level when creep balance of swelling is achieved. At the end-of-life, the assembly would be relatively straight with little bowing distortion. In the free bow concept the irradiation creep effect is small. Therefore, the refueling load induced by swelling builds up to a high level before sufficient creep occurs to offset swelling. Similarly, the high fluence bowing distortion of the free bow restraint assembly is excessive because of the small creep opposition of swelling. This analysis of the free bow concept has been verified by recent operations in EBR-II where assembly bowing distortion and refueling difficulties have been experienced in the reflector region.⁽⁸⁾ Duct bowing will be less of a problem if duct alloys are developed in which swelling is negligible. However, for 20% CW 316 stainless steel duct bowing is a life limiting factor for the free bow concept.

The allowance of generous interassembly gaps at the top end also makes the assurance of control rod insertion for highly unlikely design transients more difficult. The control rod driveline must be capable of accommodating much higher frictional forces arising from the misalignment of the core with the upper internals structure during a seismic event.

CONCLUSION

To achieve current goal core assembly lifetimes, the duct structural material must be irradiated to a level where irradiation induced distortion effects are significant. This is taken into account in the design of the core restraint system together with the need to meet system functional requirements. Given present day duct reference materials which exhibit both creep and swelling during irradiation, the limited free bow concept as utilized in CRBRP and FFTF permits both system and duct lifetime objectives to be met. As reactor core sizes are increased to commercial levels, the relative importance of the functional requirements will change but all will still need to be considered. Advanced materials with reduced creep and swelling will be used in future designs. However, operating the material to its limits will still require that irradiation induced effects be considered. Consequently, given that the safety and operational objectives of current reactor designs will be retained in future designs, it is expected that future core restraint designs will incorporate the major elements of the limited free bow design as employed in the CRBRP.

ACKNOWLEDGEMENT

This work was performed under U.S. DOE Contract EY076-C-15-2395.

NOTATIONS

B	Blanket Assembly
C	Control Assembly
F	Fuel Assembly
IB	Inner Blanket Assembly
RB	Radial Blanket Assembly
R,RS	Removable Radial Shield Assembly

REFERENCES

1. "Clinch River Breeder Reactor Plant Project 1979 Technical Progress Report," CRBRP-ARD-0254, pp. 79-93. (Availability: U.S. DOE Technical Information Center)
2. Kalinowski, J. E. and Swanson, D. V., "Nonlinear Analysis of the Core Restraint System," CRBRP-PMC76-06, pp. 7-30. (Availability: U.S. DOE Technical Information Center)
3. McLennan, G. A., "NUBOW-3D (Inelastic): A FORTRAN Program for the Static Three-Dimensional Structural Analysis of Bowed Reactor Cores."
4. Foster, J. P. and Boltax, A., "Fast Reactor Design Applications of Irradiation Creep and Swelling Data," Joint Conference of the Pressure Vessels and Piping, Materials, Nuclear Engineering, Solar Energy Divisions, June, 1981.
5. "Analyses of EBR-II Core-Component Deformations," ANL-7986, January 1973. (Availability: U.S. DOE Technical Information Center)
6. "Phenix, Prototype Fast-Neutron Nuclear Power Station," AEC-tr-7130, February 1970. (Availability: U.S. DOE Technical Information Center)
7. "Core Restraint Development Quarterly Progress Report for the Period Ending May 31, 1979," WARD-CR-94000-3, pp. 23-66. (Availability: U.S. DOE Technical Information Center)
8. Shields, J. A., "Bow in Experimental Breeder Reactor II Reflector Assemblies," Nuclear Technology, Vol. 52, February 1981, pp. 214-227.

1756-2

Figure 1. Schematic of Reactor

SYMBOL	COMPONENT NAME	NUMBER
FUEL ASSEMBLY	156
INNER BLANKET ASSEMBLY	76
RADIAL BLANKET ASSEMBLY	132
ALTERNATE FUEL/BLANKET ASSEMBLY	6
PRIMARY CONTROL ASSEMBLY	9
SECONDARY CONTROL ASSEMBLY	6

Figure 2. Reactor Core Map

A. AXIAL PROFILE

B. RADIAL PROFILE

Figure 3. Typical Duct Temperature Profiles

5412-1

Figure 4. Radial Fast Flux Distributions at Core Midplane

S412-2

Figure 5. CRBRP Core Restraint System Mechanical Interfaces

Figure 6. Load Pad Gaps and Forces at 0 FPD

5412-3

Figure 7. Irradiation Induced Assembly Deformations

Figure 8. On-Power Restrained Bow Shape Changes During Fuel Assembly Life

5412-5

Figure 9. Core Former Off-Power Loads

5412-6

Figure 10. On-Power Bowing Reactivity

5412-7

Figure 11. Total Lateral Duct Force at Refueling on an Outer Fuel Assembly

5412-8