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EXTENDED-BURNUP LEAD TEST ASSEMBLY

— Design Report —

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1. INTRODUCTION

Increased fuel burnup is widely acknowledged as a straightforward and readily backfittable means for reducing uranium requirements in light water reactors operating in the "once-through" fuel cycle. Babcock & Wilcox (B&W), in conjunction with the U.S. Department of Energy and Arkansas Power & Light (AP&L) is engaged in a program to develop and demonstrate an extended burnup fuel assembly capable of burnups in excess of 50,000 MWd/mtU.[1,2] The in-reactor demonstration phases of this program call for AP&L to irradiate four first-phase extended burnup 15 by 15 lead test assemblies in the Arkansas Nuclear One, Unit 1 (ANO-1) reactor during cycles 5, 6, and 7.

This report describes and justifies the design of the first-phase extended burnup lead test assemblies (LTAs), which are similar in design to standard 15 by 15 fuel assemblies except for changes to the fuel rod and fuel assembly structural cage to extend their burnup capability. All four LTAs are to be extensively characterized before irradiation and examined after each cycle of operation.

2. SUMMARY

The extended-burnup LTA is termed the Mark BEB. Four such assemblies will be loaded in the ANO-1, cycle 5 core. Two of the four will contain segmented fuel rods and will have a specially designed end fitting for removal of these rods in the reactor fuel pool upon assembly discharge. The segmented rod design, based on the Mark BEB full-length rod, comprises five individual fuel segments, three of which are representative of a full-length rod.

The base Mark BEB design employs fuel rods of a solid pellet design; however, four full-length rods in each assembly and certain segments of the segmented rods contain annular pellets to gain incore high burnup experience with an annular fuel design (Mark BEB-A). The annular pellet was selected because of its lower operating fuel temperatures, which result in significantly reduced fission gas release from the fuel matrix. Lower end-of-life fuel rod internal pressures result from the annular pellets' combination of lower operating temperatures and the increased void volume from the pellet central void.

The heat treatment for the guide tube and instrument tube material was changed from stress relieving to full annealing to reduce fuel assembly irradiation growth, which has been identified as a limiting condition for extended burnup operation of standard Mark B fuel.[3]

Based on mechanical, nuclear, and thermal hydraulic analyses, the loading of four extended-burnup LTAs in the ANO-1, cycle 5 core will not adversely affect the performance characteristics of the reactor and will be bounded by existing safety analyses.

3. LEAD TEST ASSEMBLY DESIGN

Four extended-burnup LTAs are being fabricated for insertion in the ANO-1, cycle 5 core. The base design for the LTAs, along with some features unique to individual LTAs, are described below. Two variations to the base fuel design included in the LTAs are annular pellets and segmented fuel rods. Table 3-1 lists the major components of the LTAs. Figures 3-2 and 3-3 illustrate in detail the locations of the various fuel rod types.

3.1. Base Design

The LTA is a Mark BEB (15 by 15) fuel assembly that has been designed for extended burnup (>50,000 MWd/mtU) operation; the assembly is shown in Figure 3-1. Outside dimensions and external interfaces for both the Mark B and Mark BEB assemblies are the same.

In addition, the envelope dimensions of the base extended-burnup fuel rod design (Mark BEB, Figure 3-4) are identical to those of the standard Mark B. A fuel rod design with extended-burnup capability was obtained by (1) reducing the fuel column stack height to increase plenum volume, (2) decreasing fuel rod initial fill gas pressure to reduce end-of-life (EOL) internal pressure, and (3) increasing the cladding thickness to provide a more creep resistant rod. The pertinent fuel rod design parameters and dimensions are given in Table 3-2.

All the basic fuel rod internal components, e.g., upper and lower spring spacers and upper and lower tubular spacers, are similar in design to those of standard Mark B fuel rods with only slight dimensional changes to maintain interface dimensions.

3.2. Annular Pellet Fuel Rod (Mark BEB-A)

Some fuel rods in each LTA will be loaded with annular pellets which have a nominal inside diameter of 0.115 inch (Figure 3-5). The selection of this design is based on the following:

1. The annulus reduces the maximum fuel temperature. The lower maximum fuel temperature aids in the reduction of fission gas release and in turn reduces EOL fuel rod internal pressure.
2. The additional void volume of the annulus contributes to reduced EOL fuel rod internal pressure.
3. The annular pellet fuel rod has lower predicted EOL creep than the solid pellet fuel rod because of a higher beginning-of-life (BOL) internal pressure under operating conditions. The higher BOL pressure is created by the elevated gas temperature within the central annulus of the pellet. Therefore, the pressure differential across the cladding, which causes creepdown, is reduced.
4. The reduced smear density of the annular pellet causes an increase in the hydrogen-to-uranium atom ratio, yielding improved uranium utilization.

Annular pellet fuel rod dimensions are presented in Table 3-2, which shows that the annular and solid pellet fuel rod designs are similar. Mixed-oxide annular fuel pellets of similar design (10 vol %) have operated successfully in the past.[4-6]

3.3. Segmented Rods

Two of the four LTAs will each contain eight segmented fuel rods. The segmented rod design (comprising five individual fuel segments) is based on both the Mark BEB and Mark BEB-A full length rods; it provides three segments which are essentially abbreviated versions of the full length rods.

Two long sections, identical in design and length, and a shorter middle segment are the three components intended for possible use in a test reactor. Eight of the 16 middle segments will contain annular fuel pellets and the other eight solid fuel pellets. Sixteen of the long segments will be loaded with annular fuel pellets and 16 with solid pellets. The upper and lower end segments contain solid fuel pellets and complete the rod, making its length equivalent to the Mark BEB and Mark BEB-A full-length rods. Active fuel lines at the top and bottom of the assembly coincide with those of full length rods. Figure 3-6 depicts the relationship of a segmented rod to a fuel assembly.

Figures 3-7 and 3-8 show the internal configurations of the long and short sections, respectively. Hafnia-yttria pellets act as flux suppressors in the coupling region between the sections. The spring, which holds the internals in place during shipping and handling, also permits fuel growth during operation. The individual segments are joined by inserting their intermediate plugs into a cladding sleeve to which they are welded. Design parameters for the segmented rods are presented in Table 3-3.

Table 3-1. Lead Test Assembly Components

Assembly component	No. of components per assembly: NJ023P[a] NJ023Q	No. of components per assembly: NJ023R NJ023S
Removable rod upper end fitting	1	--
Mark B upper end fitting	--	1
Mark B lower end fitting	1	1
Mark BEB fuel rod	196	204
Full-length annular pellet fuel rod	4	4
Segmented fuel rod	8	--
Annealed guide tubes	16	16

[a] Assembly identification.

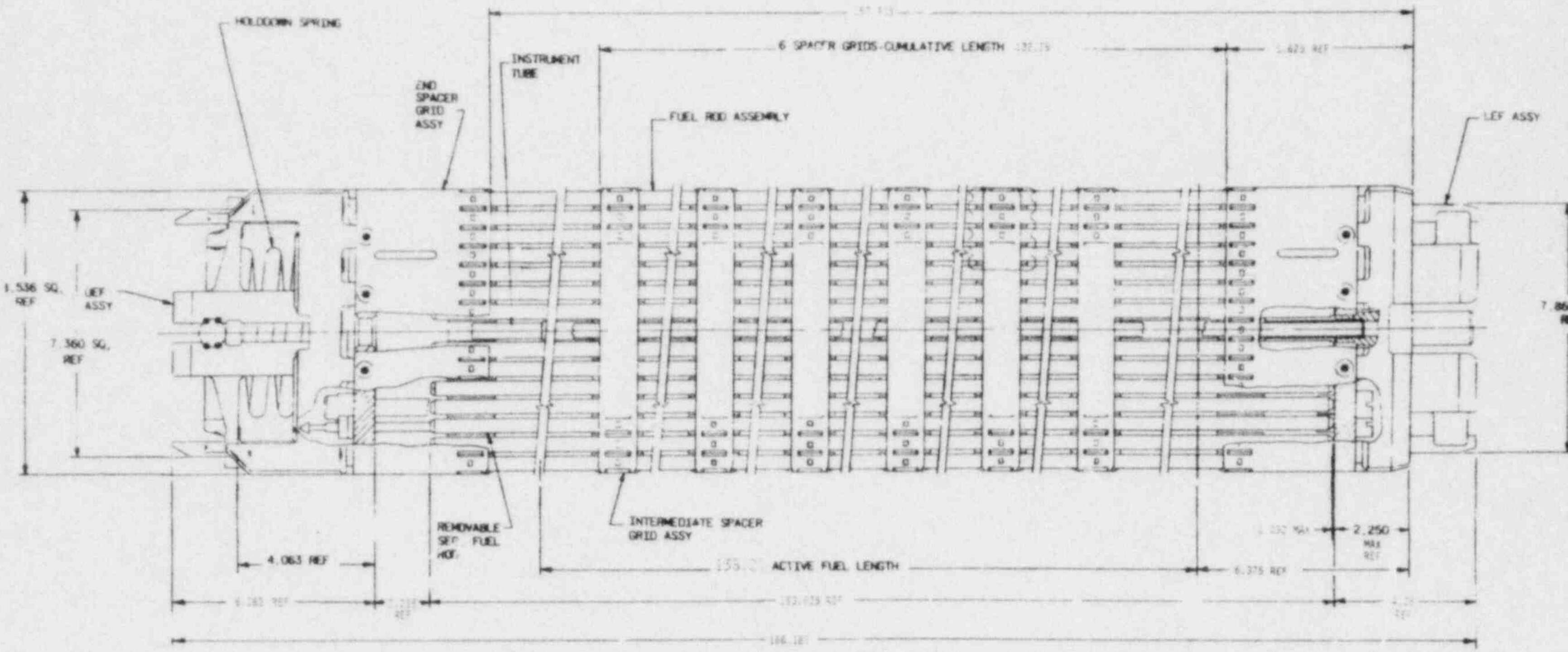
Table 3-2. Lead Test Assembly Fuel Rod Designs

Parameter	Mark B (nominal) design	Mark BEB solid pellet design	Mark BEB-A annular pellet design
Cladding			
OD, in.	0.4300	0.4300	0.4300
ID, in.	0.3770	0.3710	0.3710
Wall, in.	0.0265	0.0295	0.0295
Pellet			
OD, in.	0.3686	0.3635	0.3635
ID, in.	--	--	0.115
Length, in.	0.600	0.418	0.418
Density, % TD	95	95	95
Fuel Rod			
Stack height, in.	141.80	138.251	138.25
Fuel rod length, in.	153.6875	153.625	153.625
UO_2 loading, g	2528.6	2400.0	2200.0

Table 3-3. Segmented Rod Design Parameters

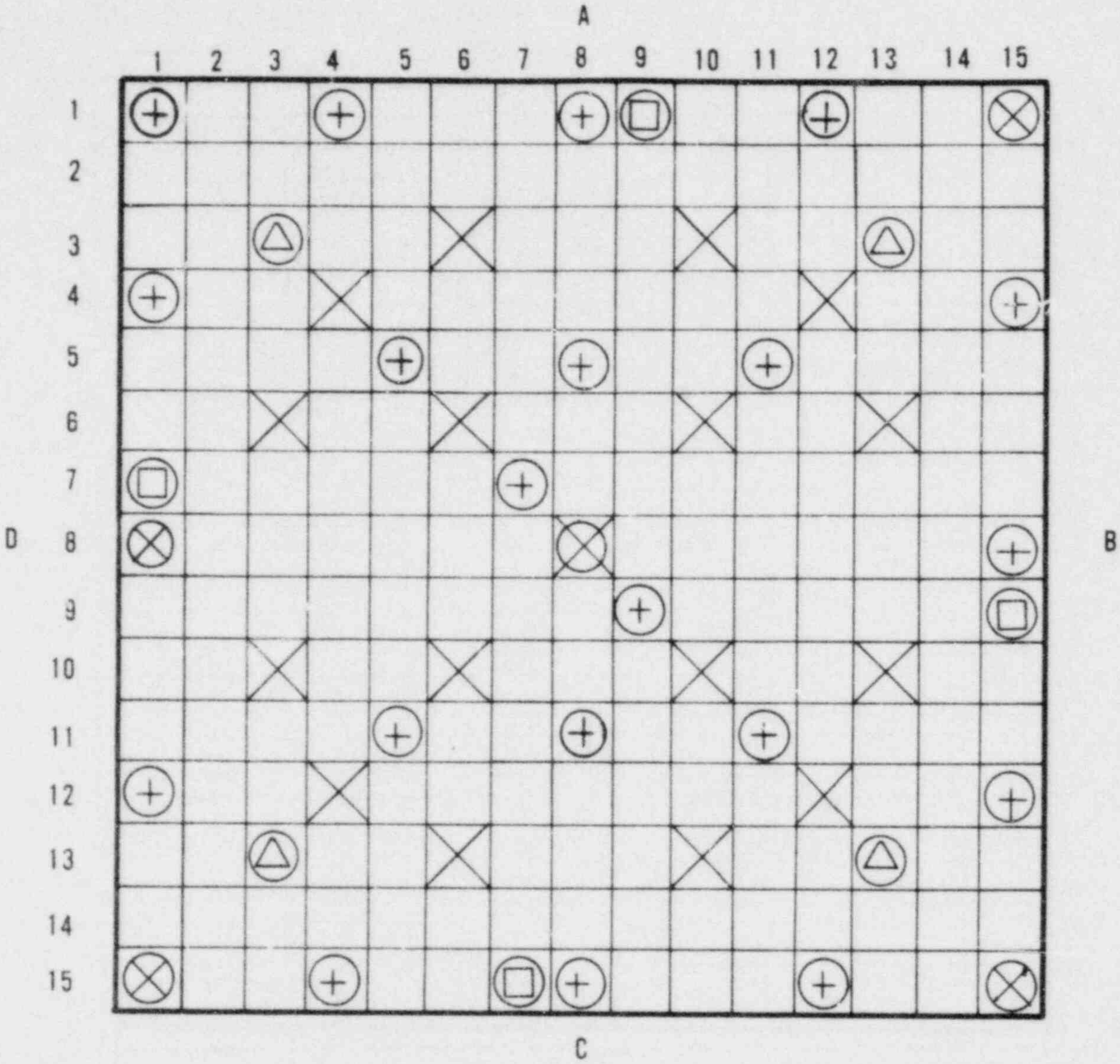
	Lower end segment	Long segment	Short segment	Upper end segment	Fuel rod total
No. per assembly	8	16	8	8	8
No. per full-length rod	1	2	1	1	5
Segment length, in.	25.932	43.307	20.005	21.077	153.625
Cladding length, in.	25.057	42.120	18.818	20.2025	148.32
Fuel stack length, in.	14.75	34.75	14.00	10.813	109.63
Fuel stack UO_2 loading, g	256.06	603.25 553.05	243.03 222.81	187.71	1893.29 1772.67
Type of pellet	Solid	Solid annular	Solid annular	Solid	--
Lower spring free length, in.	3.5	None	None	None	--
Upper spring free length, in.	2.4687	3.4687	2.4687	6.5928	--
No. of hafnia pellets	2	5	3	1	16
No. of tubular spacers	2	2	1	2	9

Figure 3-1. Mark BEB Fuel Assembly, General Arrangement



Note: Dimensions in inches.

Figure 3-2. Fuel Rod Placement Chart, Segmented Fuel Rod Fuel Assemblies



LEGEND

⊗ ANNULAR FUEL ROD ASSEMBLIES - 4 EACH

⊕ PRECHARACTERIZED SOLID FUEL PELLET ROD ASSEMBLIES - 20 EACH

INSTRUMENT TUBE LOCATION - 1 EACH

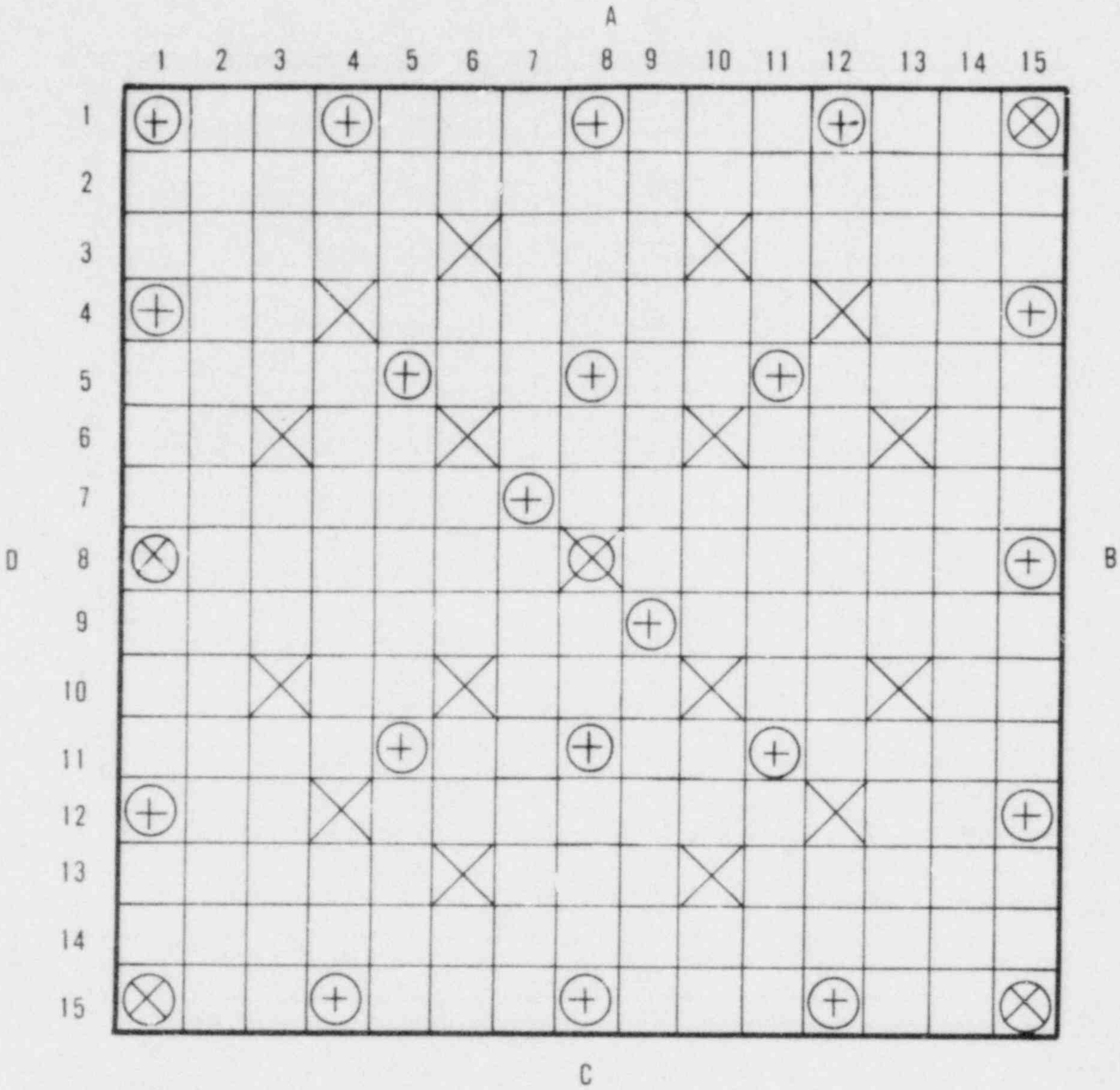
NON-REMOVABLE SEGMENTED FUEL ROD ASSEMBLIES - 4 EACH

REMOVABLE SEGMENTED FUEL ROD ASSEMBLIES - 4 EACH

× GUIDE TUBE LOCATION - 16 EACH

Note: Remaining locations are filled with non-precharacterized solid fuel pellet rod assemblies, 176 each.

Figure 3-3. Fuel Rod Placement Chart, Non-Segmented Fuel Rod Fuel Assemblies



LEGEND

⊗ ANNULAR FUEL ROD ASSEMBLIES - 4 EACH

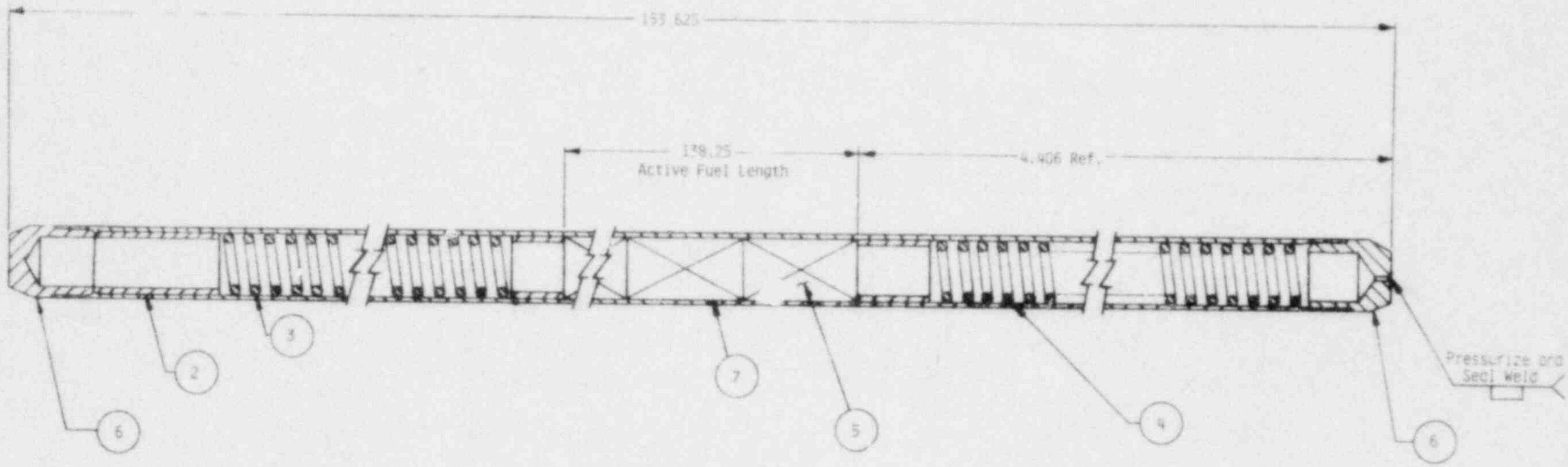
⊕ PRECHARACTERIZED SOLID FUEL ROD ASSEMBLIES - 20 EACH

⊠ INSTRUMENT TUBE LOCATION - 1 EACH

× GUIDE TUBE LOCATIONS - 16 EACH

Note: Remaining locations are filled with non-precharacterized solid fuel pellet rod assemblies, 184 each.

Figure 3-4. Mark BEB Pressurized Fuel Rod Assembly



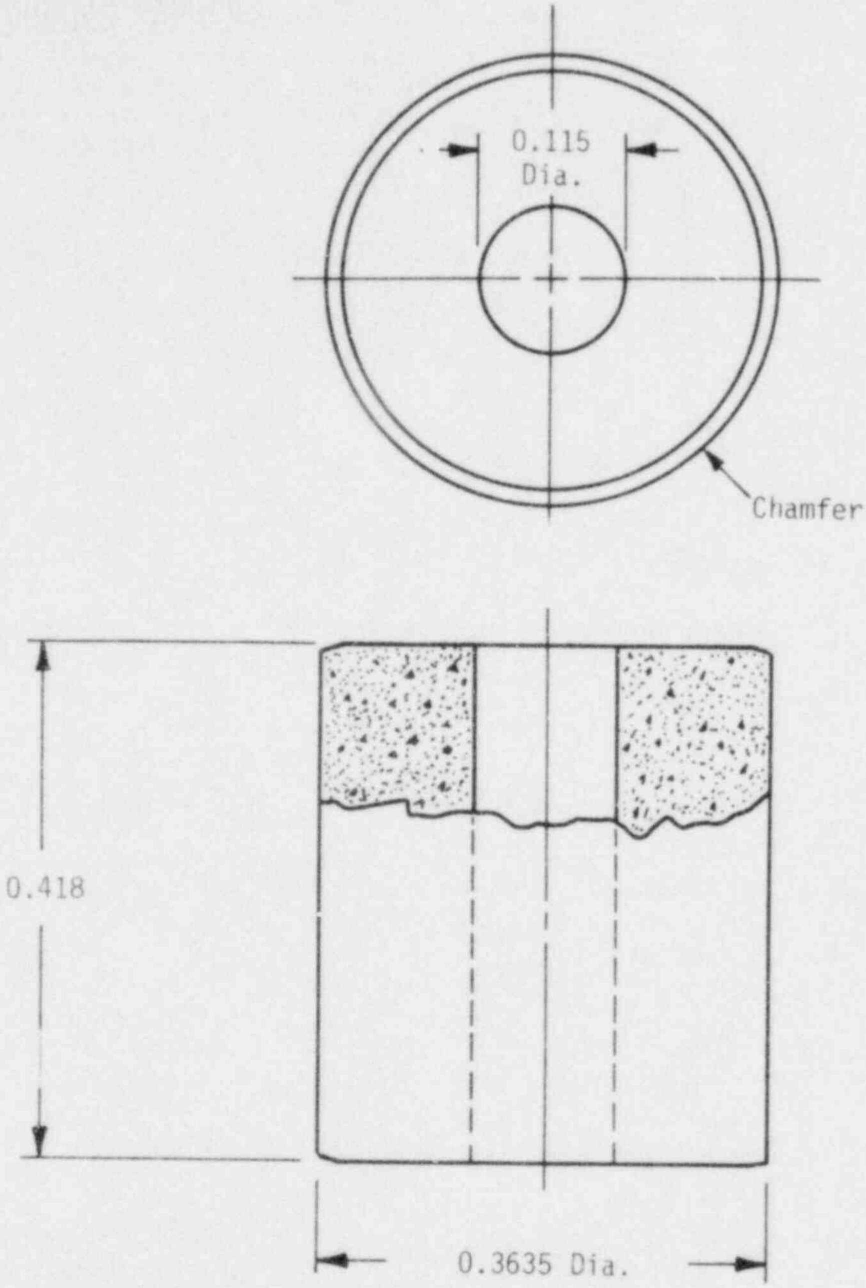
(1) MARK BEB PRESSURIZED FUEL ROD ASSEMBLY

Cladding OD, in.	0.430
Cladding ID, in.	0.371

Note: Dimensions in inches.

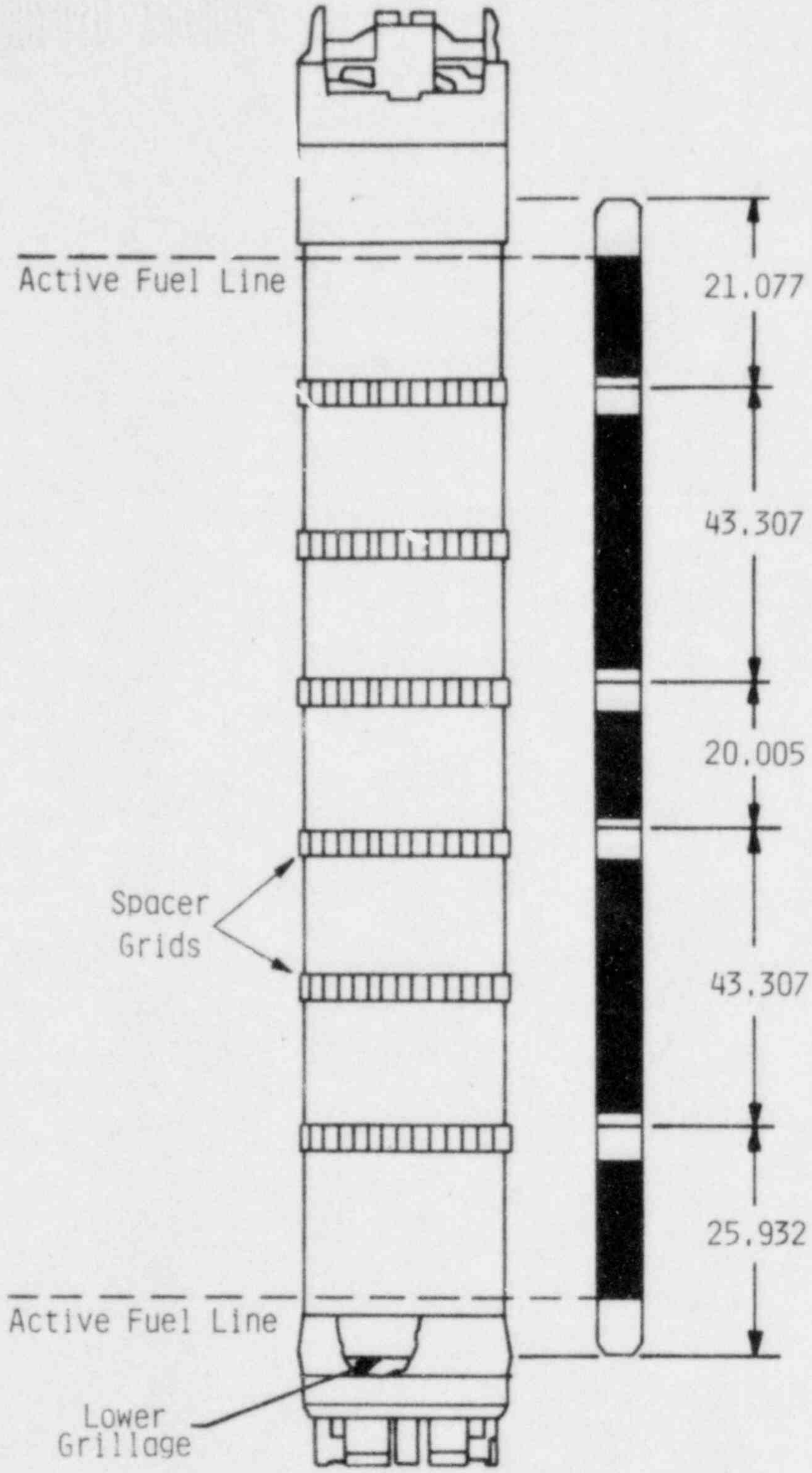
Item No.	Description
1	Mark BEB Pressurized Fuel Rod Assembly
2	Fuel Rod Tubular Spacer C
3	Upper Spring Spacer
4	Lower Spring Spacer
5	UO_2 Fuel Pellet
6	End Cap
7	Fuel Rod Cladding

Figure 3-5. Mark BEB Annular Fuel Pellet



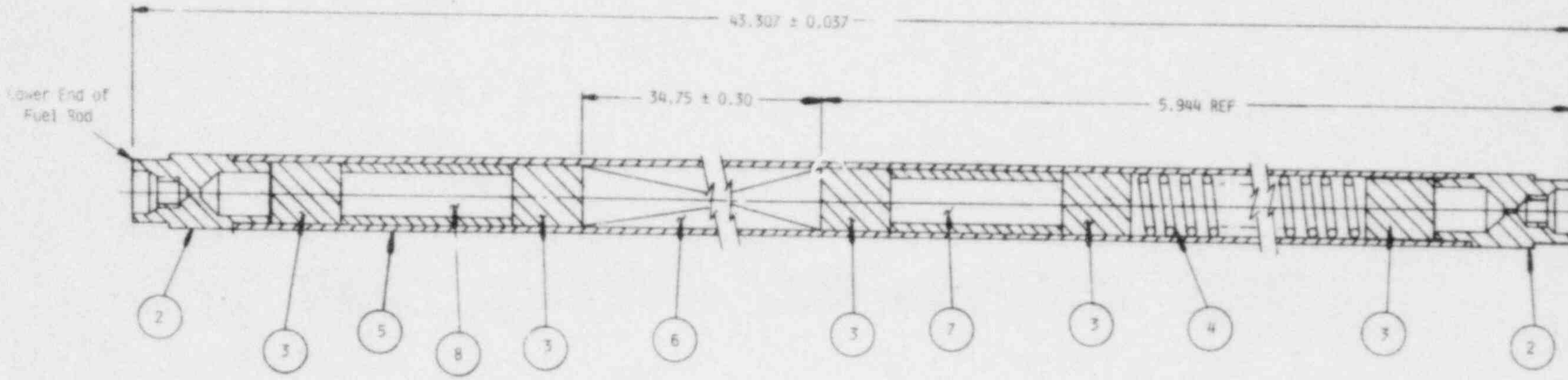
Note: Dimensions in inches.

Figure 3-6. Segmented Rod Vs Fuel Assembly



Note: Dimensions in inches.

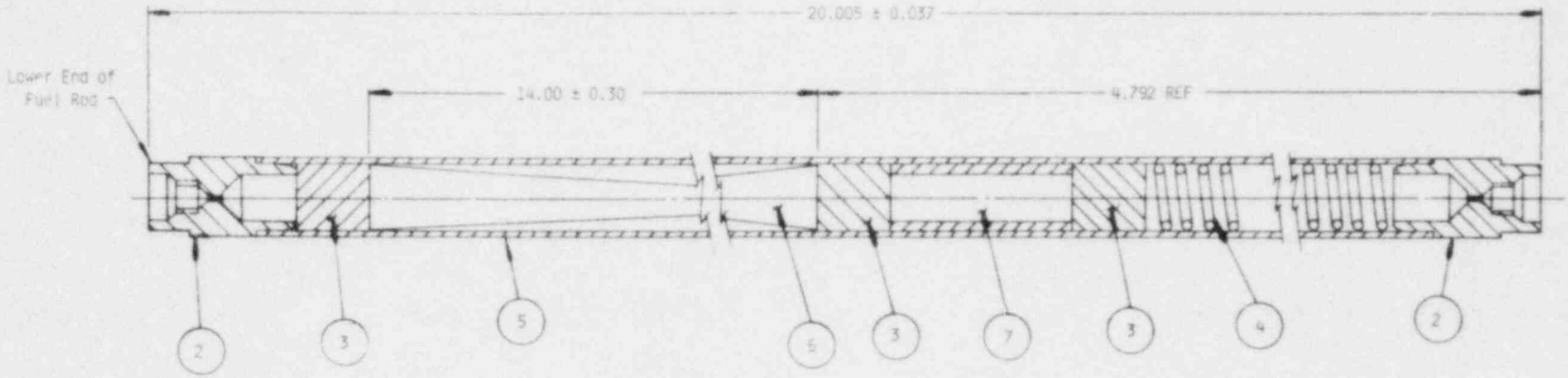
Figure 3-7. Long Fuel Rod Segment



(1) Fuel Rod Assembly, Long Segment
(2) Intermediate Plug
(3) Hafnia-Yttria Pellet
(4) Spring
(5) Cladding
(6) Active Fuel
(7) Tubular Spacer

Note: Dimensions in inches; not to scale.

Figure 3-8. Short Fuel Rod Segment



(1) Fuel Rod Assembly, Short Segment
(2) Intermediate Plug
(3) Hafnia-Yttria Pellet
(4) Spring
(5) Cladding
(6) Active Fuel
(7) Tubular Spacer

<u>Note</u>: Dimensions in inches, not to scale.

4. FUEL SYSTEM DESIGN

4.1. Fuel Assembly Mechanical Design

The LTA analysis includes those areas in which the design or service conditions of the assemblies differ from those considered in the evaluation of the sta: rd Mark B fuel assembly. Where no differences exist, the analyses performed on the standard Mark B assembly apply. Normal operation, transient events, emergency and faulted conditions, and handling are all addressed in the LTA analyses, but it is primarily in the area of normal operation that substantial differences exist. The changes in assembly hardware and the analyses of these changes are discussed below.

4.1.1. Hardware Changes in Structural Cage

The structural cage is defined as all components of the fuel assembly except the fuel rods. Changes were made in three areas: guide tubes and instrument tube, assembly holddown springs, and upper end fitting.

Fuel assembly growth has been identified as a limiting condition for extended burnup operation of standard Mark B fuel.[3] To reduce fuel assembly irradiation growth, the guide tube and instrument tube material heat treatment for the LTAs has been changed from stress-relief to full recrystallization annealing since the growth rate of the fully annealed material is about one-quarter of that for cold worked stress-relieved material. Weld strength and elastic buckling, the limiting structural criteria for the assembly, are unaffected by the material change; thus, this change does not reduce the load-carrying capacity of the guide tube assembly. With the alteration in the guide tube heat treating process, the LTA has an assembly burnup limit of 62,000 MWd/mtU from fuel assembly growth, which exceeds the target burnup of 50,000 MWd/mtU for the LTAs. Because of the decrease in fuel assembly irradiation growth, fuel rod growth becomes the limiting constraint in the LTA design, yielding an assembly burnup limit of 58,000 MWd/mtU.

The LTA is about 24 lb lighter than the standard Mark B assembly because of a reduction in fuel loading. To compensate for this weight reduction, the Inconel X-750 (No. 1 temper) holddown spring of the standard Mark B assembly has been replaced with a stronger Inconel 718 spring. As in the standard Mark B spring, the dimensions are (1) wire diameter 0.472 in., (2) coil diameter 4.665 in., and (3) free height 5.9 in. The Inconel 718 spring increases the minimum holddown force by 70 lb producing an increase in net holddown force of 46 lb. In addition, the increased strength of Inconel 718 results in improved stress margins for springs fabricated from this material when compared to the Inconel X-750 spring.

4.1.2. Removable Rod End Fitting Design

The upper end fittings (UEF) of two lead test assemblies allow for removal of four fuel rods from each assembly at the reactor site. The requisites for the removable rod UEF design were as follows:

1. Allow removal of designated fuel rods on-site, preferably in the spent fuel pool.
2. Permit reinsertion of a dummy rod in the vacated location.
3. Maintain compatibility with handling equipment and interfaces of the other fuel components.

Each removable rod has a special end cap (see Figure 4-1). The corresponding UEF has a threaded ring welded in the grillage (Figure 4-2). A hollow bolt and locking ring are installed subsequent to the positioning of the end fitting. The bolt is hollow to accommodate the fuel rod end cap, which passes through it. After assembly of the components, both sides of the locking ring are crimped onto the slotted area of the bolt (Figure 4-3).

Since the end fitting grillage is a highly redundant structure, weakening of a local area merely shifts the stress to other webs, resulting in a negligible change in maximum stress. The analysis of the grillage conservatively assumes no structural contribution from the plug and shows an increase of less than 1% in maximum stress. The plug itself has also been analyzed and has been shown adequate for impact by a fuel rod under accident conditions and for normal operating loads.

After irradiation, the rod can be removed in the spent pool by unlocking and completely unscrewing the bolt with a special mating tool and inserting an instrument which lifts the rod, bolt, and ring in a single operation. A replacement rod can be installed by reversing this procedure.

Figure 4-2 shows the location of the threaded rings in the UEF. An exploded view of the parts as they mate is presented in Figure 4-3. Figure 4-1 shows the completed assembly. Prototype parts and the assembled prototype are shown in Figures 4-4 and 4-5. The assembling procedure for the fuel assemblies with the removable rods is the same as for the standard Mark B assembly.

4.2. Fuel Rod Design

The LTAs will contain solid pellet fuel rods, rods loaded with annular pellets, and segmented fuel rods. In order to evaluate the performance of these fuel rods, various design analyses were performed.

4.2.1. Design Analyses — Solid Pellet

All the LTAs will have fuel rods containing solid pellets. The analyses described below were performed to determine the effects of extended burnup on this design.

4.2.1.1. Cladding Collapse

Using the CROV computer code*, the fuel rod was designed to preclude creep collapse within the design life. The creep collapse analyses were performed using power histories that track the most limiting assembly so that the most limiting collapse time was obtained. The collapse time was conservatively determined to exceed a design life of 35,500 EFPH (corresponding assembly burnup 50,000 MWd/mtU) which is greater than the anticipated LTA incore residence time of ~31,000 EFPH.

4.2.1.2. Cladding Stress and Strain

Stress and strain limits are imposed to ensure that the cladding stresses are less than the allowable material strength and that the strain capability of the cladding is not exceeded. The following design criteria were used for the stress and strain analyses:

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*See Glossary, page A-1.

1. Primary membrane stresses (which are not relieved by small material deformation) are not to exceed two-thirds of the minimum unirradiated yield strength.
2. Primary membrane plus bending stresses are not to exceed the minimum unirradiated yield strength.
3. The average circumferential strain is not to exceed 1% inelastic strain (+0.4% elastic strain).

The stress analysis was performed using thick shell equations with stresses evaluated at both the inside and outside diameters. This analysis follows the format and procedures outlined in Section III of the ASME Boiler and Pressure Vessel Code (1971) generally used to organize stresses into various categories; the stresses are combined to determine stress intensity. The cladding strain criterion above, based on work by O'Donnell[7], addresses failure due to plastic instability of the cladding. The criterion described in reference 7 shows that the allowable hoop strain in the temperature range of interest (>600F) is 2%. Hence, the use of 1% as a criterion is conservative.

Using the aforementioned techniques, the Mark BEB solid pellet fuel rod has been designed to operate to a maximum fuel rod average burnup of more than 60,500 MWd/mtU.

4.2.1.3. Cladding Fatigue

Combinations of system operating transients were evaluated to ensure that the cumulative usage factor as defined by the ASME Code, Section III, Paragraph NB-5222.4, would be less than 0.9 of the allowable material fatigue life (this is an additional conservatism over the ASME Code recommendation of 1.0). The system transients considered were events causing cyclic stress, such as heatup and cooldown.

A cumulative usage factor was calculated from fatigue curves based on the O'Donnell and Langer curves.[8] The cumulative usage factor for the Mark BEB solid-pellet fuel rod design was lower than the design criterion of 0.9.

4.2.1.4. Thermal Design

The thermal design objective for the extended-burnup LTA fuel is to provide a conservative fuel rod design based on the following criteria:

1. The LTA shall not restrict core allowable local power limits (kW/ft); that is, the LTA fuel shall not be limiting in terms of linear heat rate to fuel melt (HRTM) relative to the Mark B fuel. The Mark B design comprises the remainder of the ANO-1 core and forms the basis for the maximum allowable heat rates used in reload fuel cycle design and in reactor protection system trip limits.
2. The LTA fuel rod (or segment) internal pressure shall not exceed nominal reactor coolant system pressure (2200 psia) during normal operations up to a rod average burnup of 60,500 MWd/mtU.

The HRTMs and rod internal pressures were calculated using the TACO2 computer code.[9]* This fuel performance program includes models for fuel densification, swelling, cladding creep, and fission gas production and release. The TACO2 calculations were based on bounding fuel densification kinetics, in which the maximum densification was assumed for temperature and heat rate calculations to maximize the fuel-cladding gap and minimize the active fuel stack height, and the minimum densification was assumed for pressure calculations to minimize the rod free volume. This technique yields conservative predictions for both fuel temperature and rod internal pressure.

Both fuel rod temperature and internal pressure are affected by the release of fission products (xenon and krypton). Because the fission gas release model in TACO2 is temperature-dependent, fuel rod power is important since it directly affects temperature and thus fission gas release. Conservatism is built into the TACO2 predictions by using bounding axial flux and burnup shapes and a bounding fuel rod power history. The very conservative assumed fuel rod power history envelops both the ANO-1 cycle 5 fuel cycle design fuel rod peaks and burnups and the standard Mark B fuel rod power history.

The minimum HRTM for the full-length solid-pellet fuel rod was calculated to be 21.1 kW/ft based on design peaking limits. Since this maximum allowable heat rate is higher than the cycle 5 minimum HRTM (20.15 kW/ft based on standard Mark B fuel) the full-length rod with solid pellets will not make the LTA the limiting assembly in the core.

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*Glossary, page A-1.

The fuel rod maximum internal pressure of 2196 psia is shown as a function of burnup in Figure 4-6. The predicted rod internal pressure does not exceed nominal reactor coolant (RC) system pressure, 2200 psia. The actual rod internal pressure will be less than that shown in the figure by an amount dependent on the difference between the design power peaks and the actual power peaks and burnups experienced.

4.2.2. Design Analyses — Annular Pellet

Design analyses (cladding collapse, stress, strain, fatigue, and thermal evaluation) as previously discussed in section 4.2.1, were also performed for the annular fuel pellet design. These evaluations have shown that the annular-pellet fuel rod design will operate to extended burnup with lower rod internal pressure and lower EOL creep relative to the solid-pellet rod design.

The minimum HRTM for the rod containing annular fuel pellets is greater than that calculated for both the full-length rod with solid pellets and the current Mark B fuel based on the same bounding densification kinetics and design peaking. Hence, the full-length annular-pellet rods are not the limiting rods in the core.

The maximum predicted internal pressure, 1635 psia, is shown as a function of burnup for the full-length annular-pellet rod in Figure 4-6. The predicted internal pressure does not exceed nominal RC system pressure. The lower internal pressures of the annular pellets (as compared to solid pellets) is evident and is the result of both greater void volume and lower fuel temperatures in the annular-pellet rod. As with the full-length solid-pellet rod, the predicted internal pressure of the annular-pellet rod will be reviewed before each subsequent cycle of LTA residence along with the comparison of the design fuel rod power history envelope to the current cycle actual fuel rod peaks and burnups.

4.2.3. Design Analyses — Segmented Rod

The specification for the fuel pellets and cladding for the segmented rod are the same as those of the Mark BEB full-length rod. Additional mechanical analyses performed to specifically delineate the characteristics of the segmented rod included intermediate plug stress, creep collapse, and fuel rod cladding strain.

4.2.3.1. Intermediate Plug Stress

As previously mentioned in section 3.3, the individual sections of the rod are joined by inserting the intermediate plugs into a cladding sleeve to which they are welded. The design of these "plugs" must meet two requirements:

1. The entire segmented rod, when welded together, must satisfy the full length cladding straightness criterion of ±0.010 in./ft.
2. Segment integrity must be maintained.

An added design feature of the intermediate plug is the threaded area, indicated by dotted lines (see Figure 4-7), which facilitates handling of the segments after separation.

A mechanical analysis was performed for the intermediate plug; the following results were obtained: the cladding, weld, and plug showed very little thermal stress; stresses due to thermal gradients in the sleeve weld joining the plugs were insiginficant; the plug is structurally adequate for system pressure loads and withdrawal drag loads.

4.2.3.2. Cladding Collapse

Cladding creep collapse analyses were performed using the CROV* code in which the collapse time is a function of power history, temperature, changes in fuel rod pressure throughout life, fast flux, and cladding dimensions. Except for the upper end segments, each segment was analyzed for the same initial minimum fill gas pressure as the Mark BEB full-length rod. Since the upper end segment had a small amount of fuel (due to the design of the segmented rod), its large plenum volume/fuel volume ratio resulted in low internal pressures near EOL. Thus, a slightly higher initial pressure was required to provide the desired creep collapse margin. Collapse times for all segments were determined conservatively to be >35,500 EFPH, which is greater than their expected incore residence time of ~31,000 EFPH.

4.2.3.3. Cladding Strain

A cladding strain analysis was conducted for the segmented fuel rod using the TACO2 computer code[9] to simulate pellet/cladding strain — a maximum segment

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*See Glossary, page A-1.

average burnup of 62,000 MWd/mtU was modeled. Cladding transient strain was calculated for a pellet burnup of 73,000 MWd/mtU. Using conservative fuel rod dimensions and transient conditions, uniform transient strain was confirmed to be less than the design limit of 1.0%.

4.2.3.4. Thermal Design

The thermal design criteria and methods for rod segments are the same as described in section 4.2.1.4 for full-length rods. The minimum HRTM calculated for any of the rod segments is 21.1 kW/ft, which is greater than the cycle 5 minimum HRTM and equal to the full-length solid-pellet LTA rod HRTM. Hence, none of the rod segments will make the LTA the limiting assembly in the core.

The maximum internal pressure as a function of burnup for each rod segment is shown in Figure 4-8. The segment maximum internal pressures are less than those of the full-length solid-pellet LTA rod because of differences in volumes and fuel temperatures. Rod internal pressure does not exceed the nominal RC system pressure. As with the other two types of LTA fuel rods, the rod segment predicted internal pressures will be reviewed before each subsequent cycle of LTA irradiation along with the comparison of the design fuel rod power history envelope to the current cycle actual fuel rod peaks and burnups.

4.3. Material Design

The chemical compatibility of the fuel cladding/coolant/assembly interactions for the LTAs is identical to that of the standard Mark B fuel.

Figure 4-1. Removable Fuel Rod End Fitting Components

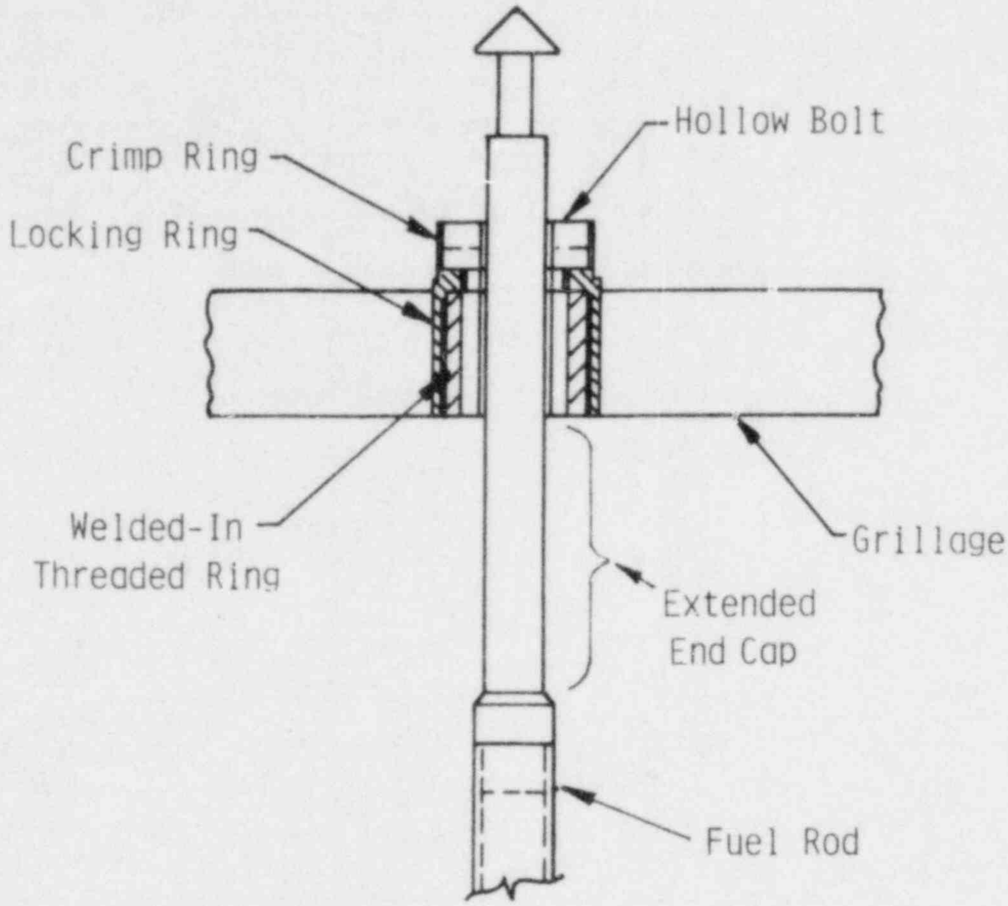

Figure 4-2. Removable Fuel Rod UEF Threaded Ring

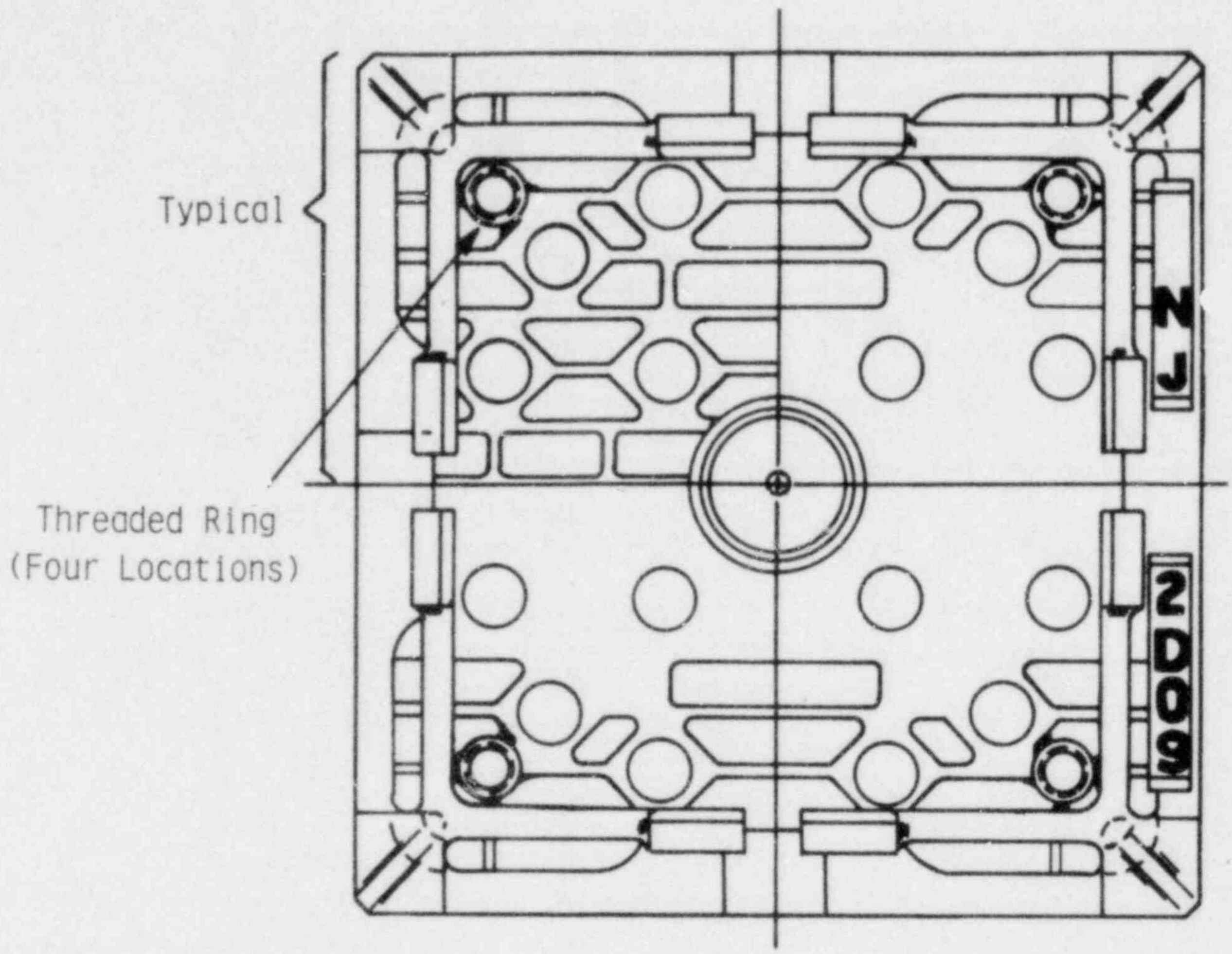

Figure 4-3. Removable Fuel Rod UEF Components

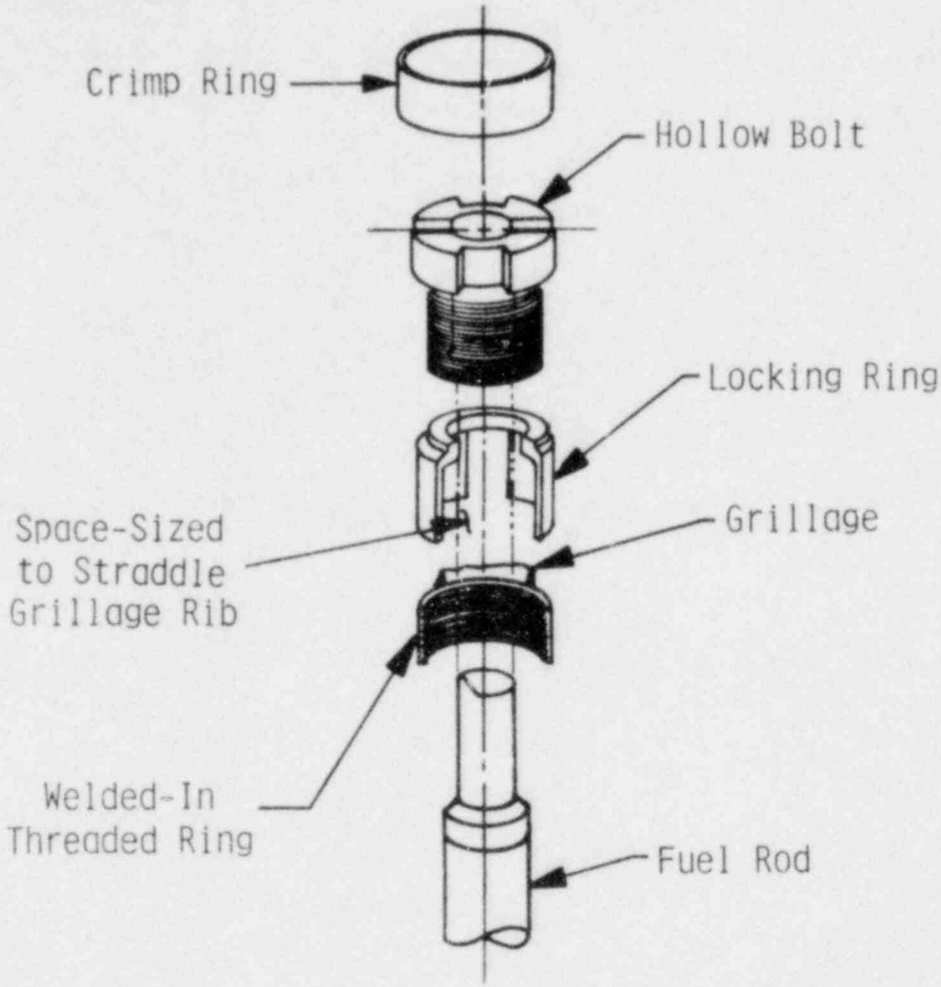

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Figure 4-4. Removable Fuel Rod UEF Components

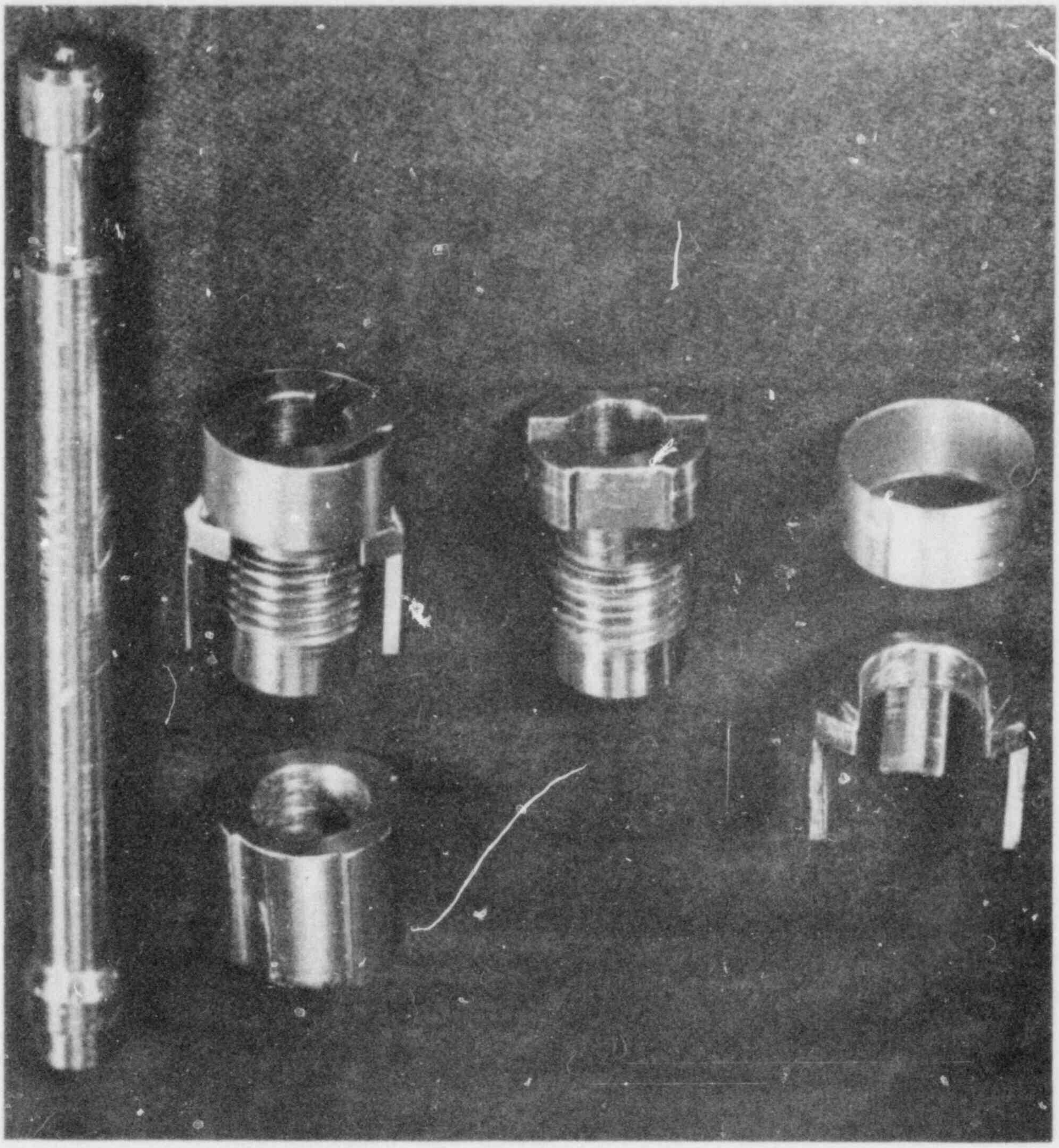
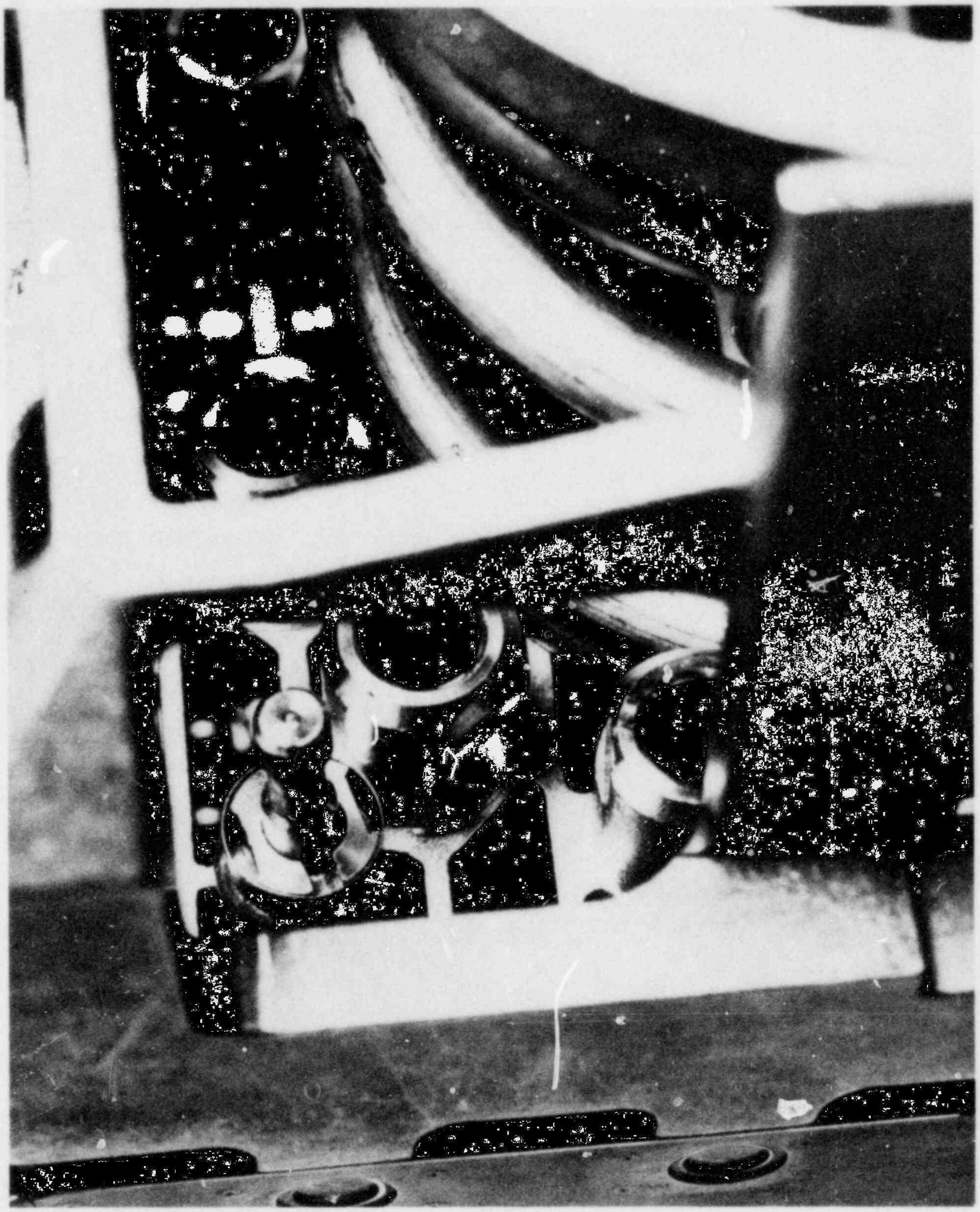


Figure 4-5. Assembled Removable Fuel Rod UEF



POOR ORIGINAL

Figure 4-6. Fuel Rod Internal Pressure Vs Burnup for Full-Length Rods

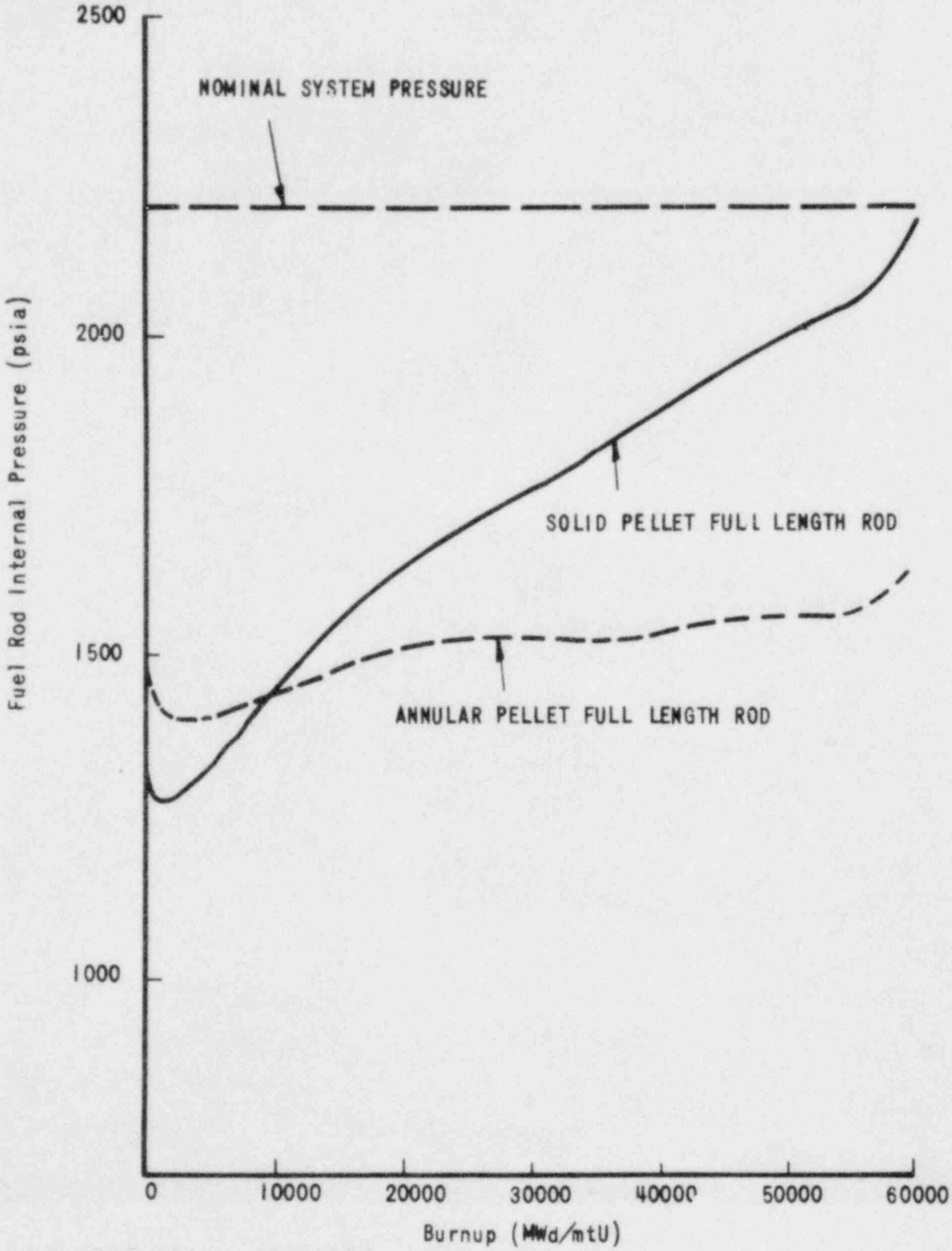


Figure 4-7. Intermediate Plug Design

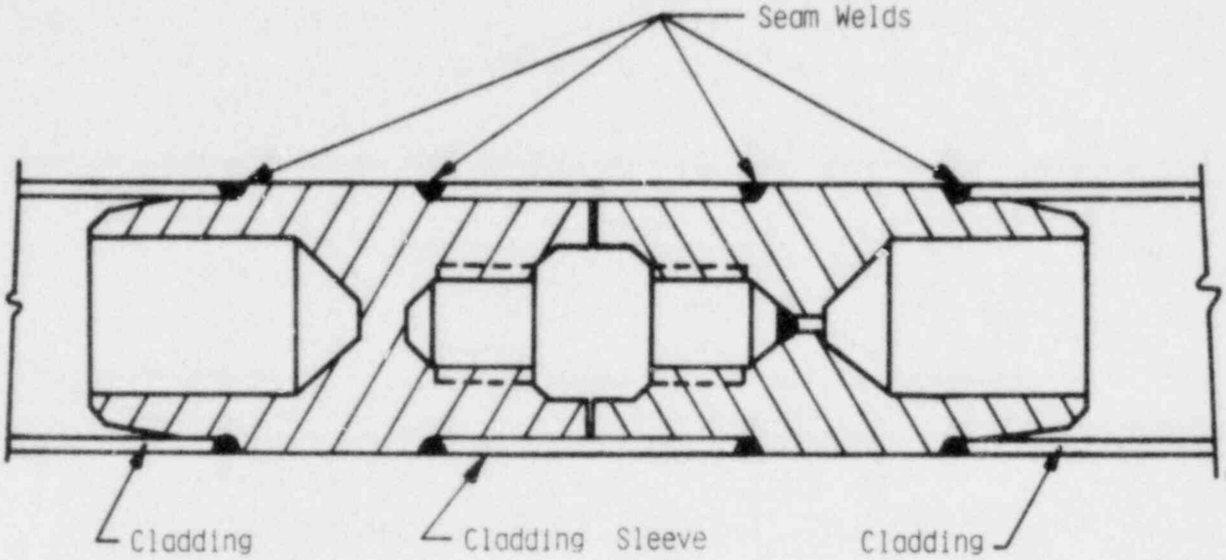
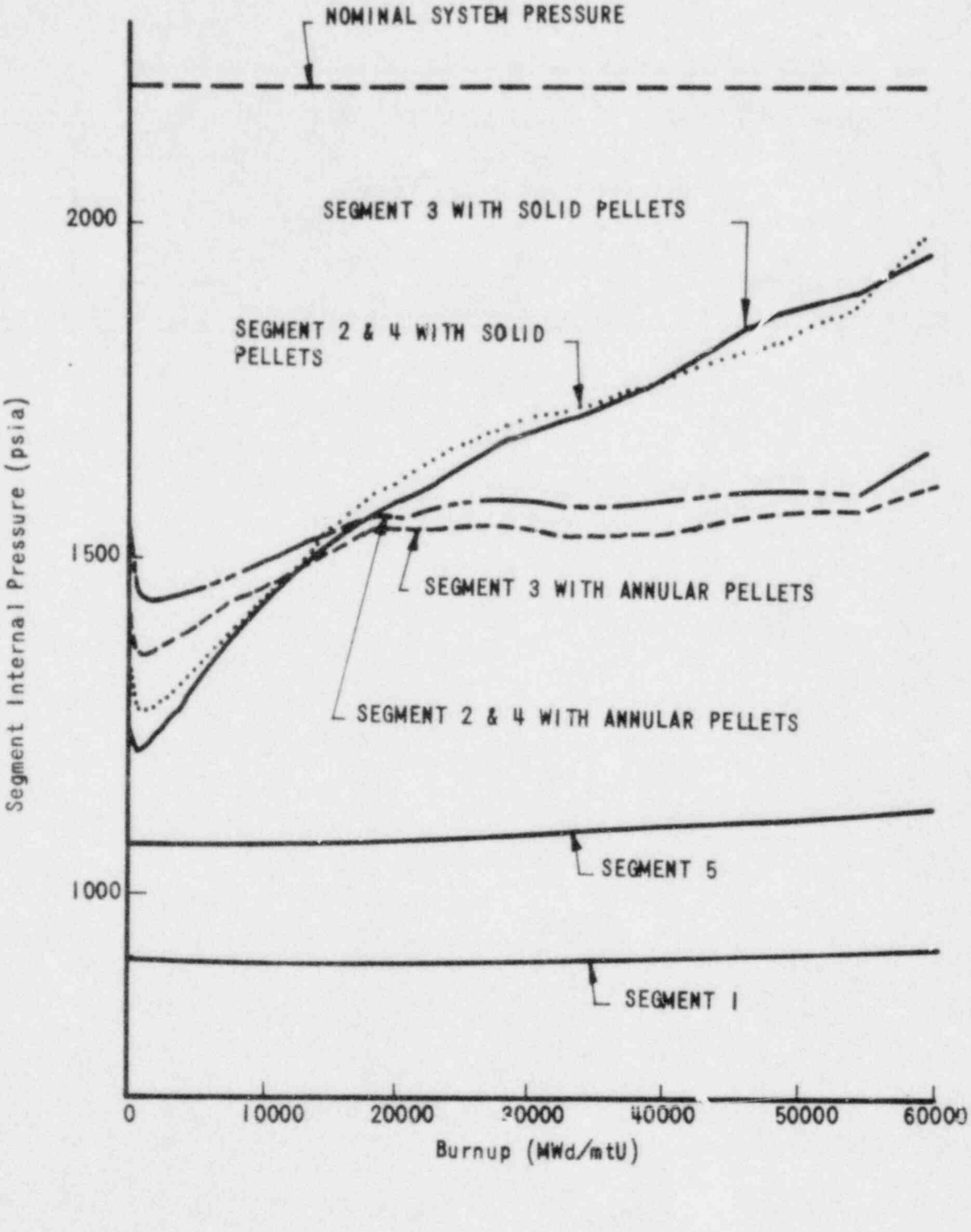


Figure 4-8. Fuel Rod Segment Internal Pressure Vs Burnup



5. NUCLEAR DESIGN

The core loading map for ANO-1 cycle 5 is shown in Figure 5-1. The Mark BEB LTAs will be located in symmetric core locations M12, M4, E4, and E12. The enrichment will be 2.95 wt % ^{235}U, the same as the standard design Mark B batch 7 fuel assemblies. Batch 7 is the feed batch for cycle 5 of ANO-1. Figure 4-2 shows the quarter core power distribution at the beginning of cycle 5.

5.1. Physics Characteristics

The LTA was modeled using the PDQ, NULIF and DOT computer codes.* Physics characteristics for the fuel and the assembly were examined to determine the maximum power peaks that would be experienced.

5.1.1. LTA Solid Pellet Fuel Rod

The overall nuclear characteristics of the LTA solid-pellet fuel rod are similar to those of the Mark B fuel rod. However, the smaller pellet diameter (0.3635 Vs 0.3686 in., Table 3-2) causes the Mark BEB fuel rod to have a higher water-to-uranium ratio, which has two effects: (1) more neutron moderation, resulting in a slightly larger thermal-to-fast flux ratio (a positive reactivity effect) and (2) a larger soluble boron-to-fuel ratio, which — combined with the larger thermal flux — results in a greater soluble boron reactivity worth. At the beginning of cycle 5 (BOC-5) when the soluble boron concentration is large, the positive reactivity effect of the larger thermal flux is overshadowed by the larger absorption rate of the soluble boron. The net result at BOC-5 is that the Mark BEB fuel rod has a 1.8% lower relative power density than the comparable Mark B fuel rod. As the soluble boron concentration decreases over the course of cycle 5, the positive reactivity effect of the larger thermal flux predominates, and by the EOC-5, relative power density of the Mark BEB rod exceeds that of a comparable Mark B fuel rod by 2.0%.

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*See Glossary, page A-1.

5.1.2. Annular-Pellet Fuel Rod

Four fuel rods with annular pellets are placed in the corner fuel rod locations of each LTA. The annulus represents a 10% decrease in fuel volume compared to that of he LTA solid pellet. Consequently, the lower uranium loading results in a relative increase in the thermal-to-fast flux ratio and a larger soluble boron worth. The annular pellet also has a reactivity gain due to its lower average fuel temperature. Cumulatively, these changes cause a reduction in the fuel rod power density to 1.9% below that of the LTA solid-pellet fuel rod at BOL. During the cycle, as the soluble boron concentration decreases, the power of the annular pellet fuel rod gradually increases to within 0.3% less than that of an equivalent LTA solid-pellet fuel rod.

5.2. Segmented Rod Analyses

In addition to its own plenum volume, each section of the segmented fuel rod has a coupling to connect the segments. This coupling-plenum region creates a gap in the fuel stack, which can cause power peaking increases at the end of the fuel stacks and in surrounding fuel rods if steps are not taken to control them. The power peaking effects caused by the coupling-plenum region were analyzed using the DOT two-dimensional transport code in cylindrical geometry. The analyses were conducted for the condition of the worst tolerance buildup on the location and size of the coupling-plenum region.

The combination of inserting 0.400 inch long hafnia-yttria pellets in the coupling-plenum region and placing the coupling region under the Inconel spacer grid will reduce power peaking, thereby eliminating the need for an additional peaking penalty. The fuel pellets at each end of the coupling-plenum region will have a power level approximately 6% below that of the non-segmented rod. Surrounding fuel rods in the vicinity of the coupling region will experience a power level increase of approximately 1%. The 1% increase is well below the 2.6% local power peaking penalty already taken for peaking between Inconel spacer grids.[10]

5.3. Assembly Characteristics

At BOC-5 the relative power density of the LTA in core location M12 is 1.8% below the power of the comparable Mark B assembly in symmetric core location N11. The LTA power gradually increases during cylce 5 to the same power as the Mark B assembly at 100 EFPD and to 2.0% above the Mark B assembly power at

EOC-5. At no time during cycle 5 does the LTA contain the highest assembly power or highest radial-local peaking factor in the core.

The nuclear characteristics of the Mark BEB design LTA represent a small departure from those of the standard Mark B fuel assembly. Consequently, the LTA will have a negligible effect on the nuclear performance characteristics of the ANO-1 core.

Figure 5-1. Core Loading Map for ANO-1, Cycle 5

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A						6 K4	6 K2	7	6 K14	6 K12					
B				6 M4	6 L3	6 N3	7	5B P6	7	6 N13	6 L13	6 M12			
C			6 H13	7	6 K6	7	6 L5	7	6 L11	7	6 K10	7	6 O8		
D		6 D11	7	6 M8	7	5B A7	7	5B P8	7	5B A9	7	6 H5	7	6 D5	
E		6 C10	6 F9	7 LTA	5B D4	7	5B A6	7	5B A10	7	5B D12	7 LTA	6 E7	6 C6	
F	6 D9	6 C12	7	5B G1	7	5B P10	7	5B K8	7	5B L2	7	5B G15	7	6 C4	6 D7
G	6 B9	7	6 E10	7	5B F1	7	5B P12	5B P4	5B N2	7	5B F15	7	6 E6	7	6 B7
H	7	5B L14	7	5B H14	7	5B H9	5B N14	5B O11	5B D2	5B H7	7	5B H2	7	5B F2	7
K	6 P9	7	6 M10	7	5B L1	7	5B D14	5B B12	5B B4	7	5B L15	7	6 M6	7	6 P7
L	6 N9	6 O12	7	5B K1	7	5B F14	7	5B G8	7	5B B6	7	5B K15	7	6 O4	6 N7
M		6 O10	6 L9	7 LTA	5B N4	7	5B R6	7	5B R10	7	5B N12	7 LTA	6 L7	6 O6	
N		6 N11	7	6 H11	7	5B R7	7	5B B8	7	5B R9	7	6 E8	7	6 N5	
O			6 C8	7	6 G6	7	6 F5	7	6 F11	7	6 G10	7	6 H3		
P				6 E4	6 F3	6 D3	7	5B B10	7	6 D13	6 F13	6 E12			
R						6 G4	6 G2	7	6 G14	6 G12					

x	Batch
xxx	Cycle 4 Location

Note: LTA: Lead test assembly.

Figure 5-2. PDQ Relative Assembly Powers at 0 EFPD — 177-FA Core, ANO-1, Cycle 5

	8	9	10	11	12	13	14	
H	1.10	1.26	1.17	1.32	1.17	1.18	0.54	0.55
K	1.26	1.26	1.25	1.19	1.29	1.23	1.00	0.49
L	1.17	1.25	0.71	1.18	1.12	1.28	0.96	0.39
M	1.32	1.20	1.19	1.08	1.27	1.13	0.69	
N	1.18	1.30	1.12	1.29	1.24	1.01	0.45	
O	1.18	1.24	1.29	1.14	1.01	0.57		
P	0.55	1.00	0.96	0.69	0.45			
R	0.55	0.49	0.39					

x.xx Lead Test Assembly

x.xx Characterized Standard Mark B Assembly

6. THERMAL HYDRAULIC DESIGN

The thermal-hydraulic design objective for the LTA was to provide a conservative fuel assembly design based on the following criteria:

1. The LTA shall cause no reduction in core thermal margin; that is, the LTA shall not be the limiting assembly in the core in terms of minimum DNBR (departure from nucleate boiling ratio), and its insertion in the core shall not reduce the thermal margin of the limiting assembly.
2. The margin to fuel assembly lift-off shall be equal to or greater than that for the standard Mark B fuel assemblies.

These design objectives will ensure that the LTA is bounded by the cycle 5 reload safety analyses and operational limits and that it will in no way restrict normal operation of the core.

6.1. DNBR Analysis

Thermal-hydraulic analyses assume design radial power distributions and axial power shapes (1.714 radial × local × 1.5 cosine) for DNBR calculations performed in the determination of initial conditions for accident analyses, reactor protection system trip limits, and Technical Specification operating limits. Maximum allowable peaking (MAP) limits are generated to ensure that safety evaluations and DNBR margins based on the design radial and axial power distributions are maintained during actual plant operations. The MAP limits are represented by a family of power shape curves that are equivalent to the design power shape in terms of DNBR. These curves depict the limiting total fuel rod peak as a function of axial power shape and axial peak location. The MAP curves are then used in plant maneuvering margin analyses to determine operating limits for the core.

The LTA has been analyzed for both steady-state minimum DNBR and maneuvering margin. The LTA is not limiting in terms of DNBR. Based on the cycle 5 fuel cycle design peaking, the LTA minimum DNBR will be greater than the minimum DNBR in the core. Hydraulically, the LTA is virtually identical to other fuel assemblies in the core; however, the shortened LTA fuel stack height will tend to increase its surface heat flux and decrease its minimum DNBR. This is conservatively accounted for by reducing the MAP curves used for the LTA maneuvering margin analysis by 1%. Thus, it was shown that the LTA will at no time reduce the cycle 5 thermal margins. Similar analyses will be performed before each subsequent cycle to demonstrate that the LTA will not be the DNBR-limiting assembly in the core.

The DNBR penalty asociated with rod bow is a function of assembly burnup. References 11, 12, and 13 established a procedure for defining the penalty, and on the basis of this procedure, there is no DNBR penalty for fuel assembly burnup values below 16,500 MWd/mtU. Beyond this burnup value the penalty increases with burnup to a value of 6% at 40,000 MWd/mtU. Since the predicted burnup on the LTA is less than 16,500 MWd/mtU during cycle 5, no rod bow penalty was applied to the LTA for cycle 5.

As discussed above, core thermal-hydraulic analyses employ design peaking distributions. For typical reload cycles the assemblies most closely approaching the design peaking factor are the fresh fuel assemblies. Thus, it is anticipated that, for subsequent cycles when the LTA burnup is high enough to result in a rod bow penalty on DNBR, the power output of the LTA (assembly radial peaking factor) will be reduced enough to fully offset the rod bow penalty. This will be verified before each cycle of LTA irradiations as a part of the thermal-hydraulic evaluation.

6.2. Hydraulic Lift Analysis

As previously stated, hydraulically the LTA is virtually identical to the standard Mark B fuel assembly. The modification to the LTA upper end fitting to allow removal of the segmented rods has been assessed and was found to have a negligible effect on LTA hydraulic resistance. Therefore, the hydraulic lift force on the LTA is the same as that for the standard reload fuel. The fuel assembly weights and holddown spring forces, however, are not the same. Because of a shortened fuel stack height and annular fuel pellets, the LTA is lighter than a standard Mark B assembly. To compensate for this lighter weight, (as discussed in section 4.1.1) a stronger holddown spring is used and the resulting margin to lift for the LTA is larger than for the standard Mark B assembly. Hence, the LTA is not predicted to lift and is not the limiting assembly in the core.

7. ACCIDENT AND TRANSIENT ANALYSES

As described in section 5, the core power distribution remains almost completely unaffected by the presence of the four LTAs. Minor local reactivity perturbations do occur, but their effect is negligible because there are only four LTAs out of a total of 177 fuel assemblies in the core. However, the presence of the LTAs in the ANO-1 cycle 5 core was modeled during the generation of physics parameters for cycle 5 and was evaluated as part of the cycle 5 reload analyses. The same procedure will be followed in subsequent cycles.

In terms of maximum fuel temperatures and fuel rod internal pressures, the LTAs are bounded by the standard Mark B fuel assemblies. Therefore, the current loss-of-coolant accident (LOCA) limits developed for Mark B fuel are applicable for the LTAs.

The loading of four extended-burnup lead test assemblies in the ANO-1, cycle 5 core will not adversely affect the nuclear, mechanical, or thermal-hydraulic character of the reactor, nor will it affect the existing safety analysis.

GLOSSARY

CROV — A computer code that calculates creep-induced fuel rod ovalization during reactor operation for creep collapse analyses.[14]

PDQ — A computer code (PDQ07) that derives one-, two- or three-dimensional solutions to the neutron diffusion depletion problem in one to five lethargy groups.[15]

NULIF — A computer code that computes neutron energy spectra over the energy range 0.0 to 15 MeV and permits generation of data for PDQ tablesets.[16]

DOT — A computer code (DOT2, 3, 5) that solves two-dimensional, energy-dependent, linear Boltzmann transport equations with general anisotropic scattering for (X,Y), (R,Z), and (R,THETA) geometries.

TACO — A computer code that computes the fuel and cladding temperature distribution, fission gas production and release, cladding creep, fuel densification and swelling, and fuel-to-cladding gap closure within a cylindrical fuel rod.[9]

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