Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division X Challenges of New Reactors

DESIGN AND ANALYSIS OF THE CORE RESTRAINT SYSTEM FOR A SMALL MODULAR FAST REACTOR

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ABSTRACT

A typical fast reactor core assembly is composed of a closely packed hexagonal arrangement of fueled, control, blanket reflector, and shielding assemblies. As the fuel assemblies are brought closer together radially, the reactivity increases whereas the reverse effect occurs as fuel assemblies move apart. This change in reactivity is either a positive or negative structural reactivity feedback and is one of the essential features of an inherently safe fast reactor design. This reactivity feedback depends upon the method that the core assemblies are supported and restrained. In order to properly design and analyze a core restraint design, the motion of the fuel assemblies both over time and during power transients needs to be understood and predictable. The assembly ducts are exposed to both a radial temperature and neutron flux distribution. The temperature gradients across the ducts initially cause the ducts to bow causing contact between adjacent ducts through load pads situated above the core and at the top of the duct. The subsequent contact creates stresses from which thermal and irradiation creep tend to relax those contact forces over time. At the same time, differential irradiation swelling due to the fast neutron flux gradient causes inelastic bowing that tends to increase the contact forces over time. The design and analysis of a core restraint system for a small modular fast reactor, the AFR100, is presented showing that the desired core restraint performance is achieved over the proposed 30 year core life.

INTRODUCTION

Alignment of fuel assemblies is important to fast reactor cores. This is needed to assure proper control rod function as well as facilitate fuel handling operations. In addition, the reactivity of fast reactors is very sensitive to fuel motion. Sources of fuel motion include seismic events and core assembly bowing due to thermal gradients in the assembly hexcans. Ideally, it would be desirable to assemble the core assemblies into a tight and constrained array to control position. This however, is not an easy solution as irradiation swelling causes bowing and dilation of the assembly hexcans resulting in contact between assemblies and eventually leads to refueling difficulties.

The fuel elements of the Experimental Breeder Reactor-I (EBR-1) were fixed at the top and bottom. During a test, a radial thermal gradient (decreasing radially outward from the center) caused the center of the fuel to bow inward toward the core center dramatically increasing reactivity resulting in the core overheating and subsequent melting. This incident demonstrated the importance of understanding fast reactor core mechanics and the importance of preventing unrestrained inward bowing of the fuel.

The Experimental Breeder Reactor-II (EBR-II) core was designed with fuel ducts containing outward dimples located near the core centerline that acted as spacers to avoid core compaction. This was a primary design consideration in view of the positive reactivity coefficient observed in EBR-I (Koch, 1978). The design of EBR-II was completed before awareness of void swelling and irradiation creep in austenitic stainless steels. For EBR-II, the combined effects of swelling at the level of the dimples along with swelling related inward bowing in the reflector rows created refueling problems and a positive bowing reactivity coefficient. The refueling issues required fuel to be changed out before excessive swelling occurred thereby limiting the fuel burn-up. It was later found that irradiation creep strain due to the thermal gradient induced stresses acted in opposition to the swelling (Walter, 1979). This supported the idea that an engineered core restraint could create favorable stresses within the core assembly leading to irradiation creep strains that counteract the swelling strains.

The core restraint designs for PHENIX, BN-350, and PFR were substantially designed prior to a better quantified understanding and prediction of duct swelling behavior (Boltax, 1992) such that these designs were not changed greatly. The only modification to the Phenix core restraint design was to relocate the mid-core load pads to above the core in a region with significantly less neutron fluence (Huebotter, 1972). Without good predictive knowledge, these reactors core restraint systems were to have a free flowering core and leave gaps for swelling. They wanted to achieve high burn-up and still be able to remove the fuel. These gaps allow unrestrained motion of the core.

The Fast Flux Test Facility (FFTF) was the first reactor designed with knowledge of the irradiation effects on core materials. Design studies revealed that void selling and irradiation creep limited the core lifetime and that the core restraint system design had a significant effect (Boltax, 1992).

This led to the limited free bow concept which was implemented in FFTF. FFTF designers observed that a relationship between swelling and creep could be used to reduce deformation. Following from the FFTF experience, the limited free bow concept was applied during the design of the Clinch River Breeder Reactor (CRBR) as well.

A conceptual small modular reactor, the AFR100, has been presented in (Grandy, et al., 2013) which includes vented and non-vented versions of the fuel assembly. The vented and non-vented cores are identical to the top of the core above which the vented core includes a venting device and the non-vented core has a larger gas plenum. The non-vented core is then significantly taller than the vented core.

The NUBOW-3D code was used to develop and analyze the preliminary core restraint design of which the details are presented in this paper. The NUBOW-3D code is a special purpose structural analysis software developed at ANL to analyze the core bowing over the life of a reactor. The code models bowing effects due to thermal, irradiation and thermal creep, and irradiation swelling using duct temperature and neutron flux calculated in physics codes as input. Additionally, using reactivity displacement worth's calculated from physics codes, NUBOW-3D calculates an estimate of the net reactivity change due to duct bowing displacements. These features allow NUBOW-3D to be used as an analysis and design tool for the design of a core restraint system.

The two common approaches to the restraint system design as discussed above are *free flowering* and *limited free bow*. Through the use of a rigid restraint ring, the limited free bow limits core motion to small amounts and provides tight alignment. The stresses induced by contacting the restraint ring provide irradiation creep which works in opposition to the irradiation swelling (Shields, 1981). Additionally the limited free bow system has been shown to provide better inherent safety characteristics (Kamal, et al., 1986). Bowing of core assemblies causes significant changes in reactivity during start-up, overpower, and loss of flow without scram (Moran, 1986). This work describes the design and analysis of a limited free bow core restraint design for the AFR-100.

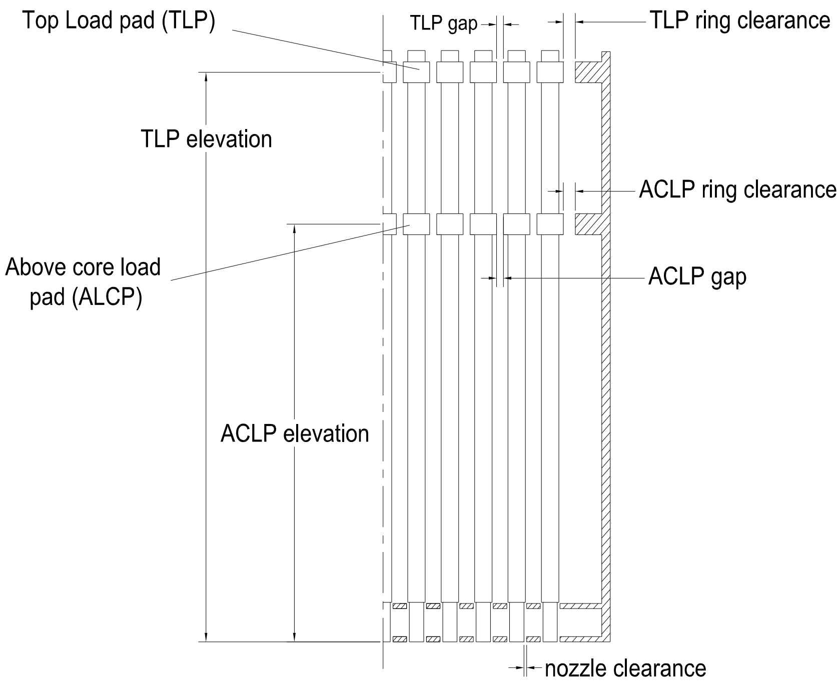

Figure 1 – Schematic representation of core restraint system components and important dimensions.

FUNCTION OF LIMITED FREE-BOW CORE RESTRAINT SYSTEM

The main components of a limited free bow core restraint system are shown in Figure 1. The limited free bow system is characterized by load pads on the ducts at the top (TLP) and in the region above the core (ACLP) along with a restraint ring at the TLP. The load pads serve as preferential contact points between the ducts and also provide clearance for assembly duct dilation due to swelling and creep. The thickness at the load pads is only marginally thicker than the main duct body (this is exaggerated for clarity in the figure).

The limited free bow core restraint system serves three functions. First, it controls the radial position of the core and maintains alignment between in- and above-core components. Second, it limits motion due to seismic events. Third, it provides a constraint on duct bowing such that negative reactivity feedback occurs in the event of an over power transient. These objectives must be met within the constraint that duct to duct loading (resulting from bowed ducts in contact) is kept within allowable limits. This constraint must include the time dependent inelastic bowing effects due to irradiation (and thermal) creep and swelling effects. This inelastic bowing leaves residual contact forces between assemblies at refueling temperatures which when considered with friction effects create additional loading during refueling. The allowable refueling loads provide a further design constraint. The reactivity response and resulting forces on the load pads are dependent on many system variables. Many of these variables are fixed from the point of view of restraint design, (core size, pitch, temperature and flux inputs, etc.). The elevation of the load pads, clearances between the individual load pads, and TLP restraint ring clearance are key factors that drive the performance of the core restraint system. These variables are shown in Figure 1.

Temperature changes in the core during power-up and power-down situations create uniform expansion in the core as well as increase/decrease thermal gradients that persist (both radially and axially) through the core. The thermal gradients can introduce significant bending effects. The core restraint system is designed to provide inherent protection against such over power events by taking advantage of thermally induced bending action of the fuel ducts (Moran, 1986). This is illustrated in Figure 2 which shows a row of three cantilevered ducts located symmetrically about the center of a core and in a radially varying thermal gradient. A two point support at the grid plate and sufficient nozzle clearance allow rotation at the support. Figure 2a shows the nominal configuration of the ducts with no temperature gradient. As a thermal gradient develops (increasing temperature as distance from centerline decreases), the ducts begin to bow outward as shown in Figure 2b. Prior to contact with the restraint ring the duct bends away from the core centerline as the temperature increases and therefore reduces the reactivity. After contacting the top restraint ring only and as the temperature gradient increases, the center of the duct bows inward which temporarily increases the reactivity. As the gradient increases, the inward bowing continues until the ducts contact at the ACLP. When the interior ducts all contact at the ACLP, the reactor is 'locked-up' and no further compaction can occur. Subsequent increased thermal gradients cause a reverse bowing below the ACLP moving the core region away from the core center as illustrated in Figure 2c. At this point the reactivity generally decreases with constant negative slope as temperature increases. The core restraint system is designed to have this lock-up occur below the nominal operating point. This description is idealized and assumes a strictly decreasing radial gradient in each duct. The radial temperature profile for the AFR-100 is shown in Figure 6 and varies from this ideal.

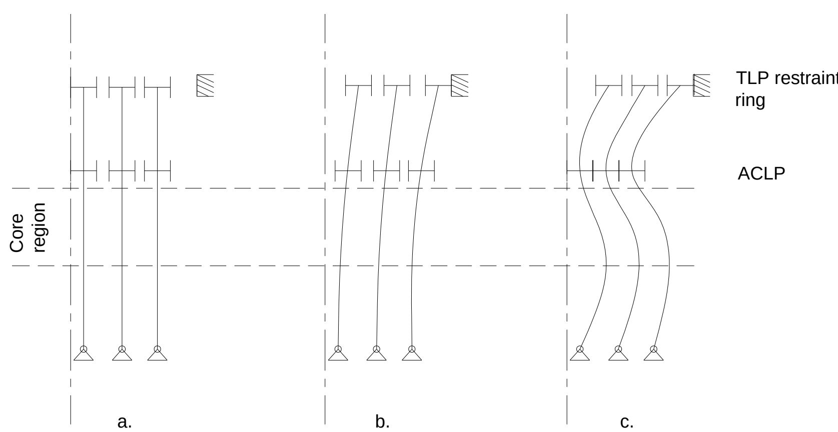

Figure 2 – Schematic illustration of limited free bow core restraint concept.

CORE RESTRAINT DESIGN

The core restraint conceptual design details are described in Figure 3 and Figure 4. The corresponding design values for the non-vented core are listed in Table 1. Note that these values are at nominal room temperature (21°C). For the analysis presented in this report, the ducts and load pads are assumed to be made of HT-9 whereas the restraint ring and duct supporting grid plate are all assumed to be made from alloy SS-316. Due to the significantly larger thermal expansion of SS-316 as compared to HT-9, the resulting load pad gaps will be larger at the refueling temperature of 205°C. Figure 3 shows the load pad dimensions and elevations on a duct. The assembly is made up of an extruded hexagonal duct, a handling socket welded to the top, and an inlet nozzle welded to the bottom. The handling socket is configured with a receptacle for the fuel handling machine and incorporates the TLP in the design. The values listed in Table 1 are used in the analysis presented subsequently.

Table 1 Key dimensions related to the core restraint design (evaluated at T_{ref} = 21°C)

Dim-ension	***Description***	***Load case*** ***non-vented core [in]***
		NV-r1
A	Nozzle length	11.8
B	ACLP elevation	86
C	TLP elevation	158
D	duct length	165.8
E	Nozzle diameter	5.118
F	duct wall thickness	0.118
G	ACLP wall thickness	0.170
	TLP wall thickness	0.170
H	duct across the flats	6.378
J	TLP across the flat	6.490
K	ACLP across the flat	6.490
M	load pad height	4
N	ACLP core former clearance at T_{ref}	0.25
P	ACLP load pad gap at T_{ref}	0.006
Q	TLP core former clearance at T_{ref}	0.036
R	TLP load pad gap at T_{ref}	0.006
	upper nozzle receptacle diameter	5.128
	lower nozzle receptacle diameter	5.128

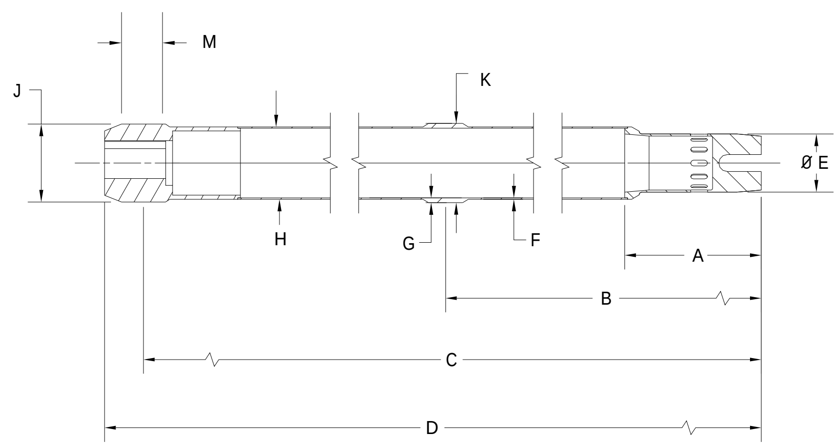

Figure 3 – Schematic for duct dimensions.

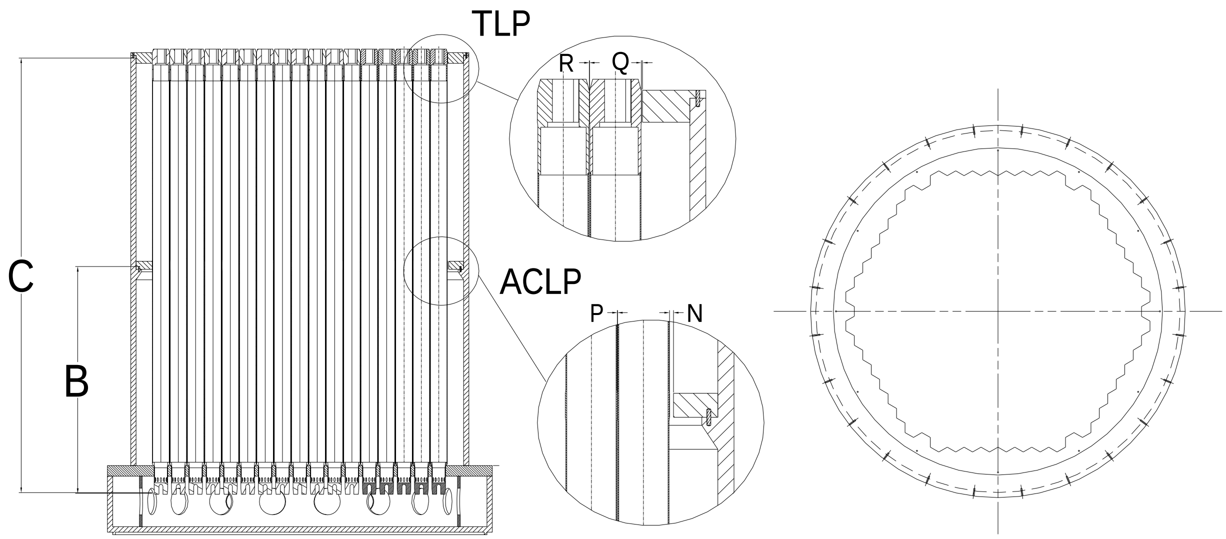

Figure 4 – Details of the core restraint system.

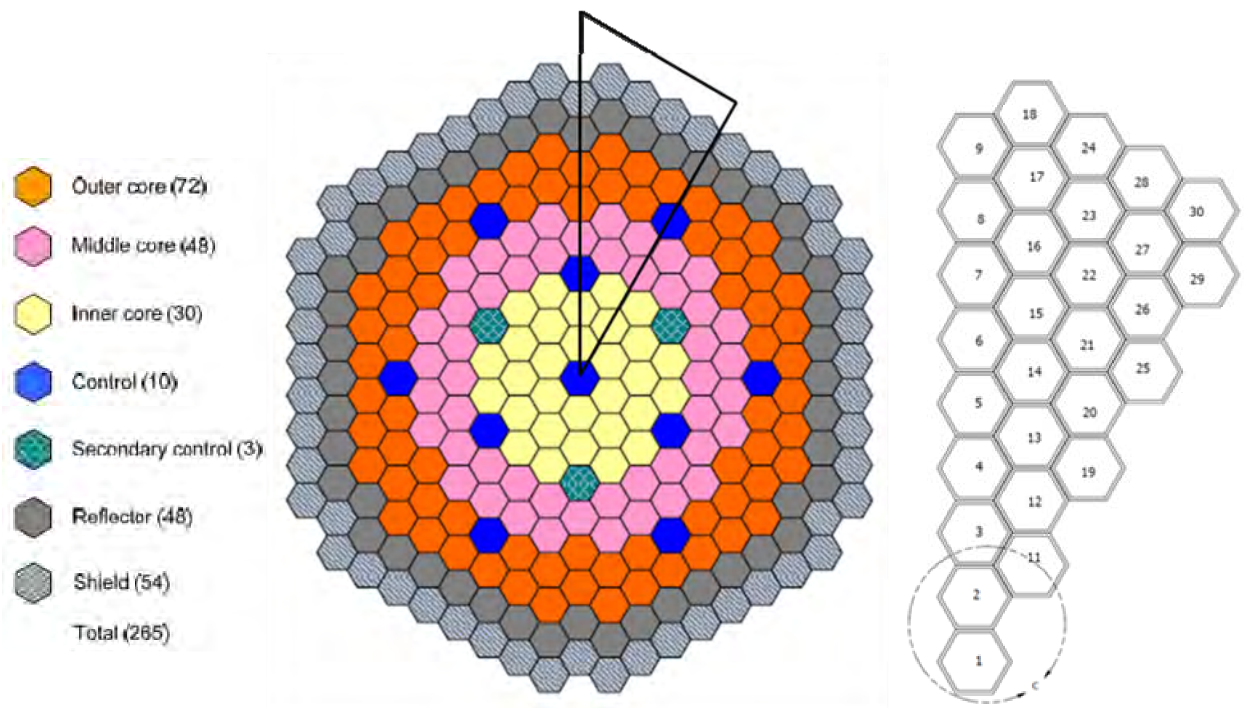

Figure 5 – AFR100 non-vented core layout (from (Grandy, et al., 2013)) and 30 degree sector used in NUBOW analysis.

Table 2 Parameters used for the NUBOW system description.

Description	Value
Pitch	16.5cm
Reference temperature	21 ° C
Inlet Temperature at zero power	205 °C
Inlet Temperature at full power	395 °C
Bulk Outlet Temperature	550 °C

ANALYSIS

The analysis and design contained within this document is based upon a 60 year plant design lifetime with 30 year refueling schedule. The NUBOW analysis is run over 30 years. Some of the system variables of the NUBOW model are listed in Table 2. Figure 5 depicts the core layout and the NUBOW representation of the core assuming 30 degree symmetry. The duct geometry and corresponding values are shown in Figure 3 and Table 1 respectively. The values in Table 1 and Table 2 are a combination of fixed inputs (based on core design) and those that can be altered to obtain better core restraint performance. In particular, the load pad thickness and location along with the restraint ring and nozzle clearances are determined for the purposes of the core restraint performance within the constraints such as existing pitch, duct thickness, and length. The values in Table 2 were arrived at after some iteration of the various parameters.

As part of the input, NUBOW uses duct temperatures and flux obtained from the physics analysis codes SE-II and DIF-3D respectively. The assembly duct temperatures were interpolated from values determined using the Super Energy-II code. Two temperature sets were provided, one at the 'beginning of cycle' (BOC) and one at the 'end of cycle' (EOC). Temperatures at intermediate times are linearly interpolated between the BOC and EOC temperatures. The neutron flux is calculated using the DIF3D physics code. Flux files were provided for the BOC, 'middle of cycle' (MOC), and EOC portions of the cycle. The MOC corresponds to 17.5 years (6400 days) and the EOC corresponds to 30 years (10950 days).

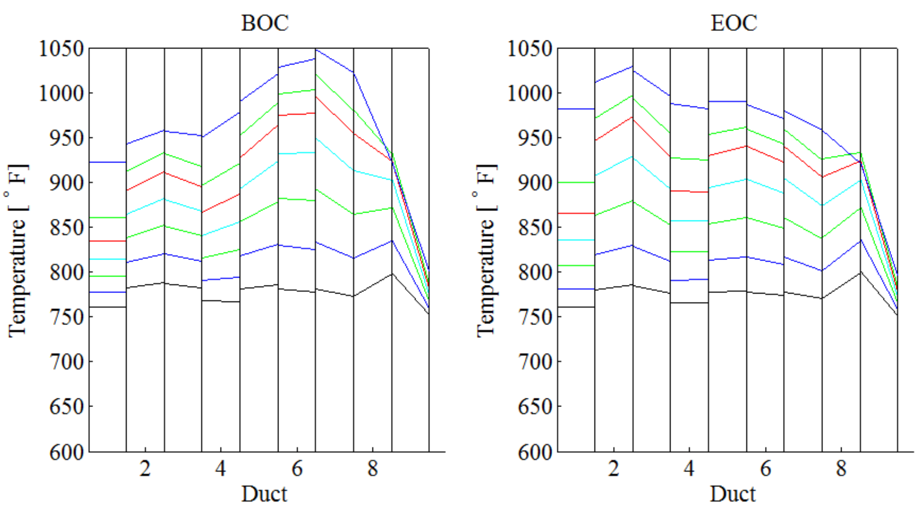

Figure 6 – Radial temperature distribution across ducts 1-9 for BOC and EOC. Colors correspond to different axial points along the duct.

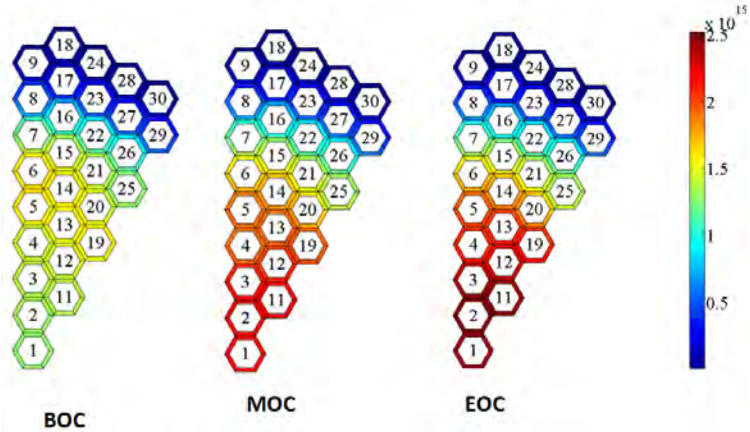

Figure 7 – Flux at mid-core (flux node 5, z = 59.2in) for the beginning, middle, and end of cycle.

DISCUSSION OF RESULTS

The main objective of the limited free bow core restraint design is to obtain lock-up of the core at the ACLP prior to reaching full power. This provides a challenge for the AFR-100 design due to two factors. The significantly larger coefficient of thermal expansion of the SS316 grid plate as compared to that of the HT-9 duct material causes the gaps to grow with increasing temperature such as during a power transient. The second factor is the decreasing thermal gradient in the outer rows as the cycle progresses (see Figure 6). This produces a smaller bending moment further reducing the tendency for the core to lock-up. To achieve the desired lock-up, the restraint is designed with small clearances. Figure 9 shows the deformation response at normal operating power, PFR (power to flow ratio)=1 and PFR=2 to illustrate the performance of the restraint system to an over-power transient. It can be seen that from the initial operating position, the core assemblies move away from the core. Analysis of the reactivity response will be performed at a later date.

Figure 8 shows the resultant duct displacements at the load pads at the EOC (10950 days) at P/F=0 to simulate the condition at refueling. As can be seen from the figure, the ducts are in a deformed state due to the inelastic bowing effects over the life of the core. The maximum refueling force of 488 lbf occurs between ducts 16 and 17. This load is within the capacity of the refueling machine.

Figure 10 shows the duct displacements and resulting contact forces at the BOC and EOC respectively. In the initial stages, the greatest compaction at the ACLP occurs in the outer core region. This is explained by observing the temperature distribution at the BOC as shown in Figure 6. The temperatures are highest in the outer core region which through thermal expansion causes bridging to occur in the circumferential direction of the core in the outer core region. The core is locked albeit lightly in the central core due to the reduction of transmitted force through the outer core bridged assemblies. As time passes the contact forces first start to relax through creep until irradiation swelling occurs which act in opposition to the creep relaxation and adds to the outward bow of the core. Again referring to Figure 6, we see that over time, the temperature distribution shifts inward with the inner core becoming hotter than the outer core. This results in an evening out of the forces at the ACLP toward the end of the cycle. The core remains locked up while at the operating temperature throughout the entire cycle and the contact forces are all within acceptable limits.

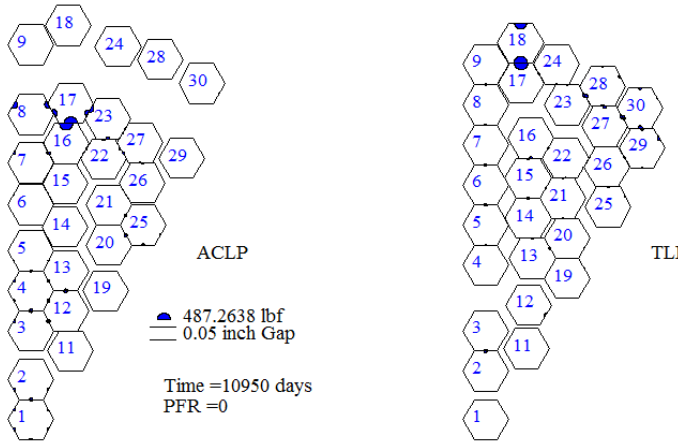

Figure 8 – Residual inelastic deformations and resulting contact loads at refueling temperatures at EOC.

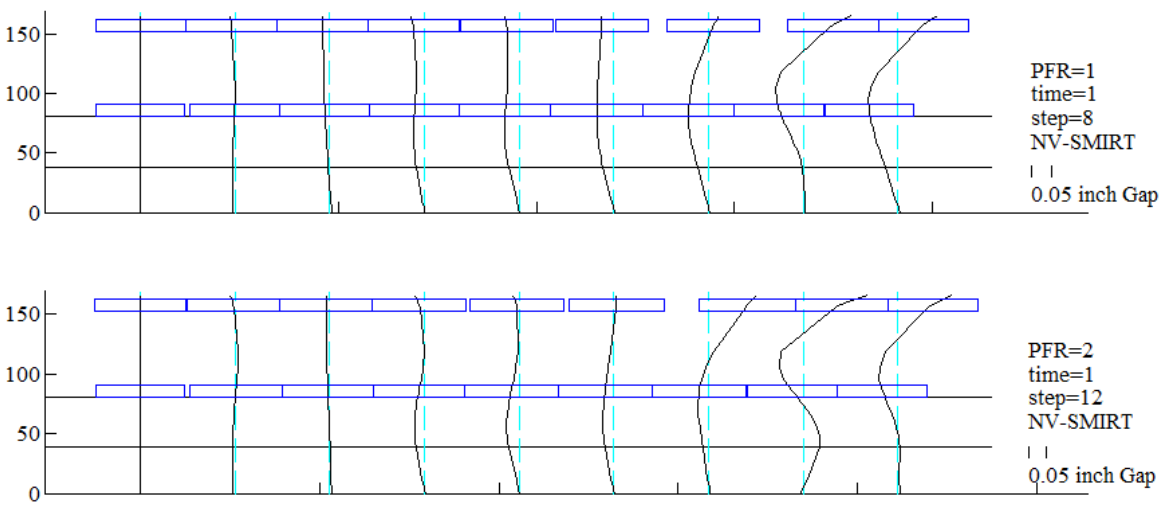

Figure 9 Duct deformations for radial row showing exaggerated duct deflections and load pads (blue rectangles) at P/F=1 (top) and P/F=2 (bottom).

CONCLUSIONS

The analysis of the core restraint system was performed using the NUBOW-3D code. The analysis was run over a 10950 day cycle (30 years). Power ramps from P/F= 0 to 2.0 were run at various times in the cycle to evaluate the core restraint performance with respect to an over power scenario such as a LOF. During the power ramps, the core moves radially outward. During nominal operation, the core remains locked limiting core motion. The resulting forces in the zero power state due to the contact resulting from inelastic duct deformations were examined at various points in the cycle to determine the maximum refueling loads. The maximum refueling forces are found to be within the capacity of the refueling machine.

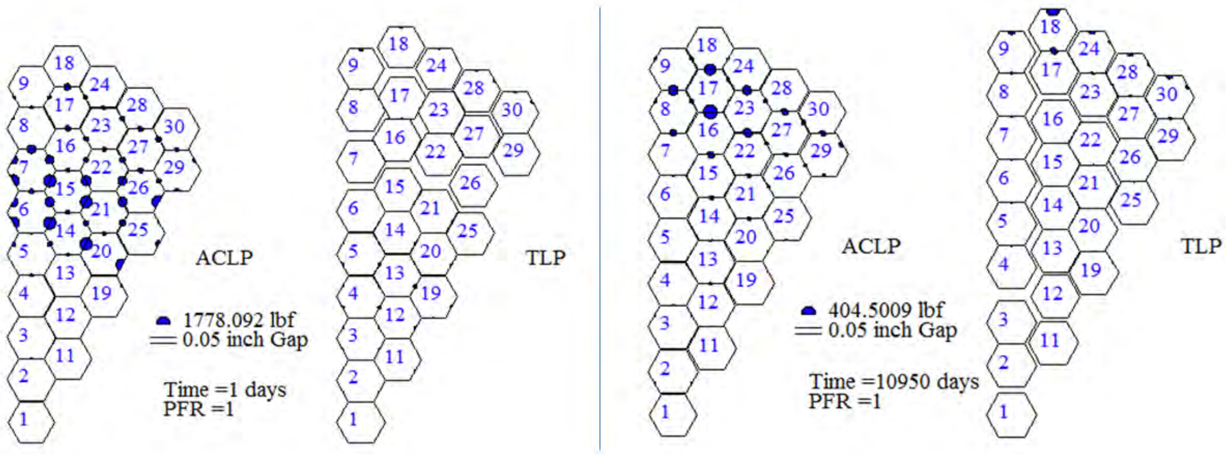

Figure 10 Exaggerated displacements and contact forces at the ACLP and TLP for days 0 (left) and 10950 (right) at P/F=1.

ACKNOWLEDGEMENT

Argonne National Laboratory's work was supported by the U.S. Department of Energy, Office of Nuclear Energy, under contract DE-AC02-06CH11357.

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