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# MARK-B11 FUEL ASSEMBLY DESIGN TOPICAL REPORT

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## 1. INTRODUCTION

Following four years of thorough design development and testing, the Mark-B11 fuel assembly is the most recent addition to FCF's Mark-B fuel product line, utilized in Babcock & Wilcox (B&W) 177 fuel assembly-designed reactors. The Mark-B11 fuel design features a smaller-diameter fuel rod to reduce enriched uranium requirements for both transition and equilibrium cycles and mixing vane grids that provide superior thermal margins.

Four Mark-B11 lead assemblies have operated successfully since installation into cycle sixteen of Duke Power Oconee Nuclear Unit 2 reactor in April 1996. Subsequent batch implementation of the Mark-B11 fuel assembly design is planned for all three Duke Power Oconee Nuclear Units beginning with cycle nineteen of Oconee Nuclear Unit 3 in 1999.

The Mark-B11 fuel assembly is designed to achieve a peak fuel rod burnup of 62,000 MWd/mtU, which is consistent with the burnup limits approved in BAW-10186P-A, "Extended Burnup Evaluation" [1].

This topical report contains the licensing bases for the Mark-B11 fuel assembly which provide justification for batch implementation. This report is divided into eight major sections, each addressing a significant aspect of the Mark-B11 fuel assembly, focusing on the primary new features, which include the reduced fuel rod diameter, flow mixing intermediate grids, and improved grid restraint system. Section 3 describes the Mark-B11 design, highlighting the standard and new distinguishing features. Section 4 presents the scope and results of the fuel assembly and component design verification testing. Sections 5 and 6 provide the fuel assembly and fuel rod mechanical evaluations respectively, which address the key structural issues as affected by the primary Mark-B11 design features. The evaluation of the thermal-hydraulic performance of the Mark-B11 assembly is presented in section 7, which addresses the mixing grid and rod diameter effects. Sections 8 and 9 provide the nuclear design and ECCS evaluations, respectively. Section 10 is an overall assessment of the impact of the Mark-B11 fuel assemblies on plant operations.

## 2. SUMMARY

The Mark-B11 fuel assembly is a natural progression of the Mark-BZ fuel design which offers improvements in departure from nucleate boiling (DNB) margins and fuel cycle economy while possessing many proven features of earlier Mark-BZ fuel assembly designs. Proven features of the Mark-BZ fuel design utilized for the Mark-B11 design include keyable spacer grids, floating grid restraint system, flow-optimized control rod guide tube assembly, quick disconnect upper end fitting assembly, anti-straddle lower end fitting assembly, Zircaloy intermediate grids, cruciform holddown spring assembly, and debris resistant fuel rod lower end plug.

The specific Mark-B11 design features that enhance the design's nuclear, thermal-hydraulic and mechanical performance include the following:

1. Reduced diameter fuel rod,
2. Flow mixing vanes on five of the six intermediate spacer grids, and
3. Improved grid restraint system.

Improved thermal mixing with the mixing vane grids increases DNB margins, which provides for more aggressive fuel cycle designs. Increased uranium utilization is also gained through the use of the reduced fuel pin diameter, providing for improved fuel cycle economy. An improved grid restraint system provides additional structural strength to accommodate the increased hydraulic loads attributed to the flow mixing grids.

The Mark-B11 design verification program addressed key factors associated with the incorporation of the three primary features of the Mark-B11 assembly. The results from the prototype testing and analyses in the mechanical, thermal-hydraulic, core physics, and ECCS areas verify that the Mark-B11 fuel assembly is a safe and reliable design. The successful operation to date of the Mark-B11 lead test assemblies (LTAs) further supports the results of the design verification program. In addition, the extensive operating experience of the Mark-BZ and the Mark-BW (17x17 design for Westinghouse-designed reactors) designs provides a performance data base for many of the critical design features which are common to the Mark-B11 fuel assembly and all FCF fuel designs. These key features, which include the floating intermediate spacer grid and seated fuel rod design concepts, serve to provide well predicted and consistent irradiation performance and models and further enhance the Mark-B11 design bases.

Based on the results of extensive testing, analysis, and reactor performance, the Mark-B11 is acceptable for batch implementation in B&W designed Pressurized Water Reactors (PWRs).

# 3. MARK-B11 DESIGN DESCRIPTION

## 3.1 Fuel Assembly Design Description

The Mark-B11 fuel assembly comprises a 15x15 rod array specifically developed for use in B&W 177 fuel assembly designed nuclear reactors. The fuel assembly maintains the same interface compatibility and many of the reactor proven features of the resident Mark-BZ fuel. Figures 3.1 and 3.2 highlight the key design features of the Mark-B11 fuel assembly and fuel rod respectively, with those unique to the Mark-B11 design designated in bold type.

### 3.1.1 Standard Design Features

#### 3.1.1.1 Fuel Assembly

The Mark-B11 (as is the Mark-BZ ) is a conventional 15x15 fuel assembly designed specifically for Babcock & Wilcox-designed 177 fuel assembly pressurized water reactors (PWR). Within its 15x15 lattice arrangement are 16 low-tin Zircaloy-4 control rod guide tubes that attach to stainless steel upper and lower end fittings. The guide tubes contain side holes designed specifically to control guide tube bypass flow while providing adequate guide tube flow for control component cooling and guidance for control rod insertion. A full length low-tin Zircaloy-4 instrument tube occupies the center lattice position, which provides guidance for in core instrumentation and support for the grid restraint system.

The Mark-B11 fuel assembly utilizes eight spacer grids, which with the guide tubes, instrument tube, and end fittings, provide the structural cage for the Zircaloy clad fuel rod assemblies. The upper and lower end grid strips are made from Inconel 718. The six intermediate grids are constructed from fully annealed, low-tin Zircaloy-4. The remaining 208 lattice positions contain low-tin cold-worked stress-relieved Zircaloy-4 clad fuel rods that rest on the lower end fitting grillage and are laterally supported by the upper and lower end spacer grids and six intermediate spacer grids.

Just as with the Mark-BZ and all FCF designs, the Mark-B11 spacer grid design is keyable and utilizes hard/soft stops in the cells to support the fuel rod. The spacer grid consists of thin strips welded together in "egg crate" style forming an array of square cells. In each cell, protrusions or "stops" are formed into the cell walls. These cells are arranged in sets - hard stops on upper and lower edges to position the fuel rod, and a soft stop at mid-height of the opposite side to clamp the rod in place. A key holds the grid cells open during manufacturing so that the fuel rods can be slipped into the assembly, rather than being forced through the grids. The keying process prevents scratching or other damage to the fuel rod cladding. Once all the rods are in place, the keys are removed. This procedure also minimizes residual stresses in the rods as a result of manufacturing and thus serves to mitigate rod bow during operation. Mark-B11 end and intermediate grids maintain the same periphery lead-in features as used in the Mark-BZ design to ensure good fuel assembly-handling performance.

As with the Mark-BZ design, the Mark-B11 spacer grids are not mechanically attached to the control rod guide tubes. Thus, the grids are free to axially accommodate any differential growth between the fuel rods and guide tubes, i.e. free to "float". The spacer sleeves around the instrument tube are designed to control the vertical location of the intermediate grids. The vertical location of the spacer grids remains unchanged from previous Mark-BZ designs. This arrangement substantially reduces the axial forces on the guide tubes and fuel rods, and the resultant forces on the spacer grids. This feature is especially important during the early-in-life assembly operation when the fuel rod grip forces are relatively high. This feature coupled with the seated fuel rods serve to reduce guide tube distortion. Local distortion attributed to grid-to-guide tube fixity is minimized by the floating grids. Guide tube axial loads are reduced with the weight of the fuel rods passing directly to the lower end fitting thereby mitigating guide tube distortion.

Features on the guide tube assemblies constrain axial motion of the end grids. The bottom end grid is restrained through guide tube lower end plugs fixed to the lower end fitting. Upper end grid motion is restrained by spacer sleeves located on the guide tubes between the bottom of the upper end fitting and the top of the upper spacer grid.

A quick disconnect mechanism utilized on the latest version of the Mark-BZ fuel design, i.e., Mark-B10, is also used for the Mark-B11 fuel assembly. The attachments at the guide tube/upper end fitting interface allow the upper end fitting to be removed for fuel assembly reconstitution. The Mark-B10 cruciform leaf spring design, consisting of multiple leaf Inconel 718 material, is also utilized on the Mark-B11 assembly. Located in the upper end fitting, the spring maintains positive fuel assembly contact with the core support structure under all normal operating conditions and also maintains positive holddown margin for the Mark-B11 hydraulic forces.

All key dimensions are maintained to ensure compatibility with existing interfaces. All of the Mark-B11 features common to earlier Mark-BZ designs have been proven through extensive operational experience.

#### 3.1.1.2 Fuel Rod

As with the previous Mark-BZ designs, the Mark-B11 fuel rod assembly comprises a Zircaloy clad fuel stack with Zircaloy end caps. The fuel rod cladding is a cold-worked, seamless, low tin, zirconium alloy. The Zircaloy upper and lower end cap designs are fundamentally unchanged from previous Mark-B designs. The upper end cap has a grippable notch to facilitate reconstitution and the lower end cap is bullet nosed and debris resistant, extending through the bottom end grid.

The fuel stack contains three zones: a central portion of enriched sintered uranium dioxide pellets and an axial blanket region at each end of the stack. The axial blanket region consists of sintered uranium dioxide pellets with a $U^{235}$ enrichment of a low weight percent.

The fuel rod spring system employs one preloaded stainless steel spring in the upper plenum region that prevents movement of the fuel stack when subjected to shipping and handling loads. The fuel stack is seated on the lower end cap.

Other features of the fuel rod assembly are consistent with the fuel rod design changes previously incorporated into the Mark-B10 fuel rod design. These changes include a reduction in the pellet to cladding diametral gap from inch to inch and the removal of the lower plenum spring. The Mark-B10 fuel rods have been supplied to all three Oconee Nuclear Units starting with Unit 3, cycle 16 and have operated free of failures.

### 3.1.2 Unique Design Features

The specific Mark-B11 fuel assembly design features that enhance the nuclear, thermal-hydraulic, and mechanical performance include the following:

1. Reduced diameter fuel rod,
2. Flow mixing vanes on five of the six intermediate grid assemblies, and
3. Improved grid restraint system.

These features have been thoroughly evaluated analytically and empirically to ensure sufficient design margins and to confirm acceptable performance for batch implementation.

### 3.1.2.1 Fuel Rod

The most significant difference between the Mark-B11 fuel rod and its Mark-B predecessors is the reduction in the outer diameter from .430 inch to .416 inch. The 0.416 inch-diameter Mark-B11 fuel rod is configured in the same 15x15 array as the 0.430 inch-diameter Mark-B fuel rods. Using the same lattice, more water is contained within the boundary of the Mark-B11 fuel assembly, producing a softer neutron spectrum and a more neutronically reactive design. The softer neutron spectrum better utilizes the residual fissionable material in the adjacent 0.430 inch-diameter fuel rods. This added efficiency lowers enrichment costs for the fresh Mark-B11 fuel in transition cycles. In addition to large transition-cycle savings, the Mark-B11 design inherently requires lower boric-acid concentrations, which further reduces both operating costs and fuel-corrosion concerns.

Table 3.1 provides a comparison of Mark-B11 and Mark-B10 fuel rod parameters.

### 3.1.2.2 Flow Mixing Intermediate Grids

The Mark-B11 spacer grids are a direct evolution of Mark-BZ spacer grids. As with the Mark-BZ, upper and lower end grids are made of Inconel 718 strip material. The six intermediate grids are built from fully annealed, low-tin Zircaloy-4 and provide a fully keyable geometry to allow scratch-free and stress-free fuel rod insertion.

Unique Mark-B11 grid features include a reduction in fuel rod cell size (hard stop to soft stop) to accommodate the smaller diameter fuel rods and the addition of flow mixing vanes on the upper five intermediate grids. The cell size reduction ensures that the resulting fuel rod slip load remains unchanged. As shown in Figure 3.3, the mixing vanes maintain a conventional tab geometry on top of the spacer grid interior strips that bend outward from the plane of the strip. The vaned intermediate spacer grids provide improved thermal hydraulic performance by locally increasing the intensity of turbulence of the reactor coolant within the subchannel. Mixing vanes are not used on the lowermost intermediate spacer grids since the mixing enhancement is not necessary for this cooler region of the assembly.

Table 3.2 provides a comparison of Mark-B11 and Mark-BZ grid parameters.

### 3.1.2.3 Improved Grid Restraint System

As with previous Mark-BZ fuel assemblies and all FCF fuel designs, the intermediate grids are not fixed to the guide tube or instrument tube to help reduce fuel rod and fuel assembly bow. The grid restraint system allows the intermediate spacer grids to follow the fuel rods as they grow due to irradiation until the Zircaloy grids relax. After the spacer grids relax, intermediate grid axial motion is restrained through spacer grid inserts that contact cylindrical sleeves on the instrument tube.

The Mark-B11 design incorporates recent strength improvements made to the grid-to-sleeve interface on Mark-BZ fuel assemblies. Restraint sleeve-to-spacer grid interface geometries have been modified to increase strength. In addition, grid restraint load path improvements have been made on the Mark-B11 that in effect isolate the hydraulic loads for the two lowermost intermediate grids from that of the four uppermost grids.

The restraint sleeves are located between each spacer grid such that the hydraulic lift loads are transmitted through the top end grid for the upper four intermediate grids and through the bottom end grid for the lower two intermediate grids. This load path improvement serves to lower the load in the uppermost sleeves, which experience an increased hydraulic resistance attributed to the mixing vane grids.

## Figure 3.1 - Mark-B11 Fuel Assembly

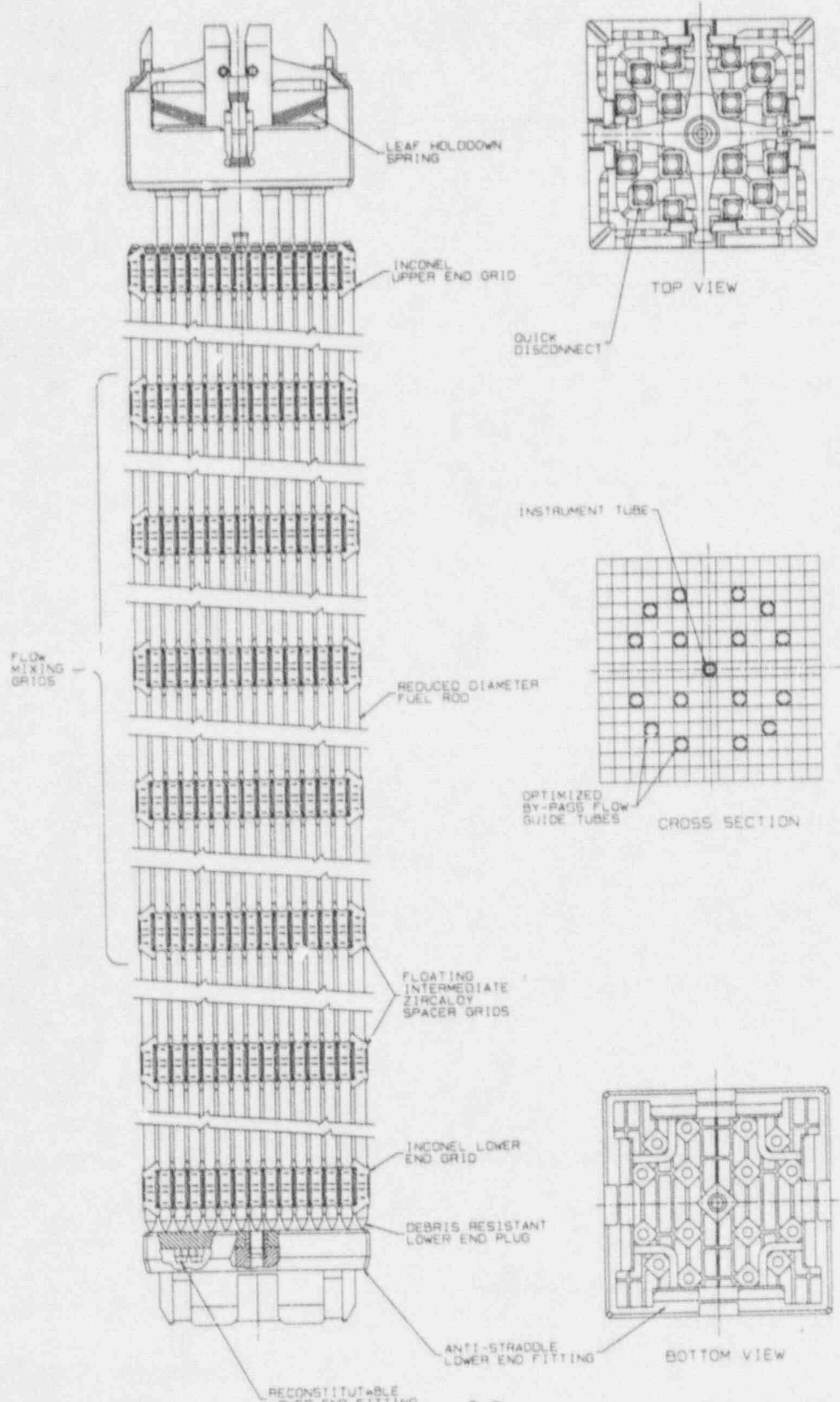

**Figure 3.2 - Mark-B11 Fuel Rod Assembly**

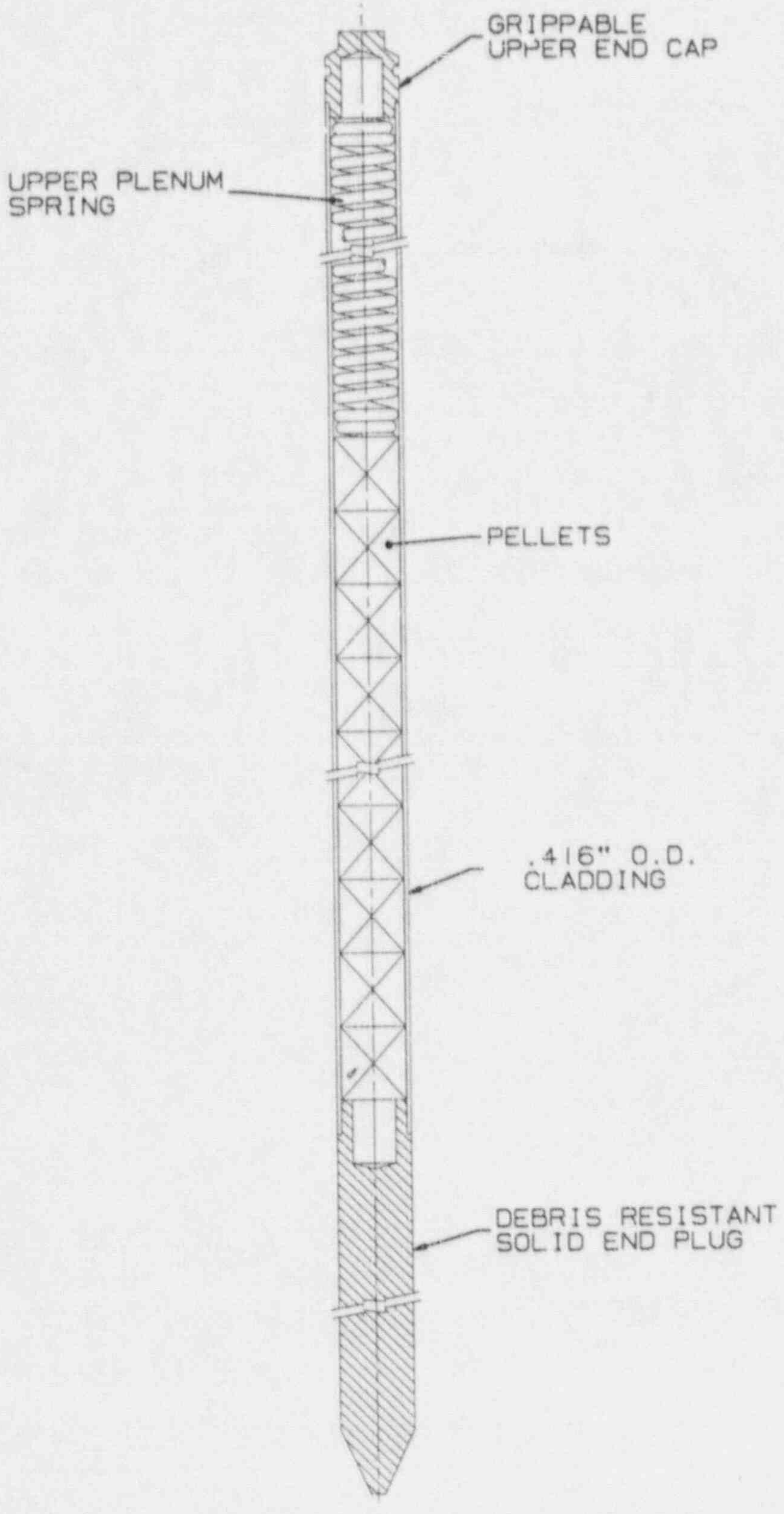

Figure 3.3 - Mark-B11 Mixing Vane Grid

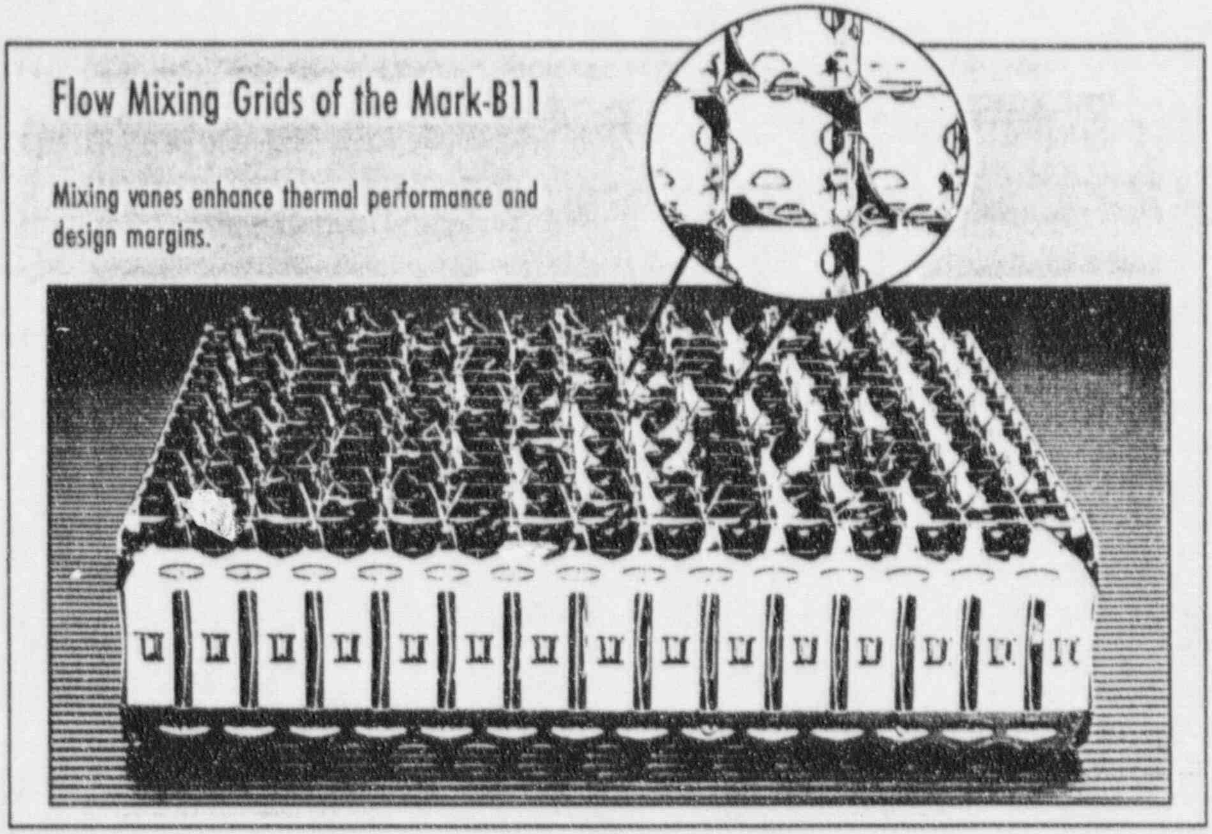

Table 3.1

**Comparison of Mark-B11 and Mark-B10 Fuel Rod Parameters**

| Fuel Rod Parameters | Mark-B11 | Mark-B10 |
|---|---|---|
| Clad Material | Cold-Worked Stress Relieved Low-Tin Zircaloy-4 | Cold-Worked Stress Relieved Low-Tin Zircaloy-4 |
| Fuel Rod Length, in. | | |
| Cladding OD, in. | | |
| Cladding Thickness, in. | [b,c,d] | |
| Cladding ID, in. | | |
| Clad-to-Pellet Gap, in. | | |
| Fuel Pellet OD, in. | | |

## Table 3.2

### Comparison of Mark-B11 and Mark-BZ Grid Parameters

| Grid Parameter | Mark-B11 | Mark-BZ |
|---|---|---|
| **Intermediate Grid** | | |
| Material | Fully Annealed Recrystallized Low-Tin Zircaloy-4 | Fully Annealed Recrystallized Low-Tin Zircaloy-4 |
| Mixing Vanes | Upper 5 Grids | N/A |
| Outer Strip Height, in. | | |
| Outer Strip Thickness, in. | | |
| Inner Strip Height, in. | [b,c,d] | |
| Inner Strip Thickness, in. | | |
| Grid Envel | | |
| Effective Cell Size, in. | | |
| **End Grid** | | |
| Material | Inconel 718 | Inconel 718 |
| Outer Strip Height, in. | | |
| Outer Strip Thickness, in. | | |
| Inner Strip Height, in. | [b,c d] | |
| Inner Strip Thickness, in. | | |
| Grid Envelope, in. | | |
| Effective Cell Size, in. | | |

# 4. FUEL ASSEMBLY TEST PROGRAM

The Mark-B11 fuel design was subjected to a comprehensive test program to verify and characterize the mechanical and thermal-hydraulic performance. All testing addressed the key factors associated with the incorporation of the new Mark-B11 design features. Verification testing was conducted at various facilities. Critical heat flux testing was conducted at Columbia University in New York. Fuel assembly flow-induced vibration and pressure drop tests were performed in the Transportable Flow Test Rig (TFTR) at the Lynchburg Manufacturing Facility (LMF) using a full scale prototype. Additional pressure drop testing in addition to life and wear testing was performed at representative reactor conditions in the Control Rod Drive Line (CRDL) facility at the Alliance Research Center (ARC) in Ohio. Fuel assembly, spacer grid, and assembly component mechanical testing was performed at the LMF and ARC facilities. Results of Mark-B11 tests are summarized in the following sections.

## 4.1 Design Verification Testing

### 4.1.1 Flow-Induced Vibration Testing

Extensive flow-induced vibration (FIV) testing was conducted in the Transportable Flow Test Rig (TFTR) at the LMF facility. The purpose of the test was to examine the vibrational response of the Mark-B11 fuel assembly and to verify that no flow related phenomena existed that would adversely affect fuel integrity. The full-scale prototype testing also included the reactor-proven Mark-B10 fuel assembly to establish a baseline vibrational response for comparison to the Mark-B11 prototype. Testing was performed at low temperature and pressure conditions. Both assemblies were tested under a wide range of flow conditions, totaling more than 150 discrete flow intervals ranging from to gpm flowrate. Data analyses of 23 discrete parameters comprised more than 2500 different plots, characterizing detailed evaluations of the fuel assembly amplitudes and associated mode shapes as a function of flow rate.

As expected, neither the baseline Mark-B10 assembly nor the Mark-B11 prototype assembly exhibited any unusual resonant condition that would jeopardize fuel integrity. Both fuel assembly types were comparable in response. The observed resonances matched those calculated analytically. The amplitudes of vibration for both assemblies were very low with amplitudes less than[b,c,d]inch for a given frequency. Vibrational peaks that did appear were predictable and well behaved. Therefore, based on these test results and the life and wear test results (section 4.1.2), the Mark-B11 fuel assembly exhibits acceptable flow induced vibration performance under all reactor flow conditions. This has been further verified in that no operational problems or fuel failures have occurred in the Mark-B11 LTAs to date (section 4.1.3).

### 4.1.2 Life and Wear Testing

Life and wear testing of the Mark-B11 fuel assembly was conducted in the Alliance Research Center Control Rod Drive Line (CRDL) facility. The full-scale prototype assembly was subjected to 1,000 hours of endurance testing at simulated full power reactor operating conditions of temperature, pressure, flow, and coolant chemistry. The prototype assembly was constructed to simulate end-of-life (EOL) relaxed grid condition, which minimized the fuel rod-to-grid grip loads. The EOL condition is considered the most conservative to evaluate the effects of flow-induced fretting wear.

Post test inspections included detailed examination of fuel rods, spacer grids, guide tubes, the holddown spring, and the quick disconnect mechanism in the upper end fitting assembly. Component inspections revealed no indications of unacceptable wear. Fuel rod spacer grid contact wear was less than that of previous Mark-B fuel assembly designs for the same test conditions. Guide tube control rod wear was similar to that seen on previous Mark-B designs.

### 4.1.3 Lead Test Assembly Program

Final in-core verification is ongoing with the operation of four Mark-B11 LTAs at Oconee 2 Cycle 16, which began operation in April 1996. Given industry fretting problems associated with new fuel designs, the primary focus of the Mark-B11 LTA program is to ensure that the Mark-B11 fuel assembly is not subject to unexpected fuel rod/grid fretting failures. Three cycles of operation are currently planned. The first cycle of operation locates the Mark-B11 LTAs in the core interior, subjecting the assemblies to aggressive peaking values and verifying the interface with the burnable poison rod assembly (BPRA). The second cycle of operation locates the LTAs on the core periphery, subjecting the assemblies to baffle crossflow conditions, thus providing a bounding operating condition for flow-induced vibration and fuel rod fretting. The third cycle of operation relocates the LTAs in the core interior to maximize burnup while operating under a control rod assembly location. The Mark-B11 LTA program, coupled with the design verification testing and analyses and the proven experience of the Mark-BZ fuel assembly design at high burnups, serve to verify the Mark-B11 fuel assembly design for batch implementation.

## 4.2 Mechanical Tests

Extensive mechanical testing of the Mark-B11 fuel assembly and components was performed to provide input into analytical models and to demonstrate similitude with baseline Mark-B10/BZ fuel design. Testing consisted of fuel assembly mechanical testing including characterization of lateral and axial stiffness, natural frequency, structural damping; spacer grid impact testing; spacer grid static crush testing; grid restraint interface testing; and grid slip load testing.

### 4.2.1 Fuel Assembly Stiffness/Frequency

Mechanical testing was performed on the Mark-B11 fuel assembly to experimentally determine its lateral stiffness, axial stiffness, natural frequency, and damping characteristics. The prototype fuel assemblies represented end-of-life (EOL), simulating relaxed fuel rod slip load conditions. The relaxed condition represents that condition which exists for most of the fuel assembly design life. The results from these tests were used as inputs to benchmark the fuel assembly analytical models. The assembly was tested in air at room temperature in a special test fixture at the LMF facility. Testing consisted of dynamic pluck, axial stiffness and lateral stiffness tests.

Table 4.1 provides the mechanical characteristics of the Mark-B11 and Mark-BZ fuel assemblies. Results show that the lateral and axial stiffness and natural frequency are within[b,c,d]for each of the two assemblies. Note that the Mark-BZ design tested was earlier design that utilized the lower end skirt, which effectively joined the lower end fitting to the lower end grid and stiffened the assembly slightly. Current Mark-BZ fuel designs do not utilize the skirt.

| Table 4.1 - Summary of Mark-B11 Fuel Assembly Mechanical Test Results | | | |
|---|---|---|---|
| **Characteristic** | **Peak Deflection (In.)** | **Mark-B11 Fuel Assembly Results** | **Mark-BZ Fuel Assembly Results** |
| Lateral Stiffness (Lbs./In.) | | | |
| Axial Stiffness (Lbs./In.) | | [b,c,d] | |
| Natural Frequency (Hz) | | | |

* Lateral Stiffness was determined using a[b,c,d] axial preload. FA had bottom end skirt which increased stiffness.

** Lateral Stiffness was determined using a[b,c,d] axial preload.

### 4.2.2 Spacer Grid Impact Testing

Impact testing was conducted to determine the dynamic characteristics of the Mark-B11 intermediate spacer grids. These characteristics were used to determine inputs to the fuel assembly analytical models, to establish allowable impact loads, and to characterize the plastic deformation of the spacer grids.

Testing consisted of dynamic tests conducted at room temperature and at 600 °F. Table 4.2 includes test results of the Mark-B11 intermediate spacer grids in addition to those of the baseline Mark-BZ for comparison. The tests showed that no plastic deformation of the guide tubes occurred during the impact testing. The results showed that the strength and stiffness of the Mark-B11 intermediate grid compare favorably with the baseline Mark-BZ, resulting in higher average elastic impact force, average kinetic energy absorption, and damping while providing a slightly lower average stiffness. These results show that the Mark-B11 spacer grid increases structural margin.

| Table 4.2 - Intermediate Spacer Grid Impact Test Results | | | | | |
|---|---|---|---|---|---|
| Grid Type | Test Temperature | Average Elastic Impact Force (lbs) | Average Initial Kinetic Energy (in-lbs) | Average Stiffness (lbs/in) | Average Damping ($\zeta_{eq}$ or $c/c_c$) |
| Mark-B11 | 600 °F | | | | |
| Mark-B11 | ~70 °F | | [b,c,d] | | |
| Mark-BZ | 600 °F | | | | |

### 4.2.3 Spacer Grid Crush Test

Static crush testing was performed on Mark-B11 intermediate spacer grids to characterize spacer grid mechanical behavior for use in verifying shipping and handling loads. The static crush load for all of the spacer grids exceeded the required load capability of [b,c,d] pounds, which is derived from worst case shipping and handling loads.

### 4.2.4 Grid Restraint Interface Testing

Testing of the spacer grid restraint system was performed to determine the structural adequacy of the spacer grid to sleeve interfaces.

The spacer grid to sleeve interfaces were tested to failure at both cold and hot temperatures. All grid interfaces with restraining sleeves were tested to determine their load-carrying capacity under normal operation and faulted conditions.

Based on the positive margins obtained from each interface, the spacer grid to sleeve interfaces were shown to be structurally adequate for normal and faulted condition loads.

#### 4.2.5 Spacer Grid Slip Testing

The purpose of the spacer grid slip testing was to measure the loads required to slip the spacer grids relative to the fuel rods, guide tubes, and instrument tube under ambient conditions. Results of this testing represent the total friction force between the spacer grids and the fuel rods and are used in the normal operating and shipping and handling analyses models. Slip load and load/deflection measurements were made for both the end and intermediate grids. The slip loads were within the expected range and were comparable to previous Mark-BZ baseline tests.

### 4.3 Hydraulic Tests

#### 4.3.1 Pressure Drop Testing

Pressure drop testing of full-scale prototype Mark-B10 and Mark-B11 fuel assemblies was conducted in both the TFTR at the Lynchburg Manufacturing Facility and the CRDL facility at the Alliance Research Center. TFTR testing represented low temperature, pressure, and Reynolds number conditions. The CRDL testing represented in-reactor hot operating conditions at high Reynolds number conditions. The Mark-B10 testing served as a benchmark for comparison. Testing in the two test loops served to provide data for correlating the effects of Reynolds number. The pressure drop testing provided form loss coefficients for the Mark-B11 components, including the upper and lower end fittings, end grids, and intermediate grids, for input into thermal-hydraulic analyses discussed in sections 7.1 and 7.2. Excellent correlation of intermediate spacer grid form loss coefficients resulted between the TFTR and CRDL testing.

Component form loss coefficients for the Mark-B11 fuel assembly are provided in Table 4.3.

| Table 4.3 - Mark-B11 Form Loss Coefficients | |
|---|---|
| Mark-B11 Component | Form Loss Coefficients |
| Lower End Fitting | |
| End Grids | |
| Non Mixing Grid | [b,c,d] |
| Intermediate Mixing Grid | |
| Upper End Fitting | |
| Fuel Assembly | |

### 4.3.2 Laser Doppler Velocimeter Testing

Extensive Laser Doppler Velocimeter (LDV) testing, conducted at the Virginia Military Institute Research Laboratories, provided a detailed description of the subchannel flow distribution within the Mark-B11 fuel assembly. The results from these tests were used to confirm the subchannel form loss coefficients, which were determined analytically, to establish the turbulent mixing coefficient used in thermal-hydraulic calculations and to ensure an acceptable velocity distribution.

The test apparatus consisted of a water flow loop, the test containment and the test rod bundle. Two test rod bundles were used. One consisted of a 5 x 5 section of fuel rods with a control rod guide tube in the center. The other consisted of four 3 x 3 fuel rod mini-bundles which simulated the corner regions of four adjacent Mark-B11 assemblies. All rod bundles were approximately[c,d]inches tall and contained three spacer grids each.

In order to characterize the velocity field of the coolant flow, velocity measurements were taken between the second and third grid. Measurements were taken along parallel lines through the subchannels at four cross-sectional planes.

The results of the two tests showed that the analytical subchannel form loss predictions could be correlated to the test results. In addition, no areas of flow starvation were found. The turbulent mixing coefficient for use in thermal hydraulic calculations is [b,c,d]which is the same value as used for similar FCF mixing grid designs.

#### 4.3.3 Critical Heat Flux Testing

Critical heat flux (CHF) testing was conducted at Columbia University's Heat Transfer Research Facility. Testing conditions covered the full range of PWR operating conditions. A 5x5 array was tested using the mixing vane pattern from the Mark-B11 intermediate mixing grid design, which is a scaled version of FCF's Mark-BW17 design. The results of this testing showed that the BWCMV CHF correlation, originally developed for the Mark-BW17 design and documented in BAW-10159P-A [12], conservatively predicted CHF for the Mark-B11 fuel assembly design. CHF performance of the Mark-B11 assembly exceeded the BWCMV predicted performance by more than[b,c,d].

Further testing was conducted to quantify the CHF capability of the Mark-B11 grid. In all, 5 tests representing 3 different geometrical configurations were run. In BAW-10199P-A [13], a new CHF correlation form (BWU) was developed and a separate version was qualified for use with several grid designs. The version qualified for use with the Mark-B11 is termed the BWU-Z. Appendix E of reference 13 quantifies the CHF capability of the Mark-B11 mixing grid in the form of a multiplier on the BWU-Z correlation. The use of a[b,c,d]multiplier on the BWU-Z correlation and a[b,c,d]design limit accurately represent the CHF performance of the Mark-B11 mixing grid.

## 5. FUEL ASSEMBLY MECHANICAL EVALUATION

The Mark-B11 fuel assembly mechanical design criteria comply with that specified in BAW-10179, "Safety Criteria and Methodology for Acceptable Cycle Reload Analyses" [2], which has been approved by the NRC. The fuel assembly design criteria ensure that the Mark-B11 fuel assembly, with the maximum credible damage, provides a path adequate for control rod insertion, maintains a coolable fuel rod geometry, and provides fuel assembly dimensions which remain within operational limits. Compliance with the criteria and methods identified in Reference 2 are discussed in the following sections.

The fuel assembly mechanical evaluation is divided into the following categories: growth, holddown, normal operation, faulted conditions (horizontal and vertical), fretting, fuel rod bow, shipping and handling, fuel assembly compatibility, material compatibility, and extended burnup. The fuel rod mechanical evaluation is considered separately from the fuel assembly and is addressed in section 6. Results of the analyses are applicable to fuel assembly operation in all Babcock & Wilcox-designed 177 fuel assembly skirt supported plants, including Duke Power Company's Oconee Nuclear Units 1, 2, and 3.

### 5.1 Fuel Assembly Growth

The Mark-B11 growth analysis conservatively predicts the maximum fuel assembly growth based on a statistical model assembled from Mark-BZ and Mark-BW post irradiation examination data. Using the minimum fuel assembly growth allowance and maximum upper confidence growth limit, the limiting fuel assembly burnup based on assembly growth is[b,c,d] MWd/mtU.

The Mark-BZ fuel assembly growth model, which includes assembly burnups as high as [b,c,d] MWd/mtU, is applicable to the Mark-B11 fuel assembly since the design changes implemented for the Mark-B11 fuel assembly will not affect assembly growth.

The Mark-B11 fuel design maintains the inherent FCF fuel design features of floating intermediate grids and seated fuel rods. This maintains the fuel assembly structural cage load paths and guide tube loads, which influence fuel assembly growth. The holddown spring remains unchanged and the fuel rod/spacer grid slip loads are comparable between the Mark-B10 and Mark-B11 designs. The reduction in fuel rod diameter is accommodated in the grid design as discussed in section 3.1.2.2, thereby ensuring the same fuel rod slip loads. The guide tube and fuel rod clad materials also remain the same as with earlier Mark-BZ designs. Given comparable axial loads and the same materials, the Mark-B11 fuel assembly growth will remain the same as that experienced in previous Mark-BZ designs.

**5.2 Holddown**

The evaluation of the Mark-B11 fuel assembly holddown capability ensures fuel assembly contact with the lower support plate during Condition I and II events. The fuel assembly upper and lower end fittings maintain engagement with reactor internals for all Condition I through IV events. The fuel assembly does not compress the hold down spring to solid height for any Condition I or II event. Mark-B11 holddown spring maximum loads and stresses are enveloped by bounding conditions evaluated for the Mark-B10 fuel application, therefore functional requirements are ensured.

The predicted lift loads are based on the Mark-B11 form loss coefficients listed in Table 4.3.1 and described in section 4.3.1. Sufficient holddown margin to prevent lift is provided. The lift evaluation is discussed in section 7.2.

## 5.3 Normal Operation

### 5.3.1 Stress

Stress intensities for Mark-B11 fuel assembly components were shown to be less than those limits established in reference 2, which were based on ASME Code , Section III criteria [6].

Temperature conditions ranging from the fourth pump startup temperature of 300°F to the operating temperature of 579°F for an operating pressure of 2,200 psia were considered. Beginning-of-life (BOL) and end-of-life (EOL) conditions were also evaluated to consider the change in load paths and loads due to material relaxation. The following fuel assembly components were evaluated:

1) Grid Restraint Sleeves/Inserts,
2) Guide Tube Assembly Components,
3) Upper and Lower End Fittings,
4) Quick Disconnect Components, and
5) Holddown Spring Assembly/Retainer.

Positive margins were determined for all fuel assembly structural components, showing that the Mark-B11 fuel assembly is structurally adequate for normal operating conditions.

### 5.3.2 Buckling

Buckling of Mark-B11 guide tubes was shown not to occur for normal operation conditions. Allowable guide tube axial loads were determined per reference 2, which limits the guide tube span axial load based on mid-span deflection criteria such as not to affect control rod insertion or trip performance. Guide tube corrosion, tolerances, and temperature effects were considered. Positive margins to buckling were determined for all temperature and fuel assembly conditions.

## 5.4 Faulted Conditions

The design bases used to establish the acceptance criteria for the Mark-B11 fuel assembly are provided in reference 2 and are consistent with NUREG-0800, Section 4.2, Appendix A [5] and follow the guidelines established by Section III of the ASME Code [6]. The design requirements for each category are as follows:

1) Operational Base Earthquake (OBE) - Allow continued safe operation of the fuel assembly following an OBE event by ensuring the fuel assembly components do not violate their dimensional requirements.

2) Safe Shutdown Earthquake (SSE) - Ensure safe shutdown of the reactor by maintaining the overall structural integrity of the fuel assemblies, control rod insertibility, and a coolable geometry within the deformation limits consistent with the Emergency Core Cooling System (ECCS) and safety analysis.

3) Loss of Coolant Accident (LOCA) or LOCA Plus SSE - Ensure safe shutdown of the reactor by maintaining the overall structural integrity of the fuel assemblies and a coolable geometry within deformation limits consistent with the ECCS and safety analysis.

The Mark-B11 faulted evaluation addresses both the vertical (LOCA) and horizontal (LOCA and seismic) effects. The axial faulted analyses methodology is consistent with that submitted and approved by the NRC in BAW-10133P, Rev. 1 [4]. The horizontal faulted analysis methodology is consistent with that submitted and approved by the NRC in BAW-2292P, Rev. 0 [3]. The results are applicable to all Babcock & Wilcox-designed 177 fuel assembly plants with a skirt-supported reactor vessel.

### 5.4.1 Horizontal Analysis

The horizontal component of the faulted analysis determines the structural integrity of the Mark-B11 fuel assembly in the horizontal direction. The following loading conditions were evaluated:

1) Operating Basis Earthquake,
2) Safe Shutdown Earthquake,
3) Loss of Coolant Accident (LOCA), and
4) Combined Seismic and LOCA Events.

#### 5.4.1.1 Stress

Stress intensities for Mark-B11 fuel assembly components were shown to be less than those limits established in reference 2, which were based on ASME Code , Section III criteria [6]. Mark-B11 fuel assembly components evaluated included those listed in section 5.3.1.

#### 5.4.1.2 Grids

The Mark-B11 grids were evaluated applying the approved criteria and methodology described in references 2 and 4. No crushing deformation of the spacer grids is allowed for Condition I and II events and the spacer grids are required to provide adequate support to maintain the fuel rods in a coolable configuration for Conditions I thru IV.

The Mark-B11 evaluation showed that the predicted grid impact loads remain below the elastic load limits for all conditions including Operating Basis Earthquake, Safe Shutdown Earthquake, LOCA and combined SSE and LOCA conditions. Core plate time history inputs were determined using leak-before-break (LBB) methodology consistent with the NRC approved topical reports BAW-1847, Rev. 1 [19,18] and BAW-1999, Rev.0 [20]. The LBB core plate time history inputs utilized in the Mark-B11 analyses are the same as those used in the NRC approved Mark-B Grid Deformation Topical Report BAW-2292, Rev.0 [3, 21]. Seismic time histories corresponded to bounding spectra for the B&W reactor vessel skirt-supported plants.

The maximum faulted loads and corresponding allowable loads are based on grid impact testing reported in section 4.2.2. Results provided in Table 5.1 show that the grids remain elastic for all loading conditions, therefore control rod insertability and a coolable geometry are maintained for the Mark-B11 grids.

**Table 5.1 - Grid Impact Loads**

| Faulted Condition | OBE | | SSE | | SSE + LOCA | |
|---|---|---|---|---|---|---|
| Direction | X | Z | X | Z | X | Z |
| Predicted Maximum Grid Force (lbs) | | | [b,c,d] | | | |
| Allowable Grid Force (lbs) | | | | | | |

### 5.4.2 Vertical Analysis

The Mark-B11 fuel assembly was evaluated for the vertical LOCA condition per the methodology provided in reference 2 to ensure control rod insertion and to ensure that all fuel assembly component stress limits are not exceeded.

#### 5.4.2.1 Stress

Stress intensities for Mark-B11 fuel assembly components were shown to be less than those limits established in reference 2, which were based on ASME Code , Section III criteria [6]. Mark-B11 fuel assembly components evaluated included those listed in section 5.3.1. Positive margins were determined for all components.

#### 5.4.2.2 Buckling

Mark-B11 guide tube buckling was evaluated for vertical faulted conditions per reference 2, considering the effects of guide tube corrosion, tolerances, and temperature effects. Allowable guide tube axial loads were determined based on the material yield stress per reference 2. Positive margins to buckling were determined for all fuel assembly conditions.

### 5.5 Fretting

The Mark-B11 fuel assembly was shown to provide sufficient support to limit fuel rod vibration and cladding fretting wear. Sections 4.1.1 and 4.1.2 provide discussion of results from the life and wear and flow induced vibration tests, both of which showed the Mark-B11 fuel assembly vibrational response is acceptable in terms of cladding and guide tube wear.

### 5.6 Fuel Rod Bow

Fuel rod bowing is evaluated with respect to the mechanical and thermal-hydraulic performance of the fuel assembly.

Post irradiation examination of Mark-B11 assemblies will determine the rod bow characteristics of the assembly. Mark-B11 fuel rod bow however is not expected to differ significantly from that of other FCF fuel assembly designs based on the same arguments presented for fuel assembly growth in section 5.1. The Mark-B11 fuel assembly maintains a similitude with earlier Mark-BZ designs with generic FCF features, materials and comparable fuel assembly loads.

### 5.7 Fuel Assembly Shipping and Handling

The Mark-B11 fuel assembly was evaluated for the structural adequacy for shipping and handling loads per reference 2. The analysis addresses loads on the Zircaloy and Inconel spacer grids, upper and lower end fittings, guide tube, and guide tube attachments.

Positive margins were predicted for all the fuel assembly components considered. Positive margin against grid crush was demonstrated for a maximum load of[b,c,d]lbs during shipment (including grid clamping load). The Mark-B11 spacer grids were shown to maintain sufficient grip loads on the fuel rods to prevent axial movement during axial shipping and handling of up to 4 Gs. Lateral loads of up to 6 Gs were shown not to cause setting of the spacer grid spring stops.

### 5.8 Fuel Assembly Compatibility

Mechanical compatibility of the Mark-B11 fuel assembly with the reactor internals, handling and storage equipment, and resident fuel assemblies is verified through the similarity of the design to previous Mark-B fuel assemblies. The Mark-B11 fuel assembly upper and lower end fittings, the fuel assembly height and fuel assembly envelope are the same as the Mark-B10 fuel assembly. The axial positioning of the spacer grids is also maintained to avoid hang up with adjacent resident fuel assemblies and to provide adequate lateral interfaces.

### 5.9 Material Compatibility

The materials used in the manufacture of the Mark-B11 fuel assembly and fuel rod are compatible with all other materials in the primary system. All core components will continue to meet their required function since the Mark-B11 fuel assembly introduces no new materials to the core. Redesigned components such as the grid restraint parts, fuel rod components, and spacer grid assemblies utilize materials used in previous Mark-BZ fuel assembly components and have been proven with extensive reactor experience.

## 5.10 Extended Burnup

All design and operational criteria are the same for extended burnup Mark-B11 fuel assemblies as for the original Mark-B fuel designs. The Mark-B11 fuel assembly will maintain its mechanical integrity at high burnups based on the existing FCF fuel database and the Mark-B11 similitude with previous fuel designs in addition to the extensive design verification program performed to date.

Extended burnup operation of the Mark-B11 fuel assembly is supported by a comprehensive series of post irradiation examinations carried out on previous Mark-B lead test assemblies, demonstration assemblies, and production fuel assemblies. As discussed earlier, similitude between the Mark-B11 and other FCF fuel assembly designs ensure satisfactory operation at extended burnups. Use of common reactor proven fea[illegible]s, materials, components, design conditions and loadings, models, and mechanica[illegible]aracteristics allow for application of the data presented in BAW-10186P-A [1] to the Mark-B11 fuel assembly. Further confirmation will be made through post irradiation examinations (PIE) of the Mark-B11 lead assemblies. Examinations are scheduled to be conducted after the first and second cycles of operation in Oconee Unit 2. Key parameters will be measured and benchmarked to the data presented in reference 1. Additional PIE will be performed as required in future cycles to ensure sufficient monitoring of the Mark-B11 operational performance.

## 6. FUEL ROD MECHANICAL EVALUATION

The Mark-B11 fuel rod mechanical design criteria comply with those specified in BAW-10179 [2], which has been approved by the NRC. The mechanical evaluation demonstrated the structural integrity of the Mark-B11 fuel rod design. The evaluation addresses the following areas of mechanical performance: corrosion, creep collapse, transient strain, stress, fatigue, shipping and handling, fuel rod growth, and fuel rod fretting. Each of these areas is discussed in the following sections. All of the following fuel rod mechanical evaluations represent generic values, which would generally be more conservative than cycle specific analyses. Thus the reported results should be treated as typical values. Cycle specific analyses using the same approved methods and models would be the analysis basis for each cycle.

### 6.1 Corrosion

Oxide layer growth on the fuel rod cladding surface inhibits several areas of mechanical performance. During the corrosion process, base metal converts to oxide, reducing the effective thickness of the Zircaloy. The cladding also operates at higher temperatures due to the lower thermal conductivity of the oxide relative to the base metal. For this reason, a conservative oxide layer thickness of [b,c,d] is assumed to be present on the cladding outer surface in the cladding stress and fatigue analyses. Further, cladding outer surface oxide thickness is predicted for comparison to a steady state operating limit of [b,c,d]. This limit and the model used to predict FCF cladding corrosion are documented in BAW-10186P-A [1]. The corrosion model is licensed to predict FCF cladding corrosion performance to a fuel rod average burnup of[b,c,d] MWd/mtU. Mark-B11 fuel rod corrosion analyses utilize the models and corrosion limit set forth in reference 1, using conservative cycle specific radial power history and axial flux shapes.

## 6.2 Cladding Transient Strain

Transient strain occurs as a result of cladding deformation caused by fuel pellet radial swelling during power increases. Uniform transient strain, both elastic and inelastic is limited to 1.0%. BAW-10186P-A [1] contains the transient strain analysis methodology.

The transient strain analysis results in a local fuel rod linear heat rate versus rod average burnup limit that prevents the fuel rod from achieving 1.0% strain. For the Mark-B11 fuel rod, the generic local linear heat rate limit remains above [b,c,d] to a rod average burnup of [b,c,d] MWd/mtU.

## 6.3 Cladding Stress

Reference 2 defines the FCF Mark-B cladding stress analysis methodology. Stress level intensities are calculated in accordance with the ASME Code, which includes both normal and shear stress effects. These stress intensities are compared to 2/3 of the minimum specified unirradiated yield strength of the material at operating temperature.

Using the reference 2 methodology, the Mark-B11 fuel rod was shown to maintain positive margins between the maximum predicted stress intensities and the allowable stress. The minimum generic margin is[c,d], achieved while combining primary membrane stresses predicted under normal and transient (non faulted) operating conditions.

## 6.4 Cladding Fatigue

During core operation of the fuel rod, various plant maneuvers cause power fluctuations, or transients, which can result in large pressure and temperature oscillations in the fuel rod and fuel rod cladding. These oscillations lead to fluctuating thermal, pressure and ovality stresses in the fuel rod cladding and can ultimately lead to fatigue failure. The cladding fatigue analysis models these transients using TACO3, FCF's fuel pin thermal analysis code described in BAW-10162P-A [8]. Reference 2 contains the FCF analysis methodology and criterion, which limits the total fatigue usage factor for all Condition I and II events to 0.9.

For the Mark-B11 fuel rod, individual utilization factors for each applicable transient were calculated and summed to find the total generic utilization factor of[b,c,d]. Since this is less than the 0.90 total allowable usage factor, the Mark-B11 fuel rod design is acceptable in terms of cladding fatigue up to a design life of 10 effective full power years.

**6.5 Creep Collapse**

The FCF cladding creep collapse analysis methodology and corresponding CROV computer code are established in BAW-10084P-A [7] and approved to a rod average burnup of[b,c,d] MWd/mtU per reference 1. Creep collapse of the cladding due to creep ovalization shall not occur during the in-core life of the fuel rod. Predicted creep collapse occurs when the creep ovalization rate exceeds 0.1 mils/hour or the maximum fiber stress exceeds the unirradiated yield strength of the cladding.

Both TACO3 and CROV codes were used to model the Mark-B11 fuel rod in core cladding creep performance. Analytical results show that Mark-B11 fuel rod creep collapse life exceeds[b,c,d] effective full power hours, which is equivalent to a burnup of 70,000 MWd/mtU for the power history analyzed. Use of a less restrictive power history would result in a longer creep collapse life in terms of hours.

### 6.6 Fuel Rod Growth

The gap allowance between the upper end fitting and the fuel rod assembly is designed to provide a positive clearance during the assembly lifetime. Reference 1 contains the analysis methodology and shows that it is approved to a rod average burnup [b,c,d] MWd/mtU.

The fuel rod growth model is based on FCF irradiation experience obtained with cladding material equivalent to that of the Mark-B11. The model predicts the fluence at which the gap closes. The predicted fluence is then related to a rod average burnup. The gap prediction uses the upper tolerance limit model for fuel rod growth in Mark-BZ type fuel assemblies and the lower tolerance limit model for assembly growth. Results for the Mark-B11 show that a positive gap is maintained at a rod average burnup greater than[b,c,d] MWd/mtU.

### 6.7 Shipping and Handling

Per reference 2, the Mark-B11 fuel rod spring system must be able to withstand a 4G axial loading from the fuel stack mass during shipping and handling without any gaps larger than[b,c,d] inch forming within the fuel rod internals. Mark-B11 fuel rod analyses demonstrated that this criterion is met using the approved method of reference 2.

### 6.8 Fuel Rod Reliability

The reliability of the Mark-B11 fuel design is expected to be excellent. The reliability of all FCF fuel designs has improved over the last few years to where all FCF fuel is now operating leaker free. This improvement was based on a comprehensive program to review and improve critical design and fabrication parameters. The Mark-B11 fuel design shares these same proven parameters from both the Mark-B and Mark-BW product lines. The Mark-B11 fuel is expected to have the same excellent fuel reliability as demonstarted by the successful design verification testing and lead test assembly operation to date.

The 0.416 inch-diameter Mark-B11 fuel rod was designed using similar parametric relationships as the proven Mark-B and Mark-BW fuel rod designs. It also has similar margins to mechanical design criteria. FCF has fabricated fuel rods with outside diameters of 0.430, 0.422, and 0.374 inch. Fabrication will be made with the same manufacturing equipment and processes used to fabricate the Mark-B and Mark-BW fuel rods.

The Mark-B11 spacer grids are similar to those used in the Mark-BZ and Mark-BW fuel designs. Mark-BZ, including Mark-B11, and Mark-BW spacer grids are similar in cell construction (hard and soft stop configuration). The Mark-B11 utilizes a similar mixing vane geometry and pattern as the Mark-BW design. Both the Mark-B11 and Mark-BW use mixing vanes on the uppermost five intermediate spacer grids. Life and wear and flow-induced vibration testing of the Mark-B11 design, using simulated end of life grid conditions, showed acceptable spacer grid to fuel rod wear and fuel assembly dynamic response under reactor flow conditions. In core operation of the Mark-B11 lead test assemblies has also shown good performance with no problems experienced.

# 7. FUEL ASSEMBLY THERMAL-HYDRAULIC EVALUATION

## 7.1 Core Pressure Drop

As described in Section 4.3.1, the pressure drop characteristics of the Mark-B11 fuel assembly were determined through a series of flow tests at the Alliance Research Center and at the Lynchburg Manufacturing Facility. The results of these tests were used as the basis for the calculation of component form loss coefficients for the end fittings and spacer grids.

Analyses were performed using the NRC approved LYNXT code per BAW-10156-A [14] to establish pressure drop characteristics of the Mark-B11 fuel assembly in full core and mixed core implementation with resident non-mixing grid fuel. The mixed core analyses compared the overall pressure drop of the Mark-B11 and Mark-B10 assemblies as well as the pressure drop of individual components. The pressure drop of the Mark-B11 is lower than the Mark-B10 up to the first mixing grid due to the smaller fuel rod diameter thereby creating a flow diversion into the Mark-B11. At the mixing grid locations flow is diverted back into the surrounding Mark-B10 assemblies. In the spans between mixing grids, flow returns back to the Mark-B11. Even with these flow diversions, the crossflow velocity is less than the[b,c,d] maximum crossflow criterion. Up to the first mixing grid, the Mark-B11 pressure drop is[b,c,d] than the Mark-B10. At each mixing grid, the Mark-B11 pressure drop is [b,c,d] than the non-mixing grid. The smaller fuel rod diameter results in lower friction pressure drop, which helps offset the increased pressure drop of the Mark-B11 mixing grids. Overall, the Mark-B11 pressure drop is [b,c,d] than the Mark-B10. This close matching of the Mark-B11 and Mark-B10 overall pressure drop ensures that there will be no adverse impact on hydraulic lift loads, core internals loading, RCS flow rate, core bypass flow rate, and control rod drop times.

### 7.2 Fuel Assembly Hydraulic Lift

The hydraulic lift force on a fuel assembly is attributed to the component and friction pressure drop across the length of the assembly. Extensive hydraulic testing on the Mark-B and Mark-BW series of fuel has included many hydraulic lift tests at the Alliance Research Center at in reactor conditions. Based on this testing, it has been observed that for all components, except the top nozzle, the hydraulic lift formloss coefficients are equal to the component pressure drop formloss coefficients. A method to adjust the upper end fitting form loss coefficient has been derived to match the analytical lift predictions to the lift experiments and this has been applied to the Mark-B11 fuel assembly.

Using the calculated form loss coefficients and the LYNXT code, along with bounding assumptions on inlet flow conditions, several analyses were performed which evaluated the hydraulic lift forces on the Mark-B11 in both a full core and in a mixed core environment. The mixed core analysis showed that the total lift force on the limiting Mark-B11 fuel assembly would be[b,c,d] than the limiting assembly in a full Mark-B10 core. A full core Mark-B11 analysis shows that the lift force on the Mark-B11 is [b,c,d] than in a full Mark-B10 core. Therefore, the Mark-B11 fuel lift loads are bounded by the Mark-B10 values.

### 7.3 Core DNB

The purpose of the core DNB analysis is to insure that there is a 95% probability, with a 95% confidence that no fuel rod will experience a departure from nucleate boiling (DNB) during normal operation or transients of moderate frequency (reference 2). The Mark-B11 fuel assembly implements two design evolutions that affect DNB performance. Mixing grids improve DNB performance and the slightly smaller fuel rod diameter decreases DNB performance relative to the Mark-B10. The impact of these competing design changes was evaluated using the LYNXT cross flow code with variable transverse scaling. The BWU-Z CHF correlation was used in the Mark-B11 LYNXT analyses as described in section 4.3.3.

Core thermal hydraulic analyses performed to demonstrate that the DNB criterion is met use a reference design power distribution, called "design peaking", that is assumed to bound, in terms of DNB performance, real power distributions occurring during plant operation. To provide assurance that this assumption is valid, maximum allowable peaking (MAP) limits are developed. These limits are a family of curves for which the minimum DNB ratio (MDNBR) is equal to a target value, typically the DNB analysis limit. The MAP limits provide linkage between the DNB analyses and the core operating and safety power distribution limits.

For the 177 fuel assembly B&W reactors, MAP limits are developed at the RCS DNB safety limit statepoints and the limiting statepoint from the most limiting loss-of-coolant flow transient. The first set is called the reactor protection system (RPS) MAPs and the second is referred to as the operating limit (OL) MAPs. The impact on both types of MAPs due to the implementation of the Mark-B11 fuel assembly in a full and mixed core configuration has been evaluated.

### 7.3.1 Steady-State DNBR

The effect on design thermal margins during steady state operation is evaluated at a constant power level (the maximum achievable steady-state power, or design overpower condition). RPS MAP limits were generated for both a full core of Mark-B10 and Mark-B11 fuel using a traditional treatment of uncertainties. Alternatively, the Statistical Core Design (SCD) technique could be used for this comparison providing similar indications of performance change on a relative basis. For the Mark-B10 fuel the BWC CHF correlation per BAW-10143P-A [15] was used and the MAPs to reach the BWC MDNBR design limit of [c,d] were determined. The BWU-Z CHF correlation was used and adjusted by the[c,d] multiplier for the Mark-B11 fuel and the MAPs to reach the Mark-B11 BWU-Z design limit of [c,d] were calculated then compared to the Mark-B10 MAPs. This comparison shows that the Mark-B11 provides at least [c,d]and up to [b,c] peaking margin depending on the axial peak / elevation combination. In terms of DNB margin this equates to at least [c,d] and up to[c,d] additional margin to the DNB analysis limit.

The limiting mixed Mark-B10/Mark-B11 core is a single Mark-B11 assembly in a Mark-B10 core. This configuration maximizes the effects of flow diversion at the Mark-B11 mixing grid locations and any associated DNB penalty. The same process as followed in the full core analysis was used and the calculation showed that the Mark-B11 DNB performance remains significantly above the Mark-B10 at between[b,c,d]and [b,c,d] increase in MAP limits. However, relative to the full core Mark-B11 RPS MAPs the mixed core values are in some cases higher and in some cases smaller. The maximum variation occurs for the[c,d]axial peak with the maximum increase being[b,c,d]at a normalized elevation (x/l) of[c,d]and the maximum decrease being[b,c,d] at an x/l of [b,c,d].

A comparison of the Mark-B11 and Mark-B10 designs shows that these results are expected. The Mark-B11 pressure drop is lower until the first mixing grid is encountered. Therefore, flow is being diverted at first into and then out of the Mark-B11. With the higher axial peaks, the point of MDNBR occurs closer to the point of maximum heat flux and, therefore, further down in the core. So, in the lower x/l cases there is a benefit in the mixed core configuration and as the point of MDNBR moves higher there is a penalty due to flow diversion out of the Mark-B11 assembly at the mixing grids.

### 7.3.2 Transient Analysis

The transient DNB analysis ensures that the 95/95 DNB criterion is met for transients of moderate frequency. The limiting, moderate frequency transient for 177 fuel assembly cores, in terms of DNB margin, is typically a partial loss of coolant flow transient such as a one or two pump coastdown. The statepoint analyzed is the steady state equivalent of the limiting time during the transient. The OL MAPs are determined in a manner similar to the RPS MAPs except that the DNB target is the MDNBR during the transient. The two pump coastdown was chosen for this margin comparison. Similar trends are expected for a one pump coastdown. The full and mixed core OL (transient) MAP analyses show that the Mark-B11 fuel provides increases in MAP margins greater than the RPS (steady state) MAP analyses. For the full core case the OL MAP margin increase is between[b,c,d] and[b,c,d] and for the mixed core case the increase is between[b,c,d] and [b,c,d].

All cases show positive MAP margin relative to the resident fuel thereby ensuring that the DNB criterion will be preserved during the transition to full core implementation of the Mark-B11 fuel design.

## 7.4 Fuel Rod Thermal-Hydraulic Evaluation

### 7.4.1 Fuel Rod Internal Pressure

The internal pressure of the peak fuel rod in the reactor is limited to a value below that which would cause the fuel-clad gap to increase due to outward cladding creep during steady-state operation thereby ensuring that extensive DNB propagation does not occur.

The Mark-B11 fuel rod internal gas pressure was determined using the TACO3 computer code per BAW-10162P-A [8] and the methodology defined in BAW-10183P-A [9]. The results show that the fuel rod can attain burnups in the range of GWd/mtU depending on the axial flux shapes used in the analysis. Inputs to the analysis include a power history that is assumed to envelop the operation of any individual fuel rod and worst case manufacturing variations allowed by the fuel rod specifications. Higher allowable burnups would be achieved on a cycle specifc basis by utilizing fuel rod specific power histories, fuel assembly as-built manufacturing data, and a more realistic total peak uncertainty.

### 7.4.2 Centerline Fuel Melt Limit

Fuel melting is not permitted during normal operating conditions or during anticipated operational occurrences. The TACO3 computer code was used to determine the local linear heat rate throughout the fuel rod lifetime that results in centerline temperature predictions exceeding $T_L$, a limit value chosen such that a 95% probability exists at the 95% confidence level that centerline melting will not occur. The most limiting time-in-life for the local linear heat rate is at the beginning of life. A typical generic centerline fuel melt limit is [b,c,d] for the Mark-B11 fuel rod.

## 8. NUCLEAR DESIGN EVALUATION

The Mark B-11 fuel assembly is similar to the Mark B-10 design from a neutronics viewpoint except that it has a smaller fuel rod diameter (0.416 inch vs 0.430 inch). Other changes, such as the design of the spacer grids, are minor.

The reduced fuel rod diameter results in a lower uranium loading and an increase in neutron moderation because of the added water in the fuel rod cell. On an equal enrichment basis, the Mark B-11 design initially exhibits greater reactivity than the Mark B-10 design. This difference diminishes with burnup and eventually it has less reactivity than the Mark B-10 design because the softer neutron spectrum resulting from the additional water in the cell has resulted in lower plutonium production. This behavioral difference has no adverse impact on the operation of the plant.

Shutdown margin is greater with the Mark B-11 design than with the Mark B-10, but this is not a significant factor because the plants that could utilize the Mark B-11 design all have more than sufficient control rod worth. Moderator coefficients are less negative throughout the cycle with the Mark B-11 design but well within the range normally encountered in reload designs. BOC moderator coefficients are easily controlled with burnable absorbers. A less negative EOC moderator coefficient is advantageous because of its beneficial effect on certain postulated accidents such as the steam line break and on shutdown margin. The Doppler coefficient is slightly less negative in the Mark B-11 design but within the range assumed in safety analyses.

From a physics viewpoint, the Mark B-11 assembly design does not present a large change from the Mark B-10 design and earlier designs already licensed and operated. The Mark B-11 can be used alone or in conjunction with the Mark B-10 or earlier designs without adversely affecting plant operation or safety.

# 9. ECCS EVALUATION

The Mark-B11 fuel assembly differs in design from other Mark-B fuel types such that its performance and coolability during a postulated LOCA must be evaluated. The two main differences affecting LOCA analyses are the change in the fuel pin outside diameter (OD) and mixing vane grids. The smaller pin OD reduces the surface area for heat transfer, while the mixing vane grids change the axial flow resistance. Analysis of the post-LOCA performance of the Mark-B11 fuel assembly has shown that it is in compliance with the five criteria of 10 CFR 50.46. The LOCA analyses were performed in accordance with the RELAP5/MOD2-based per BAW-10164P Rev. 3 [16] Evaluation Model (EM) described in BAW-10192P, Rev. 0 [17]. Analyses were performed for small and large LOCA scenarios. Noding and convergence sensitivity studies appropriate for each range of break sizes were also performed.

Two SBLOCA break spectrums were analyzed with Mark-B11 fuel using the BWU-Z CHF correlation. The first set of analyses postulated the LOCA from[c,d] percent full power and utilized two HPI pumps to mitigate the consequences of the SBLOCA. The second set of analyses was postulated from[b,c,d]percent power with one HPI pump and steam generator blowdown to augment the RCS depressurization rate.

Two sets of LBLOCA analyses were performed using the BWU-Z CHF correlation. The first set modeled an entire core of Mark-B11 fuel assemblies (whole-core). The second set modeled a core with Mark-B11 and Mark-B10, or hydraulically similar fuel assemblies, in mixed-core analyses. The increased resistance of the Mark-B11 mixing vane grid resulted in flow diversion out of the Mark-B11 assembly. Accordingly, any lead test assemblies or the first two full batches of Mark-B11 fuel incorporated into any core will have LBLOCA linear heat rate limits that are less than those calculated for the whole-core configuration.

## 10. DESIGN EVALUATION SUMMARY

The Mark-B11 fuel assembly was shown to meet all fuel assembly design criteria critical to safe and reliable operation. The features new to the Mark-B11 fuel design, which include the reduced diameter fuel rod, flow mixing vanes, and a redesigned grid restraint system, meet all fuel assembly mechanical, thermal-hydraulic, core physics, ECCS, and safety criteria. The standard Mark-BZ features maintained in the Mark-B11 assembly provide reactor proven design parameters that provide a basis for successful future performance. Design verification testing and analyses have demonstrated the acceptability of the added design features and ensure that Mark-B11 fuel assembly will operate safely and roliably. A detailed LTA program will further verifiy the Mark-B11 irradiation performance for benchmarking to existing models and data which have presently been defined as representative of the Mark-B11 design.

Acceptable Mark-B11 fuel assembly and fuel rod mechanical and thermal-hydraulic performance capability can be obtained for fuel rod average burnups up to [b,c,d] MWd/mtU. Therefore, FCF fully expects to utilize the burnups specified in BAW-10186P-A, "Extended Burnup Evaluation", and approved by the NRC, for the Mark-B11 fuel assembly design.

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