AREVA

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Poolside Postirradiation Examination of MOX Lead Assemblies

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ABSTRACT

The U.S. Department of Energy is implementing a program to dispose of a portion of the nation's surplus weapons-grade plutonium by reconstituting the plutonium into mixed-oxide fuel pellets and irradiating the fuel in commercial light water reactors. Accordingly, the Department of Energy has contracted with Shaw AREVA MOX Services (formerly known as Duke COGEMA Stone & Webster) to qualify the fuel for batch irradiation.

The qualification process includes irradiation of lead assemblies and poolside post-irradiation examination of those assemblies. This report documents the poolside examination of the lead assemblies after their first and second cycles of irradiation.

The lead assembly design is denoted as Mark-BW/MOX1. Four lead assemblies were supplied to Duke Energy's Catawba Nuclear Station, Unit 1, for irradiation starting in spring 2005. The lead assemblies were placed in high power but non-limiting locations that are expected to be representative of the batch peaking requirements. The first cycle of irradiation was completed in fall 2006, and the lead assemblies were examined at poolside after ultrasonic cleaning during the refueling outage. Consistent with previous plans, the examinations included measurements of fuel assembly growth, fuel rod growth, and fuel assembly bow, as well as fuel assembly and fuel rod visual exams. The appearance of the assemblies was normal; no damage was observed. Upon evaluation, all characteristics of the fuel assemblies were found to be within the acceptance criteria for reinsertion for a second cycle of irradiation, so the assemblies were reinserted into Catawba Unit 1.

For their second cycle of irradiation, the assemblies were again placed in high power but non-limiting locations. The second cycle was completed in spring 2008, and the assemblies were again examined at poolside. The examinations included those listed above plus spacer grid width, fuel rod oxide thickness, water channels, guide thimble oxide thickness, holddown spring height, and holddown spring stiffness. In addition, five fuel rods were removed for hot cell examination and replaced with stainless steel rods.

Acceptance criteria were again established for reinsertion of the fuel assemblies. With one exception, all characteristics of the fuel assemblies were found to be within the criteria. The exception was that the fuel assembly axial growth exceeded the criterion.

At this point, the lead assemblies are considered to have completed the irradiations that are required for fuel qualification. An optional third cycle of irradiation would provide additional data on fuel performance at higher burnups.

Nature of Changes

Item	Section(s) or Page(s	Description and Justification
Rev. 0	all	Initial release.
Rev. 1	all	Completely revised to include results from second cycle examinations
Rev. 2	4	Revised to reflect corrections in supporting document

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Nomenclature

Acronym	Definition
BPRA	burnable poison rod assembly
DOE	Department of Energy
EFPD	equivalent full-power days
GWd/MThm	gigawatt-days per metric ton of heavy metal
GWd/MTU	gigawatt-days per metric ton of uranium
LVDT	linear variable differential transformer
M5®	designation for an advanced cladding alloy
MOX	mixed oxide – uranium dioxide and plutonium dioxide
MSMG	mid-span mixing grid
NRC	U.S. Nuclear Regulatory Commission
PIE	post-irradiation examination
RCCA	rod cluster control assembly
UNS	Unified Numbering System (for metals and alloys)

1.0 INTRODUCTION

The U.S. Department of Energy (DOE) is implementing a program to dispose of a portion of the nation's surplus weapons-grade plutonium by reconstituting the plutonium into mixed-oxide (MOX) fuel pellets and irradiating the fuel in commercial light water reactors. Accordingly, the DOE has contracted with Shaw AREVA MOX Services (formerly known as Duke COGEMA Stone & Webster) to qualify the fuel for batch irradiation. A formal plan has been developed to guide the fuel qualification process (Reference 1).

The qualification plan calls for irradiation of four MOX lead assemblies for up to three cycles, as well as post-irradiation examination (PIE) of the assemblies to ensure that they perform as expected under irradiation. Poolside examinations are required after each cycle of irradiation, and hot cell examinations of selected fuel rods are required after the second cycle. If the fuel assemblies are irradiated for a third cycle, a hot cell examination is required after that cycle as well. This report documents the poolside examination of the lead assemblies after their first and second cycles of irradiation.

The lead assembly design is denoted as Mark-BW/MOX1. A detailed description of the design has been published (Reference 2). Figure 1-1 shows the general arrangement of the fuel assembly, and Table 1-1 provides selected design parameters (Reference 2, Table 5.1). Figure 1-1 also specifies the nomenclature for spacer grids, mid-span mixing grids (MSMGs), and fuel rod spans.

1.1 *First Cycle of Irradiation*

Four lead assemblies were supplied to Duke Energy's Catawba Nuclear Station, Unit 1, for irradiation starting in spring 2005. The lead assemblies were placed in high power but non-limiting locations that are representative of the batch peaking requirements. Figure 1-2 shows the locations of the lead assemblies in core during their first cycle of irradiation. In fall 2006, the first cycle of irradiation was completed. The assembly average and maximum rod average burnups are 22.0 and 26.1 GWd/MThm, respectively. The lead assemblies were in quarter-core symmetric locations, so the same burnups apply to all four.

Prior to completion of the first cycle of irradiation, quantitative acceptance criteria were developed for fuel assembly and fuel rod growth. These criteria were chosen to help provide assurance that the lead assemblies could be safely irradiated for a second cycle. The criteria are discussed in Sections 4.3.1 and 4.4.1.

The lead assemblies were examined at poolside during the refueling outage after their first cycle of irradiation. Consistent with previous plans (Reference 2, Table 8.1), the examinations included measurements of fuel assembly growth, fuel rod growth, and fuel assembly bow, as well as fuel assembly and fuel rod visual exams.

Each of the examinations helped to provide assurance that the lead assemblies could be safely irradiated for a second cycle. The visual examinations were used to ensure the mechanical integrity of the fuel assemblies, including fuel rods and structural components. Fuel assembly growth measurements were used to ensure that a positive clearance will remain between the fuel assembly and the reactor internals during the next cycle of irradiation. The clearance between the top ends of the fuel rods and the top nozzle is related to fuel rod growth. Measurement of this clearance was used to ensure that a positive clearance would remain throughout the next cycle of irradiation. Finally, measurements of fuel assembly bow were used to ensure that the fuel assemblies could be readily loaded into the core during refueling and would allow for rapid and reliable control rod insertion.

1.2 *Second Cycle of Irradiation*

The four lead assemblies started their second cycle of irradiation in Duke Energy's Catawba Nuclear Station, Unit 1, early in 2007. As in their first cycle, they were placed in high power but non-limiting locations that are representative of the batch peaking requirements. Figure 1-2 shows the locations of the assemblies. The second cycle of irradiation was completed in spring 2008. During that cycle, the fuel achieved assembly average and maximum rod average burnups of 41.8 and 47.3 GWd/MThm, respectively.

As in the first cycle, acceptance criteria were again developed to help provide assurance that the lead assemblies could be safely irradiated for a third cycle. The criteria reflected the larger scope of the second PIE. Quantitative criteria were specified for fuel assembly and fuel rod growth, fuel rod oxide, and fuel rod bow (water channels), and qualitative criteria were specified for the visual examination and fuel assembly bow. The criteria are discussed in the appropriate “End of Second Cycle” subsections of Section 4.0.

The lead assemblies were examined at poolside during the refueling outage after their second cycle of irradiation. The examinations included fuel assembly and fuel rod visual exams plus measurements of fuel assembly growth, fuel rod growth, fuel assembly bow, spacer grid width, fuel rod oxide thickness, water channels, guide thimble oxide thickness, holddown spring height, and holddown spring stiffness. The scope and extent of the exams are discussed in more detail in Section 3.0. With the exception of fuel assembly axial growth, all characteristics of the fuel assemblies were found to be within the criteria for reinsertion for a third cycle of irradiation.

Table 1-1—Design Parameters for Mark-BW/MOX1 Lead Assembly

Parameter	Value
Pellets	
Fuel pellet material	PuO_2 and Depleted UO_2
Fuel pellet diameter, in	0.3225
Fuel pellet density, % of theoretical density	95
Fuel pellet volume reduction due to chamfer and dish, %	1.11
Rods	
Fuel rod length, in	152.40
Fuel rod cladding material	M5®
Fuel rod inside diameter, in	0.329
Fuel rod outside diameter, in	0.374
Active fuel stack height, in	144
Assemblies	
Distance from top of bottom nozzle to bottom of top nozzle, inches	159.85
Lattice geometry	17 × 17
Fuel rod pitch, in	0.496
Initial shoulder gap, inches	1.295
Number of fuel rods per assembly	264
Heavy metal loading per assembly, kg	463
Number of Grids	
Bottom end	1
Vaneless intermediate	1
Vaned intermediate	5
Mid-span mixing	3
Top end	1

Figure 1-1—General Arrangement of Mark-BW/MOX1 Lead Assembly

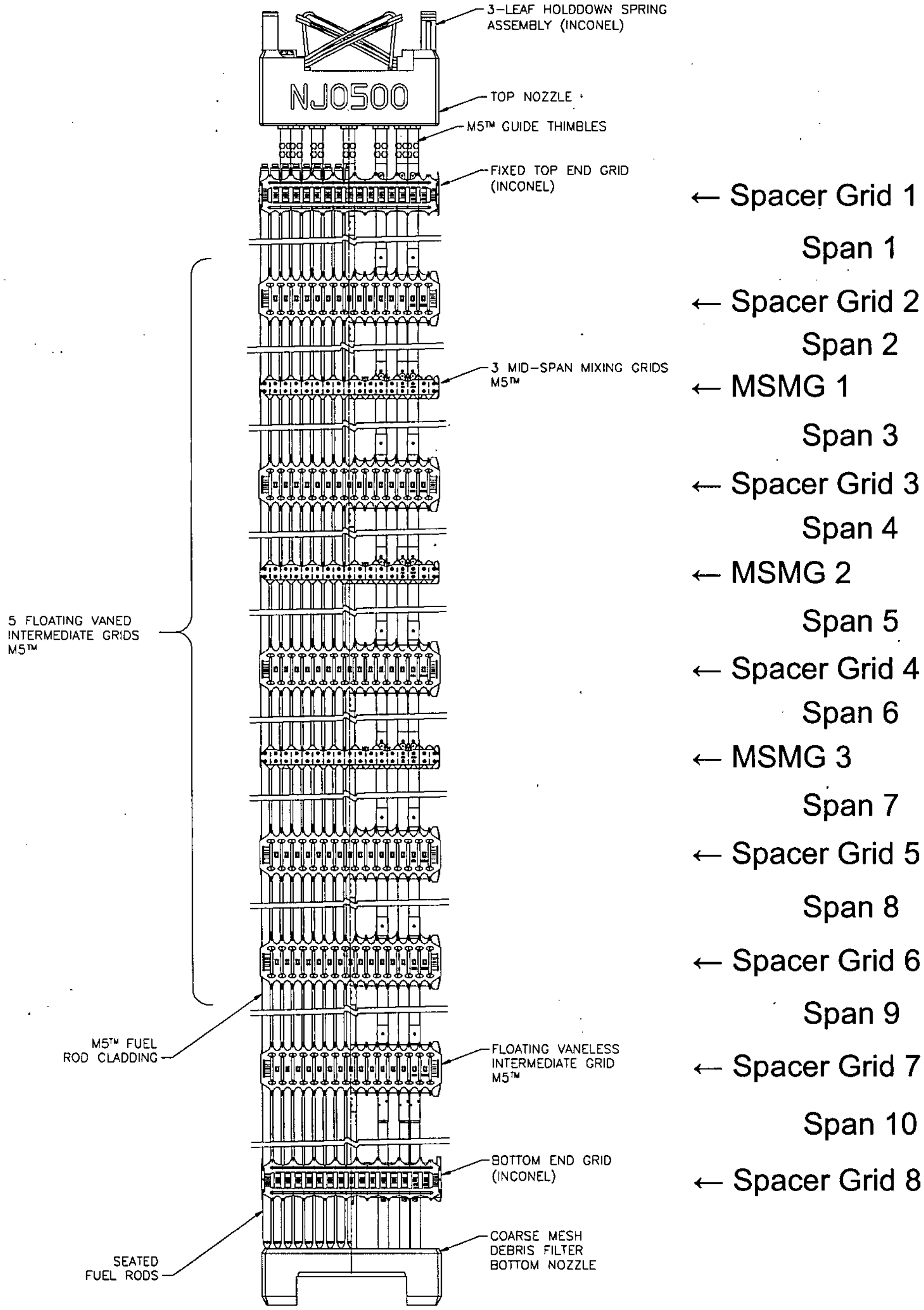
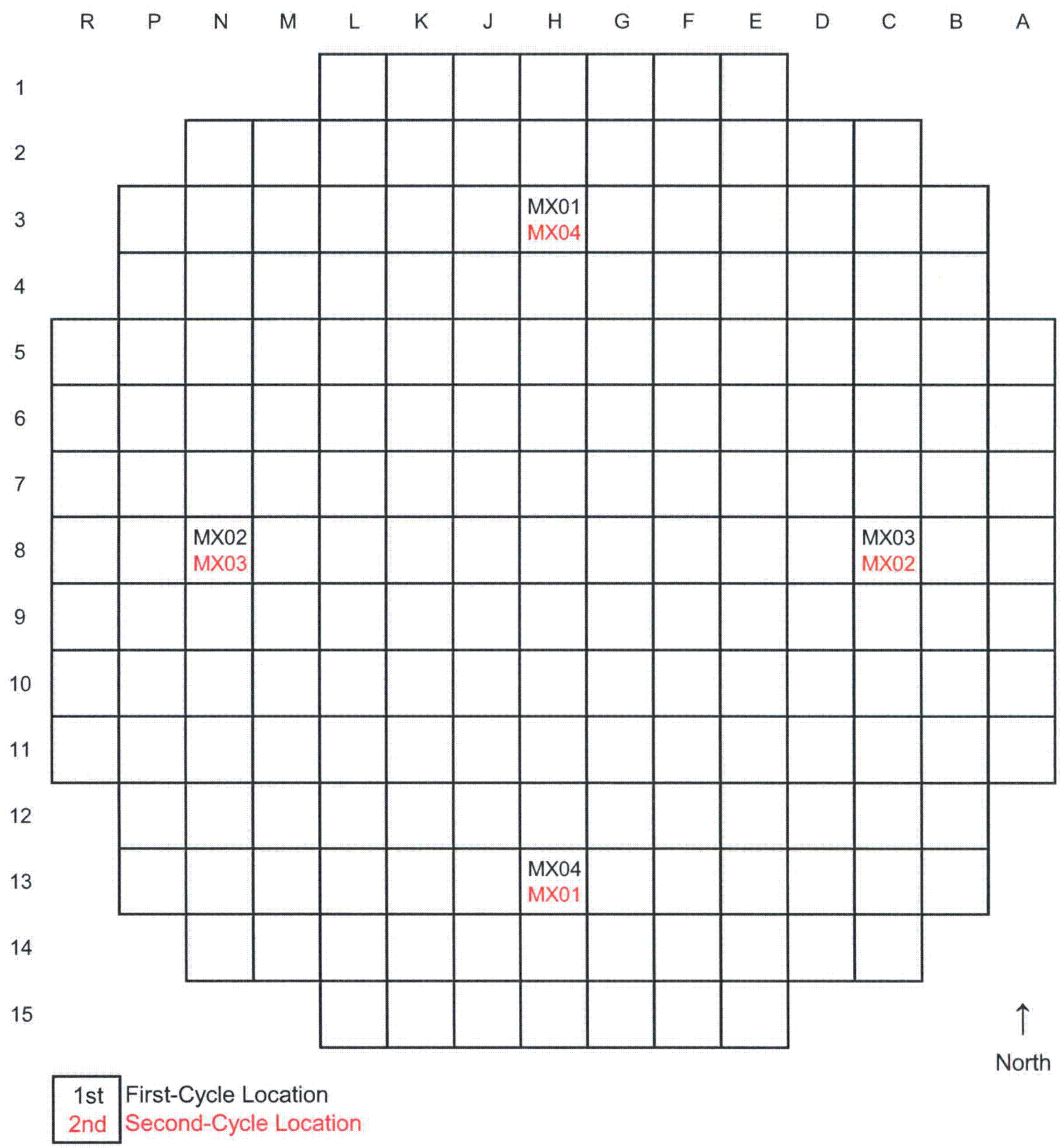


Figure 1-2—Locations of Lead Assemblies in Core



2.0 SUMMARY AND CONCLUSIONS

Upon evaluation of the results of the first-cycle poolside PIE, the MOX lead assemblies were found to be within the criteria for reinsertion for a second cycle of irradiation. The assemblies were reinserted into Catawba Unit 1.

The MOX lead assemblies were again examined at poolside after their second cycle of irradiation, and the measurements were found to be in compliance with all but one of the acceptance criteria for a third cycle of irradiation. The assemblies were therefore not reinserted for a third cycle.

At this point, the lead assemblies are considered to have completed the irradiations that are required for fuel qualification. An optional third cycle of irradiation would provide additional data on fuel performance at higher burnups.

3.0 METHODS, PROCEDURES, AND EQUIPMENT

This section discusses methods, procedures, and equipment for the poolside PIEs.

Consistent with previous plans (Reference 2, Table 8.1), the first-cycle examinations included measurements of fuel assembly growth, fuel rod growth, and fuel assembly bow, as well as fuel assembly and fuel rod visual exams. Table 3-1 compares the planned extent of examination with the actual extent. In each case, the actual extent of the examinations at the end of the first cycle equaled or exceeded the planned extent.

The poolside examinations at the end of the second cycle are described in Table 3-2. The exams were generally in accordance with previous plans (Reference 2, Table 8.1), though some measurements were added to the scope, and a few were eliminated when that was appropriate. Measurements of grid oxide thickness were considered to be unnecessary because the fuel rod and guide thimble oxide thicknesses were both quite small. Oxide thickness on interior fuel rods was likewise not measured because the oxide thickness on the peripheral rods was so small that there was no expectation of excessive oxidation of interior rods. Drag forces on rod cluster control assemblies (RCCAs) did not apply to the lead assemblies because none of them were in locations with control assemblies. Finally, guide thimble plug gauging was eliminated because information on fuel assembly bow indicated that the fuel assemblies were not distorting significantly.

On the other hand, three types of measurements were added to the scope: guide thimble oxide thickness, holddown spring height, and holddown spring stiffness. MOX and low enriched uranium fuel assemblies are expected to perform similarly with regard to these characteristics; the additional data help to confirm that.

It is often necessary to distinguish the four faces of a fuel assembly. The faces are often denoted by the compass directions (north, etc.) taken when the assembly is in reactor, but other nomenclatures are used as well. Table 3-3 provides a comparison of several different nomenclatures.

In accordance with standard practice, the fuel assemblies were inscribed with unique serial numbers (NJ13GE through NJ13GH) on the south faces of the top nozzles. Additional identifiers (MX01 through MX04) were inscribed on the north faces. This report primarily uses the additional identifiers, but many of the tables provide the equivalent serial numbers as well.

The results of the PIEs are given in Section 4.0.

3.1 *Visual Examinations*

Visual examination is a qualitative survey of the periphery of the fuel assembly. It fulfills the plans for both fuel assembly and fuel rod examinations in Reference 2, Table 8.1.

Visual examinations were recorded with a video camera. The entire vertical length, from bottom nozzle to top nozzle, was examined. To provide more detailed images, the camera was placed so that the field of view was narrower than the width of the fuel assembly. The each face was scanned twice to provide substantially full coverage.

The video signal was recorded in digital form for later review. For identification purposes, the video image was overlaid with text that identified the reactor, fuel assembly, fuel assembly face (north, east, south, or west), time, and date. The video record can be conveniently reviewed on a computer, and individual still images can be extracted and printed.

3.2 *Fuel Assembly Growth Measurements*

Fuel assembly growth was determined by measuring the length of the fuel assembly after irradiation and comparing it to the length before irradiation. The method for measuring fuel assembly length uses a gage rod, sometimes known as a "dipstick". The equipment includes [

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The net fuel assembly growth is determined by subtracting the as-built length of the fuel assembly from the length after irradiation. The as-built length was determined by averaging measurements, taken when the fuel was manufactured, [ ]. The measurements are corrected for thermal expansion [ ].

Fuel assembly growth measurements might also be called guide thimble growth measurements. Irradiation growth of the top and bottom nozzles is negligible, because (1) these components have a small vertical dimension and (2) the fast neutron fluence at the nozzles is small compared to that in the active length, so the relative change in the vertical dimension is also small.

3.3 *Fuel Rod Growth Measurements*

Fuel rod growth is not measured directly but is deduced from measurements of fuel assembly growth and "shoulder gap", where shoulder gap is the clearance between the top end of a fuel rod and the lower surface of the top nozzle.

Shoulder gap can be measured by various means. For the first cycle exams, [

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[

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For the second cycle exams, [

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The initial shoulder gaps were measured when the fuel assemblies were manufactured, so the change in shoulder gap can be determined by subtracting the as-built shoulder gap from the irradiated shoulder gap. Changes in shoulder gap are usually negative. Fuel rod growth is equal to fuel assembly growth minus the change in shoulder gap.

3.4 *Fuel Assembly Bow Measurements*

Fuel assembly bow is measured semi-quantitatively. [

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3.5 *Spacer Grid Width Measurements*

Spacer grid width is the transverse measurement from one face of a fuel assembly grid to the opposite face. The measurements are taken on the lands of the grid strips rather than in the depressed features. Measurements are made in multiple locations. [

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3.6 *Fuel Rod Oxide Thickness Measurements*

External fuel rod oxide thickness is measured by an eddy-current technique, which measures the lift-off of the eddy-current coil from the underlying metal of the cladding. The equipment is calibrated [

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3.7 *Water Channel Measurements*

Water channel spacing is the distance between adjacent rods in a fuel assembly at the mid-plane between spacer grids. These spacings can be classified as fuel-rod-to-fuel-rod, fuel-rod-to-guide tube, or fuel-rod-to-instrument tube spacings. The nominal values for these spacings are 0.122 inch, 0.068 inch, and 0.068 inch, respectively. (For the dashpot, the nominal fuel-rod-to-guide tube water channel is 0.0945 inch. [

] Water channel measurements are typically taken between all fuel rods, guide tubes, and instrument tubes in two orthogonal directions at the mid-span planes of the assembly. The result of interest is [ ] (Reference 3).

The water channel spacings are measured [

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3.8 *Guide Thimble Oxide Thickness Measurements*

Like fuel rod oxide thickness, guide thimble oxide thickness is determined by an eddy-current technique. The oxide thickness is measured on the inner surface of the guide thimble. The eddy-current apparatus is calibrated [

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3.9 *Holddown Spring Height Measurements*

Holddown spring height is defined as the difference in elevation between the top of the holddown spring and the level at which the tang of the spring enters the top nozzle. The holddown spring height was measured [

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3.10 *Holddown Spring Stiffness Measurements*

Holddown spring stiffness measurements are used to determine the spring constant. The measurements are made by [

] The apparent spring constant is smaller for the relaxation cycle because of friction between the leaves of the spring.

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Table 3-1—Extent of First-Cycle Poolside Examinations

Inspection	Planned Extent	Actual Extent
Fuel assembly visual	All assemblies	All assemblies
Fuel rod visual	Peripheral rods on all assemblies	All peripheral rods on all assemblies
Fuel assembly growth	All assemblies	All assemblies
Fuel rod growth (shoulder gap closure)	Two assemblies, two longest peripheral rods in each assembly	Two assemblies, at least 16 peripheral rods per assembly, plus qualitative evaluation of the remaining two assemblies
Fuel assembly bow	Two assemblies, two faces per assembly	All assemblies, two faces per assembly

Table 3-2—Extent of Second-Cycle Poolside Examinations

Inspection	Planned Extent	Actual Extent
Fuel assembly visual	All assemblies	All assemblies
Fuel rod visual	Peripheral rods on all assemblies	All peripheral rods on all assemblies
Fuel assembly growth	All assemblies	All assemblies
Fuel rod growth (shoulder gap closure)	Two assemblies, two longest peripheral rods in each assembly	Two assemblies, 16 peripheral rods per assembly, plus qualitative evaluation of the remaining two assemblies
Fuel assembly bow	Two assemblies, two faces per assembly	All assemblies, two faces per assembly
Grid width	Two assemblies, two adjacent sides, four grids per assembly	Two assemblies, two adjacent sides, four grids per assembly, plus an additional grid on one assembly
Fuel rod oxide thickness	Two assemblies, four faces per assembly, four rods per face, plus two assemblies, one face on an internal row	Two assemblies, four faces per assembly, four rods per face*
Grid oxide thickness	Two assemblies, four grids per assembly, two adjacent sides, duplicate measurements	None
Fuel assembly RCCA drag force	Two assemblies, but only if drop time increases	None
Guide thimble plug gauge	Two assemblies, four guide thimbles	None
Water channels (fuel rod bowing)	One assembly, two faces, seven spans in each direction	One assembly, two faces, ten spans in each direction, plus three assemblies, two faces, three spans in each direction
Guide thimble oxide thickness	None	All assemblies, four guide thimbles per assembly
Holddown spring height	None	Two assemblies, four springs per assembly
Holddown spring stiffness	None	All assemblies, one compression cycle per assembly

*Oxide thickness was measured twice on corner rods.

Table 3-3—Nomenclatures for Fuel Assembly Faces

Compass Direction	Face Number	Face Letter	Engraved Identifier	Fuel Rod Positions
North	1	C	MX_ _	A1 through Q1
East	2	D	(none)	Q1 through Q17
South	3	A	NJ_ _ _ _	A17 through Q17
West	4	B	(none)	A1 through A17

4.0 RESULTS

This section presents the results of the poolside PIE. It also compares the results to the acceptance criteria for reinsertion when such criteria are applicable.

4.1 *Fuel Assembly Visual Examinations*

4.1.1 *End of First Cycle*

A complete video record was made of all faces of all four lead assemblies. The record was stored in digital form for later review. The visual inspections indicated that the fuel assemblies were performing normally, that is, like low enriched uranium fuel assemblies. Sample photographs from the video record are shown in Figure 4-1 through Figure 4-6. As is described in Section 3.1, the individual video images do not cover the full width of a fuel assembly, so each of these figures shows first the left side followed by the right side. There is some overlap between the two images. To indicate the extent of overlap, the center (ninth) rod on the face is marked with "9" below each image.

The video record documents the appearance of the periphery of the assembly, including fuel rods, spacer grids, mid-span mixing grids, and nozzles. All grids were found to be in excellent condition, with very little corrosion and no mechanical damage.

4.1.2 *End of Second Cycle*

A complete video record was again made of all faces of all four assemblies and stored in digital form. The visual inspections indicated that the fuel assemblies were performing normally, that is, like low enriched uranium fuel assemblies. Sample photographs from the video record are shown in Figure 4-7 through Figure 4-12; these may be compared to Figure 4-1 through Figure 4-6. See Section 4.1.1 for a discussion of how the images overlap.

The video record documents the appearance of the periphery of the assembly, including fuel rods, spacer grids, mid-span mixing grids, and nozzles. All grids were found to be in excellent condition, with very little corrosion and no mechanical damage. Some grids showed evidence of crud deposition; see Figure 4-10 for an example.

The criterion for reinsertion was that [

] the fuel assemblies were considered to be in compliance with the criterion.

4.2 *Fuel Rod Visual Examinations*

4.2.1 *End of First Cycle*

The video record mentioned in Section 4.1.1 documents the appearance of the peripheral fuel rods. All fuel rods appeared to be in excellent condition, with light, uniform oxidation.

4.2.2 *End of Second Cycle*

The video record mentioned in Section 4.1.2 documents the appearance of the peripheral fuel rods. The color of the oxide was more variable than that after the first cycle, but the appearance was typical of second-cycle fuel. Fuel rod bow was apparent in some locations, but only in the bottom three spans. See Figure 4-13 and Figure 4-14 for some of the most severe examples. Apart from the bow, all fuel rods appeared to be in excellent condition.

The criterion for reinsertion given in Section 4.1.2 applied to fuel rods as well as fuel assemblies. [ ] the fuel assemblies were considered to be in compliance with the criterion.

4.3 *Fuel Assembly Growth Measurements*

Fuel assemblies are held in position by the lower and upper core support plates, and an axial clearance is provided between the top nozzle and the upper core support plate to accommodate fuel assembly growth during irradiation. The clearance is taken up by the holddown springs. However, if fuel assembly growth were excessive, the clearance could be completely consumed, and there would be interference between the fuel assembly and core support plates. Such interference is undesirable because it could result in damage to the fuel assembly. The potential for interference is greatest under cold conditions because the coefficient of thermal expansion is greater for the reactor internals than for the fuel assembly guide thimbles.

The fuel assembly axial clearance will depend on the fuel assembly design and will vary slightly from one reactor to another because of differences in the as-built dimensions of the internals. For a Mark-BW/MOX1 fuel assembly of nominal length, the minimum clearance at beginning of life was determined to be [ ] inch.

4.3.1 *End of First Cycle*

The allowable fuel assembly growth at the end of the first cycle of irradiation was chosen to be [ ] inch, or half of the initial axial clearance.

Table 4-1 reports fuel assembly growth. Because of rounding, some results may appear to be in error by 0.001 inch. In each case, the fuel assembly growth was in compliance with the acceptance criterion.

4.3.2 *End of Second Cycle*

For the second cycle of irradiation, the acceptance criterion for fuel assembly growth was that it not exceed [

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Table 4-1 reports fuel assembly growth. Because of rounding, some results may appear to be in error by 0.001 inch. For assembly MX03, assembly growth was in compliance with the acceptance criterion; the other assemblies violated the criterion.

4.4 *Fuel Rod Growth Measurements*

Just as axial clearance is required for the fuel assemblies, it is also required for the fuel rods. Fuel rod growth during irradiation typically results in a reduction in the axial clearance between the top end of a fuel rod and the lower surface of the top nozzle, or shoulder gap. Interference between the fuel rods and nozzles is undesirable because it could result in distortion of the fuel rods and damage to the assembly.

4.4.1 *End of First Cycle*

The fuel rod shoulder gap was measured directly as described in Section 3.3. Only MX01 and MX02 were measured, but the visual examinations indicated that the shoulder gaps for MX03 and MX04 were comparable to those for MX01 and MX02.

Table 4-2 provides a summary of the shoulder gap measurements, adjusted to room temperature. Blank cells indicate that a measurement was not taken. The peripheral fuel rods are identified by a face (north, west, etc.) and a number (1 to 17), where the number is assigned by counting from left to right across the face of the assembly. Alphanumeric fuel rod locations are provided in parentheses after the shoulder gap measurements. The shoulder gaps for some corner rods were measured twice because these rods are in two different faces.

The minimum and average measured shoulder gaps were [ ] inches and [ ] inches, respectively, on the basis of the combined data for MX01 and MX02. The criterion for reinsertion after one cycle was that the remaining shoulder gap be at least half of the initial shoulder gap, or [ ] inch. The criterion was based on the minimum initial shoulder gap that was consistent with design tolerances rather than on the nominal value given in Table 1-1. The fuel assemblies satisfied the criterion.

It will be noted from Table 4-2 that the shoulder gaps for fuel assembly MX02 are fairly tightly distributed, whereas assembly MX01 has some unusually large shoulder gaps, such as [ ] inches for rod 12 on the south face. The large shoulder gaps occur where the fuel rods have been reworked during manufacturing, that is, where the first seal weld was unsatisfactory. Rework involved cutting off the upper end plug and weld, and welding a new upper end plug. The length tolerance for the overall length of the fuel rods had been chosen to accommodate such rework.

Table 4-3 lists the as-built and irradiated shoulder gaps for each measured fuel rod, plus the derived fuel rod growth, which is the decrease in shoulder gap plus the assembly growth. As in Table 4-2, duplicate measurements for corner rods are both tabulated.

4.4.2 *End of Second Cycle*

Fuel rod shoulder gaps were measured at the end of the second cycle. As for the first cycle, only MX01 and MX02 were measured, but the visual examinations indicated that the shoulder gaps for MX03 and MX04 were comparable to those for MX01 and MX02.

Table 4-2 provides a summary of the shoulder gap measurements, adjusted to room temperature. Blank cells indicate that a measurement was not taken. The rod nomenclature is as described in Section 4.4.1. The shoulder gaps for the corner rods were measured twice because these rods are in two different faces.

The minimum and average measured shoulder gaps were [ ] inches and [ ] inches, respectively, on the basis of the combined data for MX01 and MX02. The criterion for reinsertion after two cycles was that the remaining shoulder gap be at least [ ] inch. In developing the criterion, it was noted that [

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The acceptance criterion accounted for all three of these effects. All of the fuel assemblies satisfied the criterion.

Table 4-3 lists the as-built and irradiated shoulder gaps for each measured fuel rod, plus the derived fuel rod growth, which is the decrease in shoulder gap plus the assembly growth. As in Table 4-2, duplicate measurements for corner rods are both tabulated.

As expected, each rod shows greater total fuel rod growth after two cycles than after one.

4.5 *Fuel Assembly Bow Measurements*

Fuel assembly bow was measured for two adjacent faces of all four assemblies. Measurements were taken in accordance with the process described in Section 3.4. A displacement of the fuel assembly to the left, relative to the tape, is taken as positive.

The nomenclature follows that in Figure 1-1; spacer grid 1 is near the top of the assembly and spacer grid 8 is near the bottom.

4.5.1 *End of First Cycle*

The results of the fuel assembly bow measurements are tabulated in Table 4-4 and plotted in Figure 4-15 and Figure 4-16. The north and west faces of each assembly were measured. The maximum displacement was about [ ] inch; that value was reached on the north face of assembly MX03. This amount of bow is within the experience base for low enriched uranium fuel assemblies and was considered acceptable for reinsertion of the fuel assemblies for a second cycle of irradiation.

There does not appear to be a strong correlation among the fuel assembly bows. If the entire core had a significant bow in one compass direction, all four curves in Figure 4-15 and Figure 4-16 should be similar, but that is not seen. Similarly, if there had been a systematic tendency for the lead assemblies to bow away from the center of the core, MX01 should bow northward, MX03 eastward, MX04 southward, and MX02 westward. Such a correlation may be present, but it appears to be weak. All four assemblies bow in the indicated directions, but the amount of bow for MX04 and MX02 is small, with a maximum magnitude of about [ ] inch. The lack of a strong correlation among the fuel assembly bows is reasonable in light of the small bow displacements.

4.5.2 *End of Second Cycle*

The results of the fuel assembly bow measurements are tabulated in Table 4-4 and plotted in Figure 4-15 and Figure 4-16. The north and west faces of assemblies MX01, MX03, and MX04 were measured, as were the south and west faces of assembly MX02. The maximum displacement was about [ ] inch; that value was reached on the west face of assembly MX04. This amount of bow is within the experience base for low enriched uranium fuel assemblies and was actually slightly smaller than the maximum displacement at the end of the first cycle. The acceptance criterion for reinsertion was [ ]. The assemblies were considered to be in compliance with the criterion.

For the purposes of the discussion below, the measurements on the south face of MX02 were reversed in sign and treated as if they had been measured on the north face. That approach allows consistent handling of eastward and westward bows.

The results of the bow measurements after the first and second cycles of irradiation were compared to determine if there were any trends. There did not appear to be a tendency for the assemblies to remain bowed in the same direction; MX01, for example, was bowed in a northeastward direction after the first cycle and in a southwestward direction after the second. There may be a slight tendency for the fuel assemblies to bow outward. In that case, the assembly in location H3 should bow northward, C8 eastward, H13 southward, and N8 westward. The curves in Figure 4-15 and Figure 4-16 are labeled "out" if the indicated component of bow is toward the outside of the core. (Tangential components are not labeled.) In seven out of eight cases, the components are outward; in the eighth, labeled "?", there is no clear direction.

4.6 *Spacer Grid Width Measurements*

4.6.1 *End of Second Cycle*

The results of the spacer grid width measurements are tabulated in Table 4-5. Because of rounding, some results may appear to be in error by 0.001 inch. There was no acceptance criterion for reinsertion.

Spacer grid width was measured in both the north/south (N / S) and east/west (E / W) directions on assemblies MX01 and MX02. The top four intermediate spacer grids (spacer grids 2 through 5 as shown in Figure 1-1), which are made entirely of M5 alloy, were measured for both assemblies. The upper end grid (spacer grid 1), which is made of nickel-base alloy UNS N07718, was also measured for assembly MX02. Because of its material, little or no growth was expected on the upper end grid.

4.7 *Fuel Rod Oxide Thickness Measurements*

4.7.1 *End of Second Cycle*

Fuel rod oxide thickness was measured on selected peripheral rods of assemblies MX01 and MX02; the results are provided in Table 4-6. Note that corner rods are tabulated twice. North-17 and West-1, for example, refer to the same rod, though different results are obtained because of experimental error and variability in oxide thickness. The length of the oxide scan was about [ ] inches, and the averages reported cover the entire length of the scan.

The criterion for reinsertion was that [

] it is clear that the fuel was in compliance with the criterion.

4.8 *Water Channel Measurements*

4.8.1 *End of Second Cycle*

Water channel measurements were taken on all four assemblies. For assemblies MX01, MX02, and MX04, only the bottom three spans were measured; for assembly MX03, all ten spans were measured. As is discussed in Section 3.7, water channels may be classified as fuel-rod-to-fuel-rod, fuel-rod-to-guide tube, or fuel-rod-to-instrument tube. The criterion for reinsertion was that [

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The results of the water channel measurements are summarized in Table 4-7. All of the fuel assemblies satisfied the acceptance criteria.

4.9 *Guide Thimble Oxide Thickness Measurements*

4.9.1 *End of Second Cycle*

Oxide thickness was measured on the inner surfaces of guide thimbles in all four assemblies. Measurements were made in the four guide thimbles closest to the northeast, southeast, southwest, and northwest corners of the fuel assembly. The results of the measurements are summarized in Table 4-8. There was no acceptance criterion for reinsertion.

4.10 *Holddown Spring Height Measurements*

4.10.1 *End of Second Cycle*

Holddown spring heights were measured for each spring pack on MX01 and MX02. The results of the measurements are summarized in Table 4-9. There was no acceptance criterion for reinsertion.

4.11 *Holddown Spring Stiffness Measurements*

4.11.1 *End of Second Cycle*

Holddown spring stiffnesses were measured for fuel assemblies MX01 and MX02. The results of the measurements are summarized in Table 4-10. There was no acceptance criterion for reinsertion.

Table 4-1—Fuel Assembly Growth

Measurement	Fuel Assembly			
	MX01 (NJ13GE)	MX02 (NJ13GF)	MX03 (NJ13GG)	MX04 (NJ13GH)

Table 4-2—Fuel Rod Shoulder Gaps

Assembly MX01 (NJ13GE)	Face			
	North	West	South	East
Rod Number	**Shoulder Gap, End of First Cycle, inches**			
Rod Number	**Shoulder Gap, End of Second Cycle, inches**			

Assembly MX02 (NJ13GF)	Face			
	North	West	South	East
Rod Number	**Shoulder Gap, End of First Cycle, inches**			
Rod Number	**Shoulder Gap, End of Second Cycle, inches**			

Table 4-3—Fuel Rod Growth

Assembly MX01 (NJ13GE)					
Rod Location	Shoulder Gap, inches			Fuel Rod Growth, inches	
	As-Built	End of First Cycle	End of Second Cycle	End of First Cycle	End of Second Cycle

Table 4-3—Fuel Rod Growth *(Continued)*

Assembly MX02 (NJ13GF)					
Rod Location	Shoulder Gap, inches			Fuel Rod Growth, inches	
	As-Built	End of First Cycle	End of Second Cycle	End of First Cycle	End of Second Cycle

Table 4-4—Fuel Assembly Bow

Assembly MX01 (NJ13GE)	Face			
	North		West	
	End of First Cycle	End of Second Cycle	End of First Cycle	End of Second Cycle
Spacer Grid Number	Assembly Bow, inches			
[				]

Assembly MX02 (NJ13GF)	Face			
	North*		West	
	End of First Cycle	End of Second Cycle	End of First Cycle	End of Second Cycle
Spacer Grid Number	Assembly Bow, inches			
[				]

*Bow was inadvertently measured on the south face of MX02 at the end of cycle 2. The values reported here have been reversed in sign to simulate measurement on the north face.

Table 4-4—Fuel Assembly Bow *(Continued)*

Assembly MX03 (NJ13GG)	Face			
	North		West	
	End of First Cycle	End of Second Cycle	End of First Cycle	End of Second Cycle
Spacer Grid Number	Assembly Bow, inches			

Assembly MX04 (NJ13GH)	Face			
	North		West	
	End of First Cycle	End of Second Cycle	End of First Cycle	End of Second Cycle
Spacer Grid Number	Assembly Bow, inches			

Table 4-5—Spacer Grid Width

Assembly MX01 (NJ13GE)				
		Spacer Grid Width, inches		Spacer Grid Growth, inch
Spacer Grid Number	Measurement Direction	As-Built	End of Second Cycle	End of Second Cycle

Assembly MX02 (NJ13GF)				
		Spacer Grid Width, inches		Spacer Grid Growth, inch
Spacer Grid Number	Measurement Direction	As-Built	End of Second Cycle	End of Second Cycle

Table 4-6—Fuel Rod Oxide Thickness

Assembly MX01 (NJ13GE)			
		Oxide Thickness, μm	
		End of Second Cycle	
Face	Rod	Average	Maximum

Table 4-6—Fuel Rod Oxide Thickness *(Continued)*

Assembly MX02 (NJ13GF)			
		Oxide Thickness, μm	
		End of Second Cycle	
Face	Rod	Average	Maximum

Table 4-7—Standard Deviation of Water Channel Measurements

		Standard Deviation, 0.001 inch		
		End of Second Cycle		
Assembly	Span	Interior FR-FR	GT-FR	All FR-FR

Table 4-8—Guide Thimble Oxide Thickness

Assembly	Maximum Oxide Thickness, µm
	End of Second Cycle

Table 4-9—Holddown Spring Height

Face	Spring Height, inches	
	End of Second Cycle	
	MX01 (NJ13GE)	MX02 (NJ13GF)

Table 4-10—Holddown Spring Stiffness

Assembly	Spring Stiffness, pounds/inch
	End of Second Cycle

Figure 4-1—Top Ends of Fuel Rods as Seen on West Face of MX01, End of Cycle 1

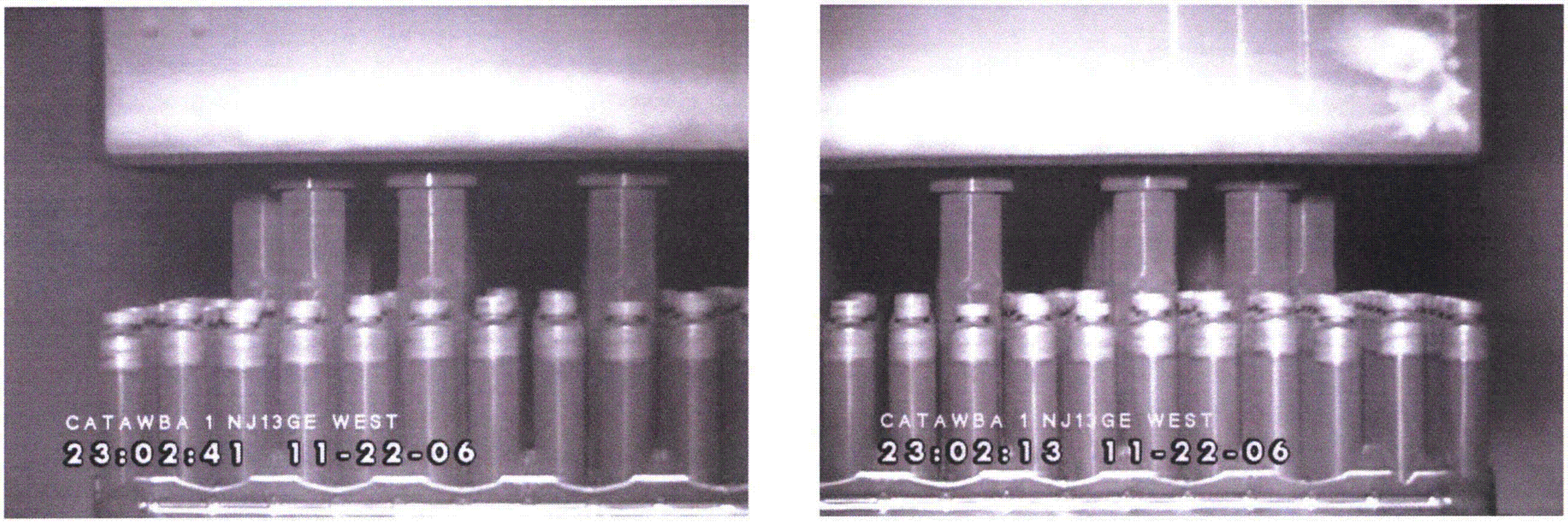

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Figure 4-2—Top End Grid as Seen on West Face of MX01, End of Cycle 1

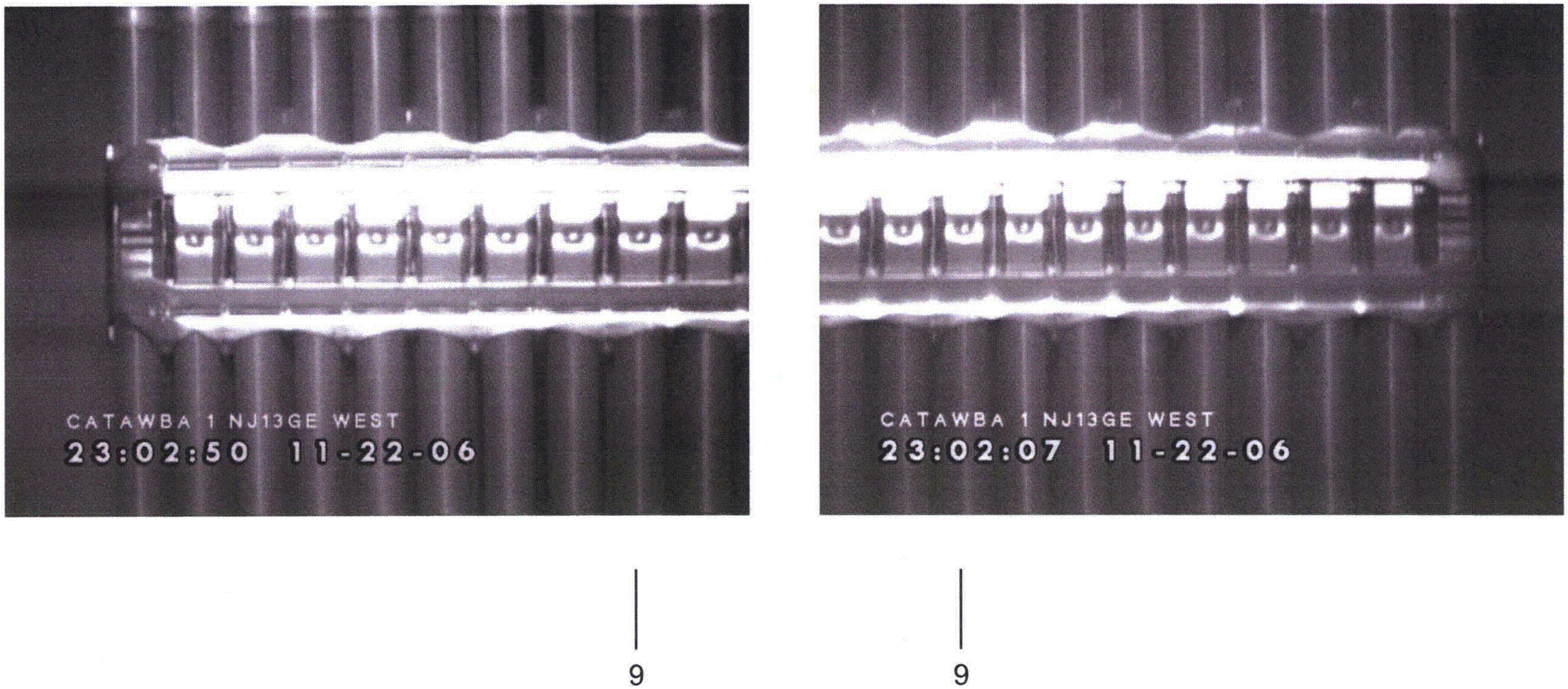

Figure 4-3—Third Spacer Grid from Top as Seen on West Face of MX01, End of Cycle 1

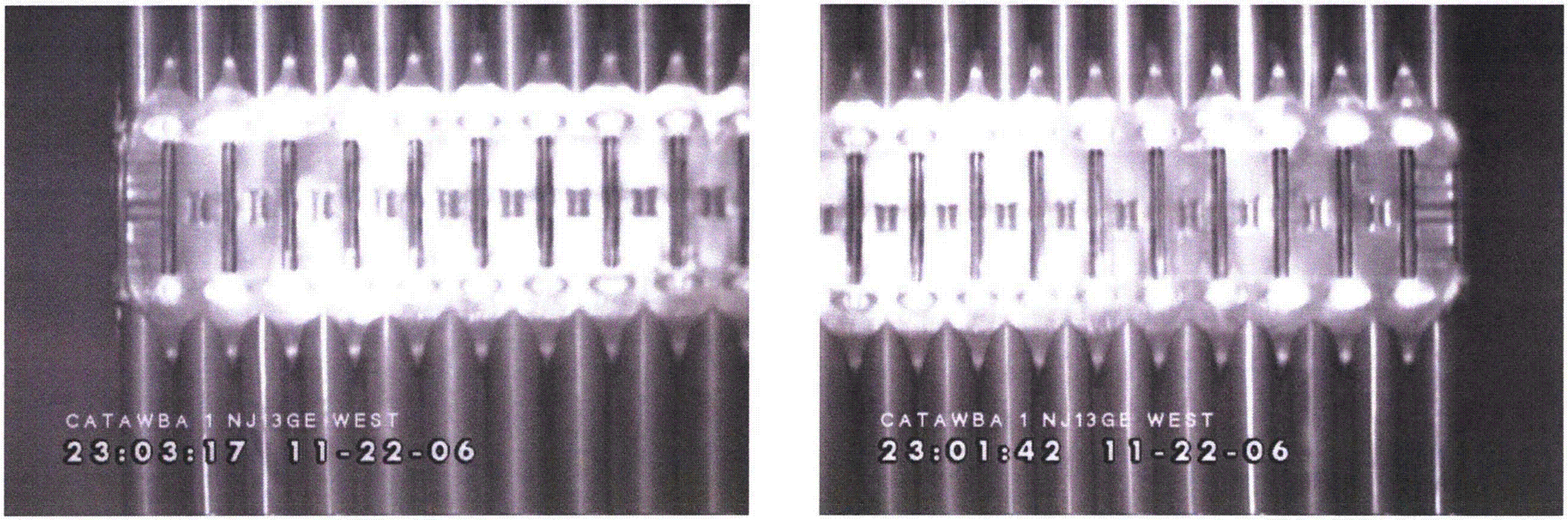

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Figure 4-4—Middle Mid-span Mixing Grid as Seen on West Face of MX01, End of Cycle 1

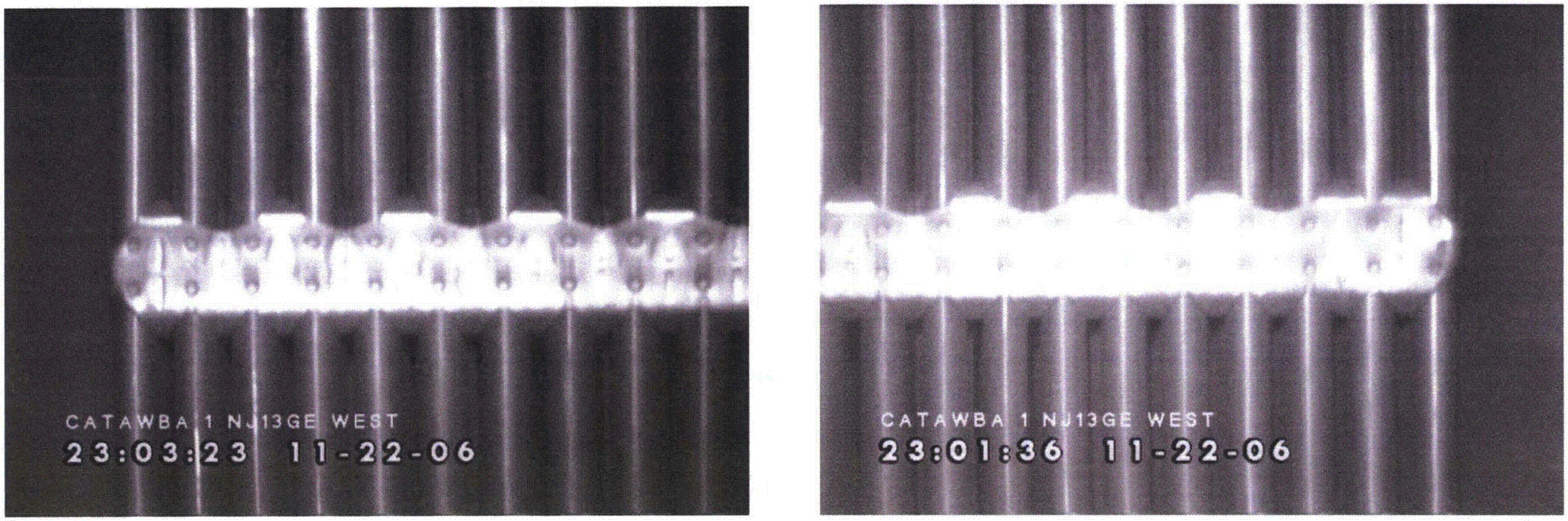

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Figure 4-5—Bottom End Grid as Seen on West Face of MX01, End of Cycle 1

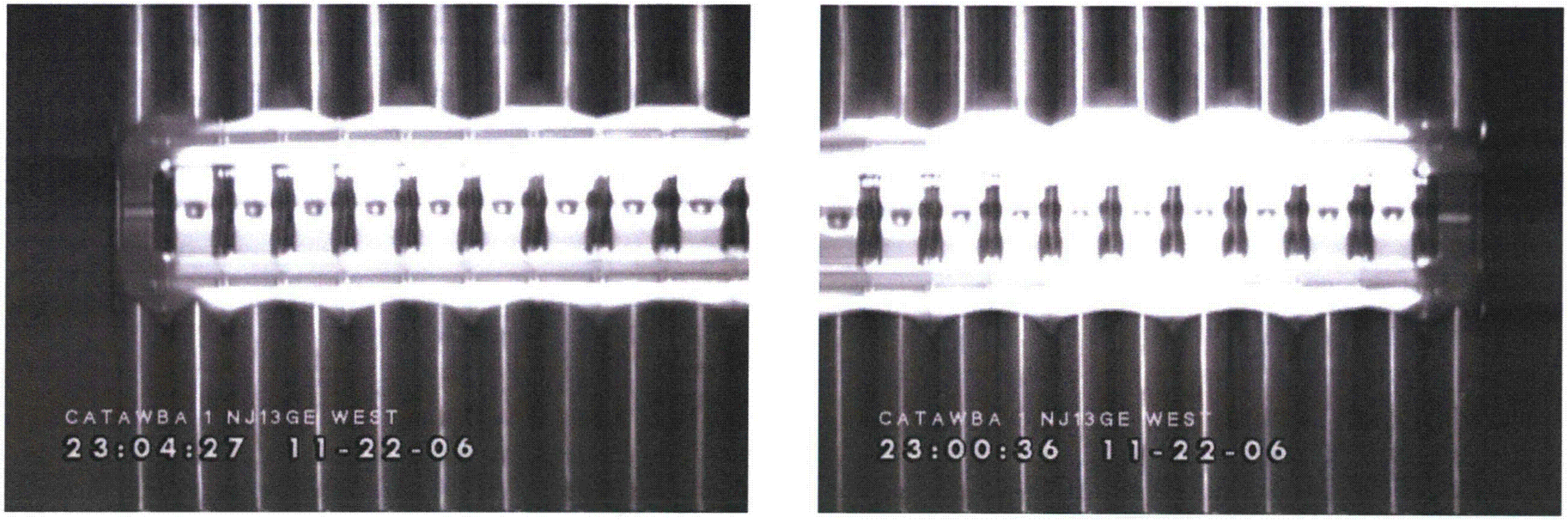

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Figure 4-6—Bottom Ends of Fuel Rods as Seen on West Face of MX01, End of Cycle 1

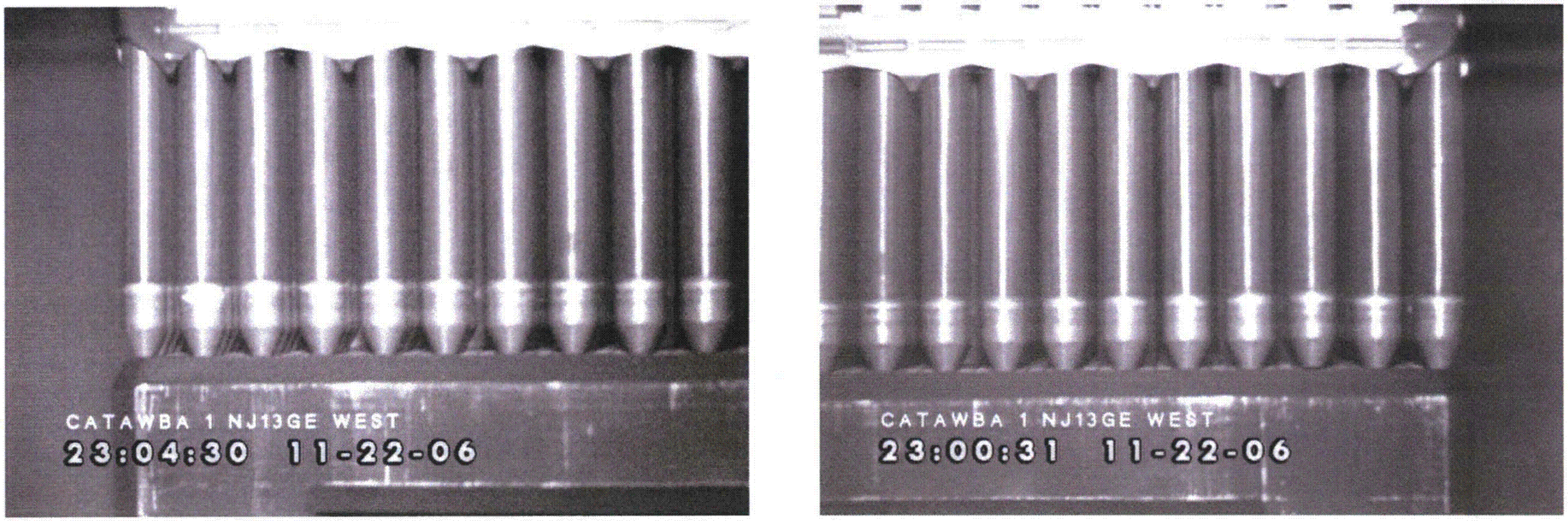

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Figure 4-7—Top Ends of Fuel Rods as Seen on West Face of MX01, End of Cycle 2

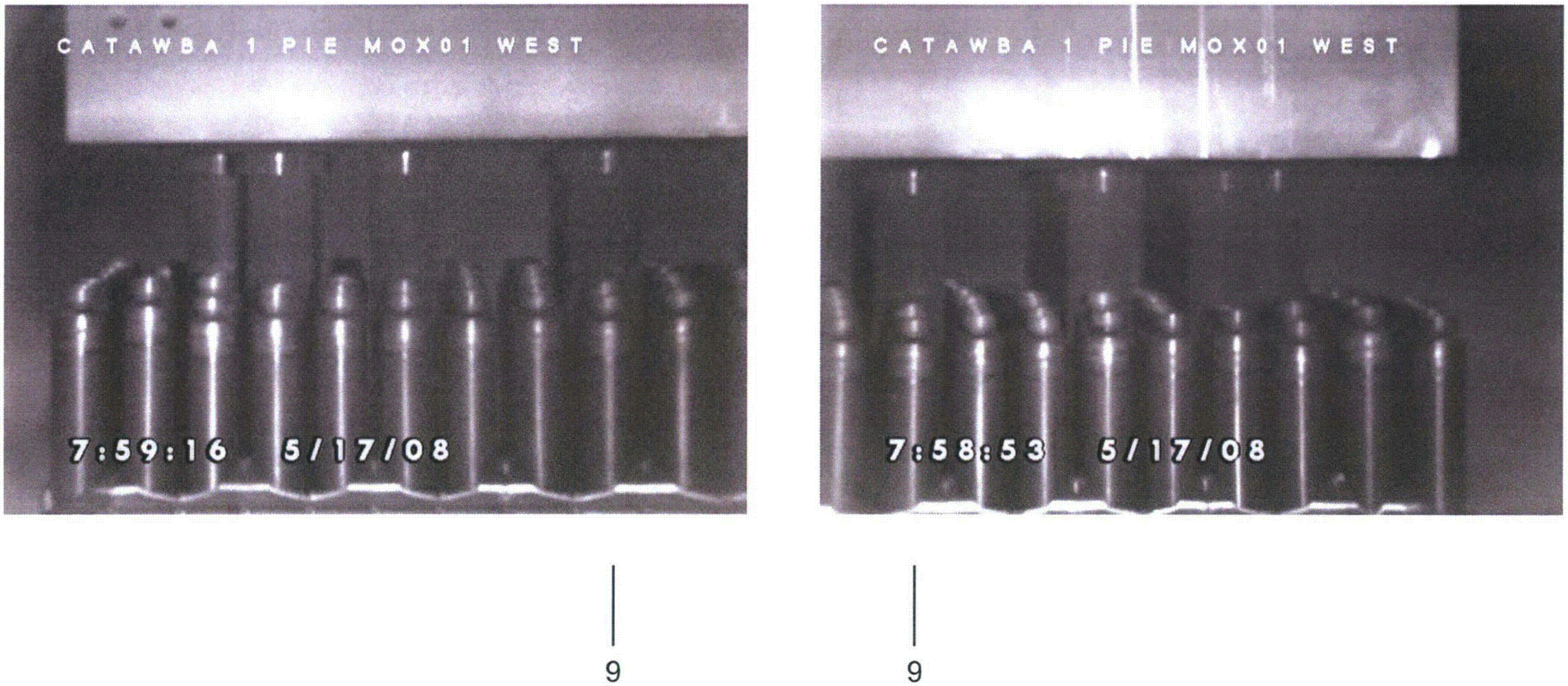

Figure 4-8—Top End Grid as Seen on West Face of MX01, End of Cycle 2

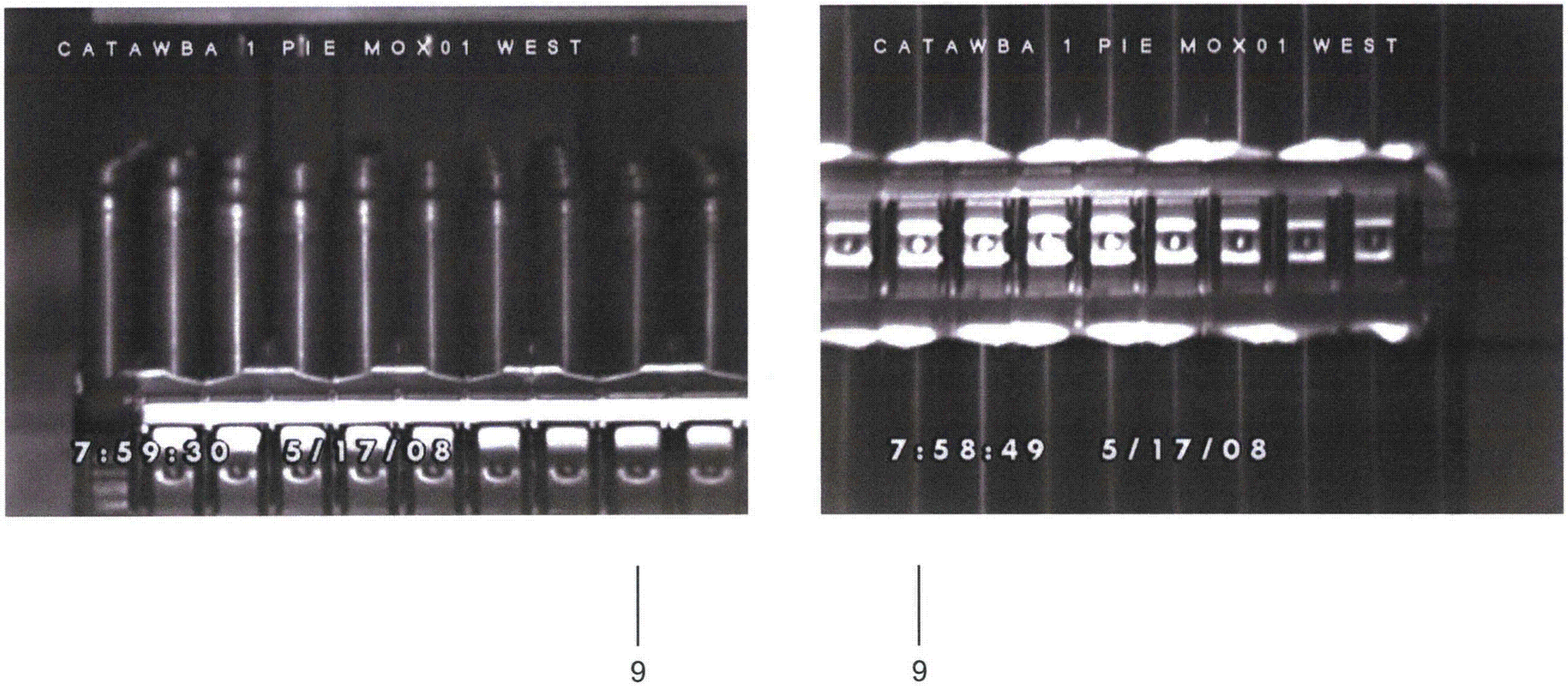

Figure 4-9—Third Spacer Grid from Top as Seen on West Face of MX01, End of Cycle 2

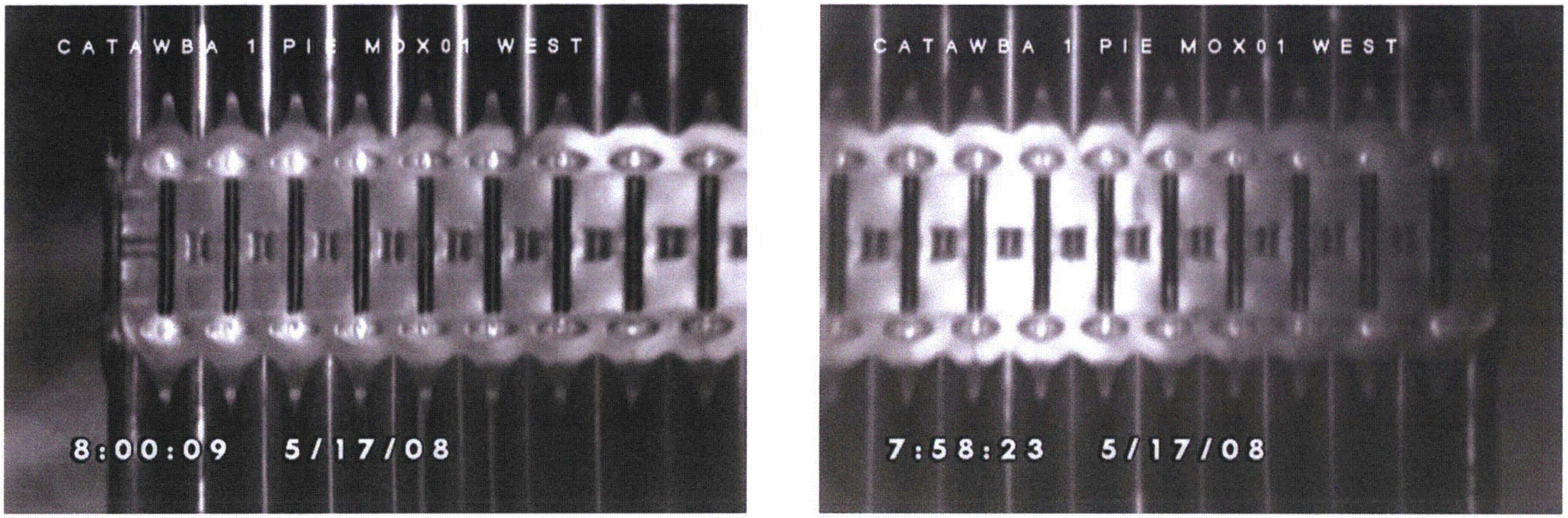

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Figure 4-10—Middle Mid-span Mixing Grid as Seen on West Face of MX01, End of Cycle 2

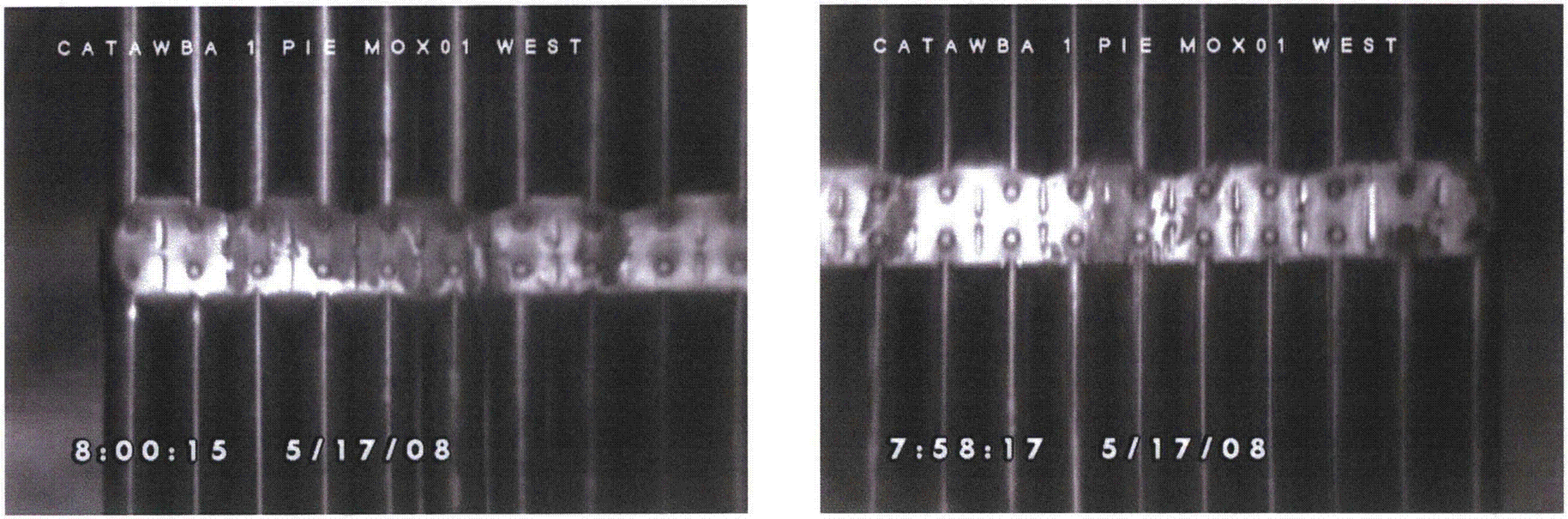

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Figure 4-11—Bottom End Grid as Seen on West Face of MX01, End of Cycle 2

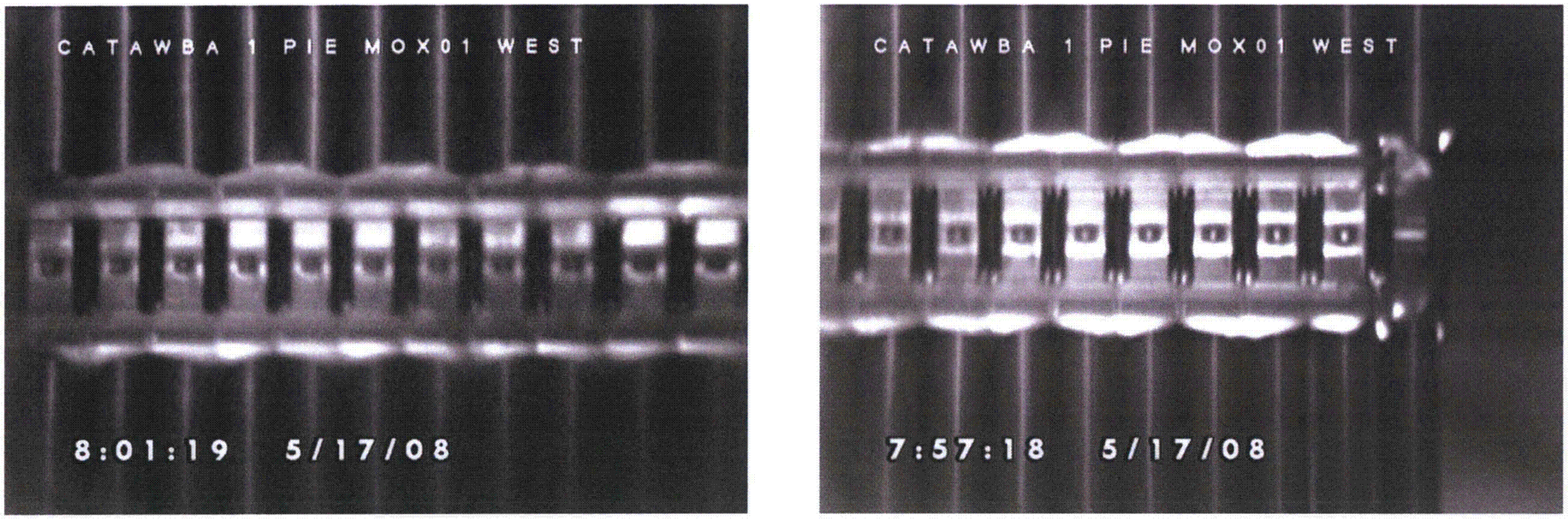

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Figure 4-12—Bottom Ends of Fuel Rods as Seen on West Face of MX01, End of Cycle 2

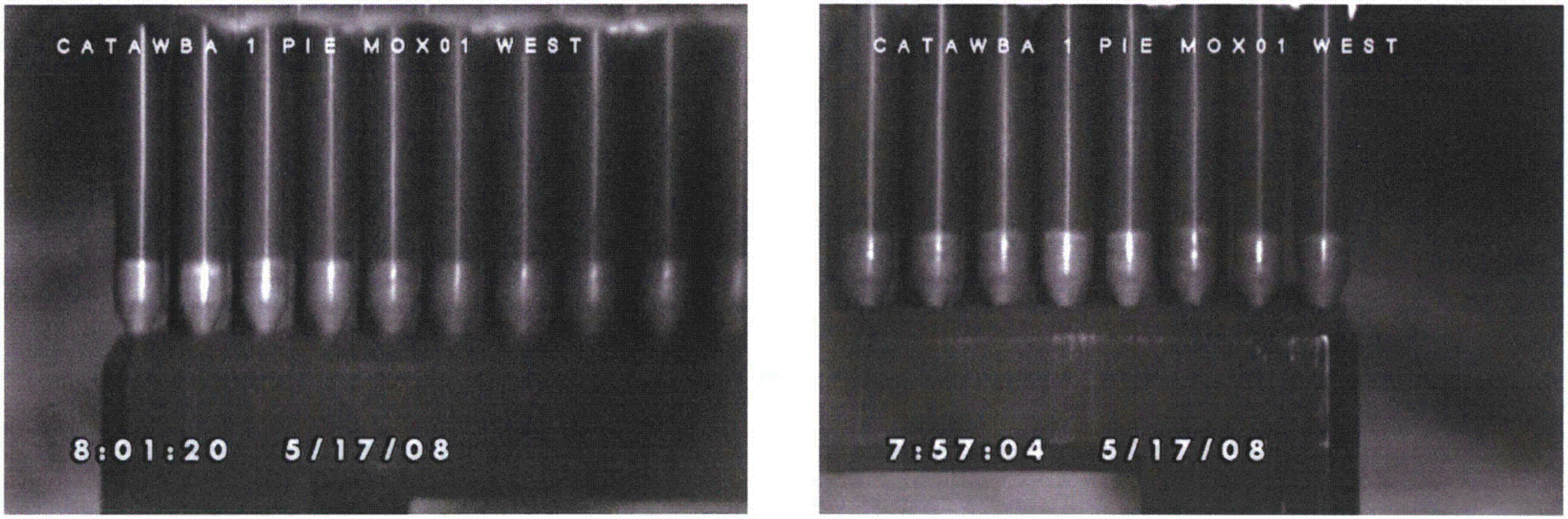

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Figure 4-13—Bowed Fuel Rods on East Face of MX03, Span 8, End of Cycle 2

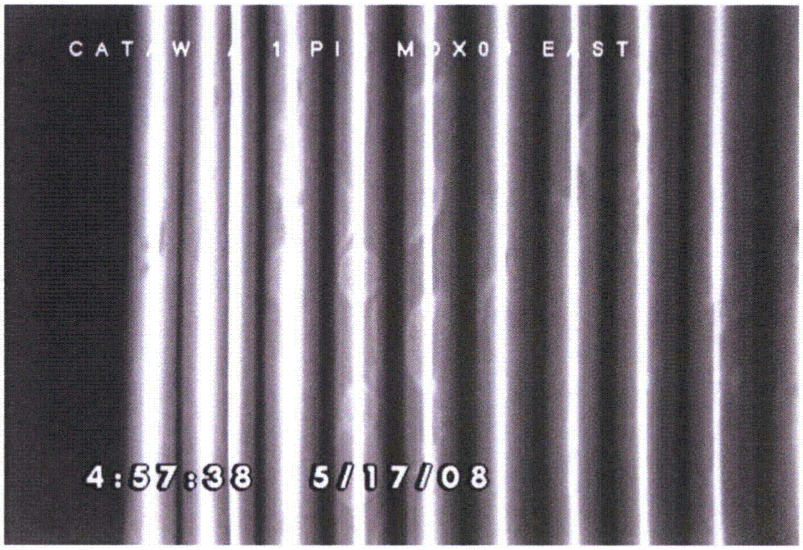

Figure 4-14—Bowed Fuel Rods on South Face of MX04, Span 9, End of Cycle 2

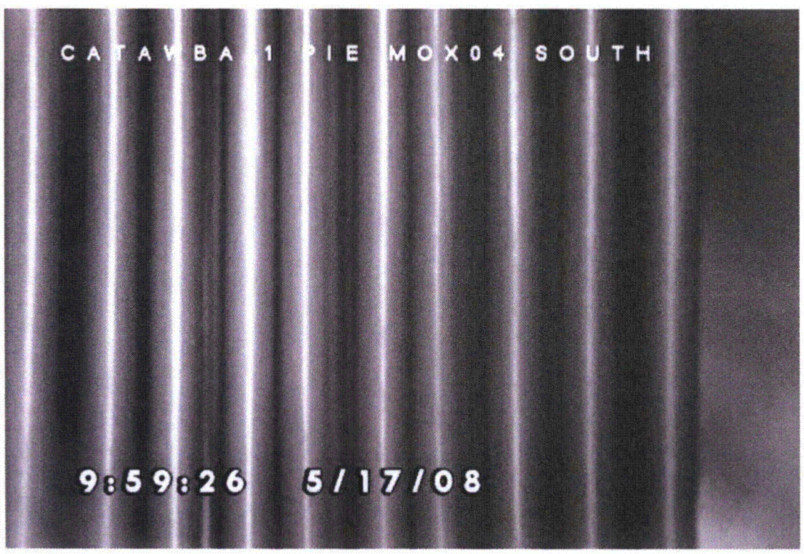

Figure 4-15—Fuel Assembly Bow, North Face

[ ]

Figure 4-16—Fuel Assembly Bow, West Face

[ ]

5.0 REFERENCES

1. DCS-FQ-1999-001, Rev. 4, *Fuel Qualification Plan*, July 2008.

2. BAW-10238PA, Rev. 1, *MOX Fuel Design Report*, July 2004.

3. BAW-10147P-A, Rev. 1, *Fuel Rod Bowing in Babcock & Wilcox Fuel Designs*, May 1983.

4. Letter from James R. Morris (Duke Energy) to Document Control Desk (U.S. NRC), January 9, 2007, “Duke Power Company LLC d/b/a Duke Energy Carolinas, LLC (Duke), Catawba Nuclear Station, Unit 1, Docket Number 50-413, Operating Report for Cycle 16 Operation with Mixed Oxide (MOX) Fuel Lead Assemblies”, with attachment.

6.0 APPENDIX

This appendix provides information on operation of Catawba Unit 1 during the first cycle of irradiation of the MOX lead assemblies.

A report issued by Duke (Reference 4) provides boron concentration and full-core flux maps for various times during cycle 16. Reference 4 includes the measured assembly relative radial power density for the lead assemblies at selected times during irradiation. The locations of the lead assemblies in core are shown in Figure 1-2.

Table A-1 summarizes the core operation history for Catawba Unit 1 Cycles 16 and 17. Cycle 16 included one outage due to loss of offsite power (NRC event 42592), which lasted from May 20, 2006 to June 10, 2006.

Table A-1—Catawba Unit 1 Cycles 16 and 17 Core Operation History

Lead Assembly Cycle	Start Date	End Date	Cycle Length (EFPD)	Assembly Average Burnup (GWd/MThm)	Maximum Rod Average Burnup (GWd/MThm)
1	Jun. 5, 2005	Nov. 11, 2006	499	22.0	26.1
2	Dec. 29, 2006	May 3, 2008	485	41.8	47.3