Materials Reliability Program: Functionality Analysis for Flexible Operations of Westinghouse-Design Representative PWR Internals (MRP-230, Revision 2—Supplement 2)

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Product Description

This report supplement summarizes the functionality assessment of degradation for Westinghouse representative pressurized water reactor (PWR) internals under flexible operation conditions. The content is only applicable to plants that have switched from out-in fuel loading to low-leakage loading by the completion of seven fuel cycles, along with the limits provided in MRP-227-Revision 1-A, Appendix B. The evaluations in this report are also only applicable to plants conducting flexible operation within the rate and power reduction limits defined by the simulations performed.

Background

In recent years, a number of domestic and foreign utilities operating nuclear power plants have considered operating their plants as flexible operation units, and several plants have already begun flexible operation. To support the first period of extended operation (PEO) the Electric Power Research Institute's (EPRI's) Materials Reliability Program (MRP) developed inspection and evaluation (I&E) guidelines for the reactor vessel internals in MRP-227-A and MRP-227, Revision 1. However, these two documents specifically limit their applicability to plants that have operated and continue to operate as baseload units (see Section 2.4 of either document). To use the I&E guidelines, the utility currently must either perform a plant-specific justification for why this applicability criterion has been met or develop its own plant-specific reactor vessel internals aging management program to meet the requirements of license renewal. The MRP has published interim guidance on flexible operation and the I&E guidelines in letter MRP 2019-002, which supports addressing the baseload applicability criterion.

Objective

- To document the work underlying the interim guidance in letter MRP 2019-002 in more detail, particularly the aging simulations

Approach

The first part of the work included evaluations of the existing fatigue calculations for two pilot plants—one 3-loop design plant and one 4-loop design plant. The second part of the work used simulations performed with the MRP-230 functionality analysis finite element model (FEM) of a Westinghouse-designed 3-loop downflow plant to determine the impact of several flexible operation scenarios on the baffle-former bolts (BFBs). Included in this analysis is the evaluation

of selected austenitic stainless steel components that are judged as susceptible to irradiation-induced degradation of mechanical and/or physical properties using an ANSYS®-based subroutine, IRADSS, developed by ANATECH Corporation. The data gathered from the FEM runs were then processed to evaluate the amount of fatigue damage the BFBs would accumulate during flexible operation.

A previous evaluation, published in EPRI report 3002008119, concluded that the BFBs are the component in the Westinghouse-designed reactor internals that is most susceptible to the fatigue effects of flexible operation. That report also concluded that the Combustion Engineering (CE)-designed reactor vessel would not be impacted by flexible operation as long as the CE unit operates within its design transient cycles. Based on this previous evaluation, the focus of the current work was directed at evaluating the Westinghouse-designed BFBs.

Results

The functionality analysis model of a 3-loop plant was modified to simulate three different flexible operation cases: 100% to 80% power, 100% to 70% power, and 100% to 30% power. Out-in and low-leakage core loading patterns and the presence or absence of baffle-edge bolts were considered among the various model simulations conducted. Fatigue damage for the BFBs was extracted from these runs and used to determine allowable numbers of fatigue cycles or effective full-power years (EFPY) for each of the flexible operation cases evaluated.

Applications, Value, and Use

The allowable fatigue cycles and EFPY calculated by this study can be used as screening criteria to indicate the potential for accelerated fatigue damage due to flexible operation. These screening criteria will allow a plant to determine if the baseload operation applicability assumption of MRP-227 is still valid. Note that the analyses performed here using a 3-loop plant model were assumed to be applicable to other Westinghouse plant designs based on the various conservatisms applied. However, it is recommended that future analyses using the 4-loop functionality analysis model under development by the Materials Reliability Program be performed to confirm this approach.

It should be noted that the understanding of the irradiation effects included in the IRADSS module is still growing within the industry and the scientific community. The analyses documented here were based on current understanding at the time the work was conducted.

Keywords

Degradation mechanism
Functionality analysis
Westinghouse design
Flexible operation
PWR internals
Fatigue

[redacted]

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EXECUTIVE SUMMARY

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Product Title: Materials Reliability Program: Functionality Analysis for Flexible Operations of Westinghouse-Design Representative PWR Internals (MRP-230, Revision 2—Supplement 2)

PRIMARY AUDIENCE: PWR utility program engineers

SECONDARY AUDIENCE: Utility inservice inspection engineers

KEY RESEARCH QUESTION

Penetration of wind and solar electric power generation into the electric grid of a number of domestic and foreign utilities operating nuclear power plants has occurred in recent years, to the extent that these utilities have considered operating their plants as flexible operation units. Several plants have already begun flexible operation, reducing power output in response to the needs of the local electric grid. This new operational characteristic accommodates the intermittent nature of electric power generation by renewable sources, such as wind and solar, without energy storage. Prior to this, most nuclear plants operated as baseloaded units—that is, they supplied electricity at a constant rate for a lengthy period of time (months to years).

However, the inspection and evaluation (I&E) guidelines developed by the Electric Power Research Institute's (EPRI's) Materials Reliability Program (MRP) to support extended operation of the reactor vessel internals (MRP-227-A and MRP-227, Revision 1) are only applicable to baseload operation plants. To use the I&E guidelines, the utility currently must either perform a plant-specific justification for why this applicability criterion has been met or develop its own plant-specific reactor vessel internals aging management program to meet the requirements of license renewal.

RESEARCH OVERVIEW

The MRP has published interim guidance on flexible operation and the I&E guidelines in the EPRI letter MRP 2019-002, which supports addressing the baseload applicability criterion. The first part of the work included evaluations of the existing fatigue calculations for two pilot plants—one 3-loop design plant and one 4-loop design plant. The second part of the work used simulations performed with the MRP-230 functionality analysis finite element model (FEM) of a Westinghouse-designed 3-loop downflow plant to determine the impact of several flexible operation scenarios on the baffle-former bolts (BFBs). Included in this analysis is the evaluation of selected austenitic stainless steel components that are judged as susceptible to irradiation-induced degradation of mechanical and/or physical properties using an ANSYS®-based subroutine, IRADSS, developed by ANATECH Corporation. The data gathered from the FEM runs were then processed to evaluate the amount of fatigue damage the BFBs would accumulate during flexible operation.

A previous evaluation concluded that the BFBs are the component in the Westinghouse-designed reactor internals that is most susceptible to the fatigue effects of flexible operation. The report also concluded that the Combustion Engineering (CE)-designed reactor vessel internals are substantially less susceptible to fatigue effects from flexible operation than the Westinghouse-designed internals and would not be impacted by flexible operation as long as the CE unit operates within its design transient cycles. Based on this previous evaluation, the focus of the current work was directed at evaluating the Westinghouse-designed BFBs.

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The functionality analysis model of a 3-loop plant was modified to simulate three different flexible operation cases: 100% to 80% power, 100% to 70% power, and 100% to 30% power. Out-in and low-leakage core loading patterns and the presence or absence of baffle-edge bolts were considered among the various model simulations conducted.

KEY FINDINGS

- Fatigue damage for the BFBs was extracted from the simulation runs and used to determine allowable numbers of fatigue cycles or effective full-power years (EFPY) for each of the flexible operation cases evaluated.
- Flexible operation with power reduction to 80% of full power applied deflections to the BFBs that were below the endurance limit.
- Core loading type had a significant effect on the amount of deflection, with low-leakage core loading resulting in higher flexible operation screening values.
- The case without edge bolts installed resulted in slightly higher fatigue damage and lower numbers of allowable flexible operation events.
- The screening criteria for 30% of full-power flexible operation events were significantly lower than for the other cases evaluated—put another way, the fatigue damage increases with larger power reductions.
- The top former level was limiting for each of the flexible operation cases, as would be expected due to the low level of irradiation-induced stress relaxation and the larger impact of thermal growth.

WHY THIS MATTERS

The allowable fatigue cycles and EFPY calculated by this study can be used as screening criteria to indicate the potential for accelerated fatigue damage due to flexible operation. These screening criteria will allow a plant to determine if the baseload operation applicability assumption of MRP-227 is still valid.

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EXECUTIVE SUMMARY

HOW TO APPLY RESULTS

Revised recommendations for MRP-227 for Westinghouse-designed plants are provided in detail in Section 8 of the report. These are summarized as screening criteria for the number of flexible operation cycles a plant can undergo before requiring further actions to continue implementing the MRP-227 aging management program. Per earlier flexible operation evaluations, CE-designed reactor vessel internals are substantially less susceptible to flexible operation than Westinghouse-designed plants and would not be impacted by flexible operation as long as the CE unit operates within its design transient cycles.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- MRP Assessment and Inspection Technical Advisory Committees (TACs)

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PROGRAMS: Flexible Operations, P41.11.01; Materials Reliability Program, P41.01.04

IMPLEMENTATION CATEGORY: Technical Basis Report, Reference

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Acronyms and Abbreviations

BFB	baffle-former bolt
BMI	bottom-mounted instrumentation
BOC	beginning of cycle
Btu	British thermal unit
CE	Combustion Engineering
CFD	computational fluid dynamics
CRGT	control rod guide tube
CUF	cumulative usage factor
dpa	displacements per atom
EAF	environmentally assisted fatigue
EFPY	effective full-power years
EOC	end of cycle
EPRI	Electric Power Research Institute
FEM	finite element model
I&E	inspection and evaluation
in	inch
MOC	middle of cycle
MRP	Materials Reliability Program
NRC	United States Nuclear Regulatory Commission
PEO	period of extended operation
psi	pounds per square inch
PWR	pressurized water reactor
s	second
SV	state variable
TAC	Technical Advisory Committee
UT	ultrasonic test

[redacted]

Unit Conversion Factors

1 inch = 0.0254 m = 2.54 cm = 25.4 mm

1 °F = 1.8 °C + 32

1 °FΔ = 1.8 °CΔ

1 psi = 6,895 Pa = 6.895×10^{-3} MPa

1 Btu = 1,055 J

1 Btu/s-in^3 = 6.438×10^{7} W/m^3

1 Btu/s-in^2-°F = 2.944×10^{6} W/m^2-°C

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Section 1: Introduction

Penetration of wind and solar electric power generation into the electric grid of a number of domestic and foreign utilities operating nuclear power plants has occurred in recent years, to the extent that these utilities have considered operating their plants as flexible operation units. Several plants have already begun flexible operation, reducing power output in response to the needs of the local electric grid. This new operational characteristic accommodates the intermittent nature of electric power generation by renewable sources, such as wind and solar, without energy storage. Prior to this, most nuclear power plants operated as baseload units—that is, they supplied electricity at a constant rate for a lengthy period of time (months to years).

Even though domestic nuclear power plants were originally designed to be flexible operation units, this was assuming a 40-year design life for the plants. Now, most plants will be operated up to 60 years, and some utilities are considering operating selected plants to 80 years. To support the first period of extended operation (PEO) the Electric Power Research Institute's (EPRI's) Materials Reliability Program (MRP) developed inspection and evaluation (I&E) guidelines for the reactor vessel internals. These I&E guidelines exist as both a Nuclear Regulatory Commission (NRC) approved version (MRP-227-A [1]) and an updated MRP-227, Revision 1 [2]. These two documents specifically limit their applicability to plants that have operated and continue to operate as baseload units (see Section 2.4 of either document).

This limitation has a direct impact on a plant where flexible operation is currently implemented or is planned for the future. To use the I&E guidelines, the utility must either perform a plant-specific justification for why the baseload applicability criterion has been met or develop its own plant-specific reactor vessel internals aging management program to meet the requirements of license renewal.

The MRP published interim guidance on flexible operation and the I&E guidelines in letter MRP 2019-002 [3]. The interim guidance permits a PWR to implement flexible operation while in the first PEO under the I&E guidelines. This is accomplished by monitoring the number and size of the flexible operation cycles used by the plant. These flexible operation cycle counts are then compared to screening criteria to allow application of MRP-227.

[redacted]

Letter MRP 2019-002 provides an overview of the evaluations, calculations, and simulations performed to develop the interim guidance. The objective of the current report is to document the work underlying the interim guidance in more detail, particularly the aging simulations that were conducted. The first part of the work included evaluations of the existing fatigue calculations for two pilot plants—one 3-loop design plant and one 4-loop design plant. The second part of the work used simulations performed with the MRP-230 functionality analysis finite element model (FEM) of a Westinghouse-designed 3-loop downflow plant [4] [5] to determine the impact of several flexible operation scenarios on the baffle-former bolts (BFBs). Included in this analysis is the evaluation of selected austenitic stainless steel components that are judged as susceptible to irradiation-induced degradation of mechanical and/or physical properties using an ANSYS®[1]-based subroutine, IRADSS, developed by ANATECH Corporation [6] [7]. The data gathered from the FEM runs were then processed to evaluate the amount of fatigue damage the BFBs would accumulate during flexible operation.

A previous evaluation [8] concluded that the BFBs are the component in the Westinghouse-designed reactor internals that is most susceptible to the fatigue effects of flexible operation. The report also concluded that the CE-designed reactor vessel internals are substantially less susceptible to flexible operation than the Westinghouse-designed internals and would not be impacted by flexible operation as long as the CE unit operates within its design transient cycles. Based on this previous evaluation, the focus of the current work was directed at evaluating the Westinghouse-designed BFBs.

In the United States, even though the nuclear power plants were designed for flexible operation, most have operated at 100% rated thermal power for the majority of the plant operating life. Based on a 40-year plant life and depending on the vintage of the plant, either 18,300 (Westinghouse fleet), 15,000 (CE fleet), or 13,200 (Westinghouse fleet) flexible operation cycles were typically accounted for in the design basis structural stress and fatigue analyses. Because the plants in the U.S. have operated as baseload units, very little of this cycle allowance has been used. Even in cases where major components such as the steam generators have been replaced or where a power uprate was performed, the plant design basis was updated to maintain the flexible operation capability.

[1] ANSYS, ANSYS Workbench, CFX, AUTODYN, and any and all ANSYS, Inc. product and service names are registered trademarks or trademarks of ANSYS, Inc. or its subsidiaries located in the United States or other countries.

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Section 9: Conclusions and Recommendations

MRP-227-A/Revision 1 [1] [2] originally limited the applicability of the I&E guidelines for license renewal to plants operating as baseload units. The interim guidance in letter MRP 2019-002 [3] provided a set of screening criteria that could be used as an alternative for plants that have implemented both the MRP-227 guidance and flexible operation. The work documented in the current report provides additional detail on the technical basis for the summary and conclusions contained in letter MRP 2019-002.

A fatigue study was performed for 3-loop and 4-loop pilot plants. The data from these plants are indicative of the general fatigue behavior (though not necessarily bounding) of the reactor vessel internals components and were used to develop a flexible operation fatigue damage screening criterion. The pilot plant fatigue usage data provided in this report should not be used directly in a plant-specific cumulative usage factor evaluation. The results from the pilot plant and previous studies showed that the BFBs would be the lead indicator for fatigue degradation in plants that are using or have used flexible operation. The evaluation also provided an indication of the relative impact of flexible operation as compared to baseload operation. Additional conservatism was applied to this relative ratio, and it was used to develop flexible operation event screening criteria.

The functionality analysis model of a 3-loop plant was modified to simulate three different flexible operation cases: 100% to 80% power, 100% to 70% power, and 100% to 30% power. Out-in and low-leakage core loading patterns and the presence or absence of baffle-edge bolts were considered among the various model simulations conducted. Fatigue damage for the BFBs was extracted from these runs and used to determine allowable numbers of fatigue cycles or EFPY for each of the flexible operation cases evaluated. These allowable fatigue cycles and EFPY can be used as screening criteria to indicate the potential for accelerated fatigue damage due to flexible operation. These screening criteria will allow a plant to determine if the baseload operation applicability assumption of MRP-227 is still valid. Note that the analyses performed using a 3-loop plant model were assumed to be applicable to other Westinghouse plant designs based on the various conservatisms applied. However, it is recommended that future analyses using the 4-loop functionality analysis model under development by the MRP be performed to confirm this approach.

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