U.S. NUCLEAR REGULATORY COMMISSION STAFF ASSESSMENT OF PWROG-14048-P, REVISION 1, "FUNCTIONALITY ANALYSIS: LOWER SUPPORT COLUMNS"

1.0 BACKGROUND

By letter dated March 1, 2017 (Reference 1), the Pressurized Water Reactor Owners Group (PWROG) submitted PWROG-14048-P, Revision 1, "Functionality Analysis: Lower Support Columns," to the U.S. Nuclear Regulatory Commission (NRC) for information. The PWROG developed PWROG-14048-P, Revision 1 to extend the applicability of the functionality analysis to all Combustion Engineering (CE) and Westinghouse lower-support column (LSC) designs to account for the range of parameters of the plants participating in the PWROG program (herein called "participating plants") and to address the NRC staff concerns described in the conclusions of the summary assessment of PWROG-14048-P, Revision 0 issued on December 17, 2015 (Reference 2).

PWROG-14048-P is a supporting document to licensees' responses to Applicant/Licensee Action Item 7 (A/LAI 7) of the NRC staff safety evaluation for MRP-227-A (Reference 3) regarding the functionality of LSCs during the period of extended operation (PEO), or plant operating life of 60 years.

Section 2 of this assessment contains the NRC staff assessment of the additional analyses in PWROG-14048-P going from Revision 0 to Revision 1. As in the NRC staff assessment of PWROG-14048-P, Revision 0 this assessment focuses on the technical merits of the report and does not make any regulatory findings. Furthermore, the NRC staff's main objective of this assessment is to determine if the conclusions in its assessment of PWROG-14048-P, Revision 0 are still valid.

2.0 TECHNICAL ASSESSMENT

Section 1 "Executive Summary" of the report states that due to the significant changes going from Revision 0 and Revision 1, change bars were not included. The NRC staff reviewed these changes and determined that many of them are due to discussions that have been moved from one section into another section. For example, the discussion of column stresses has been moved from Section 5 of PWROG-14048-P, Revision 0 to Section 6 of Revision 1. These relocated discussions are mainly due to extending the applicability of the functionality analysis to all CE and Westinghouse LSC designs.

The NRC staff identified nine changes, as shown in Section 2.1, "Identification of Changes," of this assessment, and assessed each change in Section 2.2, "NRC Staff Assessment of Changes." The NRC staff listed the changes within the five main topics of the report: (1) *Plant Applicability*, (2) *Grouping of LSC Designs Into Four Design Categories*, (3) *Finite Element Analysis of Four LSC Design Categories*, (4) *Lower Support Column Flaw Tolerance Analysis*, and (5) *Lower Support Structure Redundancy Analysis*. The section of the report where the change is located is listed under each change.

2.1 Identification of Changes

Plant Applicability

1. Discussion of special considerations for two plants.
   Location: Section 3, "Limits of Applicability"

Grouping of LSC Designs into Four Design Categories

2. Establishment of four design categories that represent the LSC designs.
   Location: Section 6.1, "Establishing Bounding Parameters"

Finite Element Analysis of Four LSC Design Categories

3. Use of bounding values for loss-of-coolant-accident (LOCA), seismic, and heat generation loads; simulation of heat generation directly within the lower core plate (LCP) rather than simple temperature difference between the LCP and lower support structure (LSS) assembly.
   Location: Section 6.1.3, "Load Parameters." Section 6.3.2, "Thermal Analysis," and Section 6.3.3, "Structural Analysis"

4. Addition of buckling and dynamic response criteria.
   Location: Section 6.2, "Acceptance Criteria"

5. Finite element model (FEM) and finite element analysis (FEA) of four LSC design categories
   Location: Section 6.3, "Functionality Evaluation"

6. Change in pattern of clustered columns.
   Location: Section 6.4, "Lower Support Column Results"

Lower Support Column Flaw Tolerance Analysis

7. Addition of neutron fluence estimates for CE plants.
   Location: Section 5.2, "Neutron Fluence Estimates"

8. Change in irradiation assisted stress corrosion cracking (IASCC) initiation screening curve.
   Location: Section 5.3, "Crack Initiation Mechanisms"

9. Inclusion of separate flaw tolerance tables for CE and Westinghouse LSC designs.
   Location: Section 5.4, "Flaw Tolerance"

Lower Support Structure Redundancy Analysis

The redundancy analysis of the LSS has been subsumed in the discussion of the FEA of the four LSC design categories in the report. Therefore, the NRC staff assessment of LSS redundancy analysis are addressed in the assessment of the changes related to the FEA (items 3 through 6 above).

2.2 NRC Staff Assessment of Changes

Assessment of Change 1

Section 3 of the report discusses the applicability of the report to resolve A/LAI 7 for the range of loads and LSC designs of participating plants, except for the following plants:

For Plant W[1], the NRC staff agrees that further plant A/LAI 7-specific analysis will be required for faulted conditions for the "Case 2" failed LSC pattern analyzed in Section 6, "LSC Failure Tolerance Analysis," of the report. The NRC staff also agrees that the failure analysis in Section 5, "Assessment of Failure Likelihood," of the report showing low likelihood of LSC failure applies to Plant W. Also, for normal/upset conditions, the structural redundancy analysis in Section 6 of the report applies to Plant W.

For Plant X, the NRC staff agrees that no functionality analysis is needed. The report identifies Plant X as a CE-designed plant. In addition to the information provided in the report for Plant X, the NRC staff verified in MRP-227-A that CE LSCs are binned as in the primary inspection category, and therefore, their aging management during the PEO is adequate under the MRP-227-A program with no need for a functionality analysis.

Assessment of Change 2

As mentioned in Section 1.0 of this assessment, the PWROG developed the report to extend the applicability of the functionality analysis to all CE and Westinghouse LSC designs. Because of the range of designs of the LSS assembly—consisting of the LSCs, LCP, and LSP of participating plants, Section 6.1 of the report includes a discussion of the grouping of LSC designs based on geometric and material considerations (Sections 6.1.1 and 6.1.2 of the report) and loading considerations (Sections 6.1.3 and 6.1.4 of the report).

Section 6.1.1 of the report discusses a set of key geometric parameters in the LSS, such as number of LSCs in the LSS, the diameter and length of the LSCs, and thickness of LCP. Section 6.1.2 of the report discusses the four LSC design categories based on these key geometric parameters. Any participating plant is represented by one of the four categories. Section 6.1.2 of the report also discusses the grouping of the LSC designs into two major material groups: LSCs made of cast austenitic stainless steel (CASS) and LSCs that are not made of CASS. In this section, the report states that all non-CASS LSC plants are bounded by the CASS LSC plants.

The NRC staff determined that the four categories in the report reasonably represent the LSC designs of the participating plants because they were based on key geometric parameters in the LSS that could impact the function of LSCs. The NRC also determined that bounding all non-CASS LSC plants by CASS LSC plants is reasonable since the same key geometric parameters were used to bound the non-CASS LSC plants.

Assessment of Change 3

Section 6.1.3 of the report summarizes the thermal and mechanical loads applied to the FEA. The thermal load is core heat generation within the LCP. The mechanical loads are dead weight, control rod drop impact, hydraulic forces, seismic, and LOCA.

Section 6.3.2 and Section 6.3.3 of the report discusses details of the thermal and structural FEA. In the thermal FEA, short-term heat generation loads are applied on the LCP elements for

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1 As indicated in the report, due to proprietary reasons, alphabetic indentifiers (e.g., Plant W) are used to refer to specific plants.

both normal/upset and faulted conditions. The NRC staff finds this thermal loading approach acceptable because internal heat generation within the element is a better representation of the heating phenomena in the LCP compared to the approach in PWROG-14048-P, Revision 0 which is a simple temperature difference between the LCP and the rest of the LSS assembly. In the structural FEA, the same mechanical loads (dead weight, spring and hydraulic lift forces, seismic, LOCA) and load combinations as in PWROG-14048-P, Revision 0 were applied and analyzed. Therefore, the NRC staff finds the mechanical loads and load combinations acceptable.

For significant loads such as heat generation, seismic, and LOCA, bounding values in each LSC design category were used. For less significant loads, such as dead weight and spring forces, representative values in each LSC design category were used. The NRC staff finds this loading approach adequately bounds the loading conditions of each of the four LSC design categories.

Assessment of Change 4

In Section 6.2 of the report, acceptance criteria were added for LSC buckling and dynamic response of the LSS assembly in the presence of failed LSCs. The buckling and dynamic response criteria were two items the NRC staff concluded in Reference 2 needed to be considered for cases when failed LSCs are present.

The buckling acceptance criterion, discussed in Section 6.2.1.5, “Buckling,” of the report, is based on LSC critical buckling stresses calculated from the Euler column formula. The critical buckling stresses for all four LSC design were in the range of hundreds of thousand pounds per square inch. As discussed in Section 6.2.1.5, since the primary membrane stress limits for all loading conditions are much lower than the critical buckling stress (at least an order of magnitude lower) the LSCs are not susceptible to buckling.

In addition, it was noted in Section 6.2.1.5 that the LSCs in the periphery of the LCP have eccentric buckling loads. An eccentric buckling load is a compressive axial load off-center of the LSC axis and can cause buckling of the LSC at the same value as a non-buckling, center-aligned load. However, as discussed in Section 6.2.1.5, LSCs at the periphery share loads with the core barrel ledge and therefore, have compressive loads that are lower than those in the center of the LCP.

The NRC staff verified the calculations of critical buckling stress and found the results reasonable. The NRC staff finds the evaluation for potential LSC buckling acceptable since the critical buckling stresses are at least an order of magnitude higher than compressive membrane stresses in the LSCs. The NRC also agrees that the LSCs in the periphery would have lower compressive loads because the core barrel ledge shares the load with the LSCs. However, because of the bending moment caused by the off-center axial compressive load, the NRC staff determined that LSCs could fail at stresses below the critical buckling stress, as discussed in the next paragraph.

The eccentric loading described above prompted the NRC staff to assess the effect of bending moment in general on column buckling. The NRC staff reviewed the literature on column buckling theory and determined that a column subject to a bending moment in addition to a compressive axial load can fail at the compressive yield stress of the material before reaching the critical buckling stress. The report presented high bending stresses in the LSCs for the faulted condition in the redundancy analysis (i.e., when some LSCs have failed).

The NRC staff is concerned that for these cases, the LSCs would fail under faulted loads due to compressive yielding. There is no discussion in the report on the effect of high compressive bending stresses on LSC failure. Therefore, the NRC staff determined that the report does not fully address LSC redundancy for faulted conditions. However, the NRC staff observed that the faulted condition analyzed in the report is very conservative and an unlikely condition since LOCA and seismic events are assumed to occur at the same time.

Furthermore, the NRC staff determined that the flaw tolerance evaluation in the report demonstrated that the likelihood of full-section failure of the LSCs is low (see “Assessment of Change 9”). This means that the likelihood of having an LSC configuration with broken LSCs is low. Since high bending stresses occur under faulted loads for cases with broken LSCs, the likelihood of having LSCs subject to high bending stresses is low.

Section 6.2.1.4, “Dynamic Response Criteria,” and Section 6.5, “Effect on Dynamic Response,” of the report discuss the dynamic acceptance criteria. A modal analysis of each of the four LSC designs was performed for the case with all LSCs intact (baseline case) and compared to the modal analysis of the case with failed LSCs (Case 2). The objective of the modal analyses was to determine the impact of failed LSCs to the mode shapes or natural frequencies of the LSS assembly that are considered significant. The out-of-plane dishing mode of the LCP was determined to be the significant mode based on a review of mass participation factors. The report states that the analyses were for a comparative study and not intended to match the true natural frequencies of the LSS assembly. Thus, the modal analyses were performed without fluid and fuel mass. The results of the comparative modal analyses showed that there was little difference in the out-of-plane LCP dishing frequencies between the baseline case and Case 2 of each of the four LSC designs.

The NRC staff observed that the comparative modal analyses presented in the report show very little impact of the failed LSCs to the natural frequencies of the LSS assembly, particularly in the out-of-plane dishing frequencies of the LCP. The NRC staff noted that because of the relatively flexible LCP to which the top of the LSCs is attached, and the much stiffer LSP to which the bottom of the LSCs is attached, it is reasonable that there would be little change in the natural frequencies of the LCP even though the number of failed LSCs is large.

The number of failed LSCs is not enough to change the stiffness (and therefore, the natural frequencies) of the LCP relative to the combined stiffness of the remaining LSCs and LSP. The NRC staff also observed that although fluid and fuel mass were not included, the NRC staff determined that the FEM of each LSC design category included enough detail of the LSS assembly such that conclusions on the impact of failed LSCs to the natural frequencies of the

LSS assembly are reasonable. Therefore, the NRC staff determined that the results of the comparative modal analyses are acceptable.

The results show that if LSCs lose their load carrying capacity, the out-of-plane LCP dishing modes of the LSS assembly would remain essentially unchanged from the baseline case. Moreover, the FEMs of the LSS assembly used in the modal analyses did not include the reactor coolant and frictional effects between components. In real reactors, the reactor coolant and friction between components would dampen, and therefore reduce the impact of, the out-of-plane LCP dishing in the LSS assembly.

Assessment of Change 5

Section 6.3.1, “Finite Element Models,” summarizes the FEMs developed for each of the four LSC design categories discussed in the assessment of Change 2. The four FEMs were created with standard modeling techniques and included the same level of detail of the LSS assembly as in the FEMs in PWROG-14048-P, Revision 0. Therefore, the NRC staff concludes the FEMs are acceptable for analysis.

FEAs were performed for each LSC design category to determine deflections and stresses in the LSCs and LCP due to normal, upset, and accident loading conditions. These deflections and stresses were compared to deflection and stress criteria. The deflection and stress criteria were determined based on the same principles as in PWROG-14048-P, Revision 0. The deflection criteria ensure that controls rods can be inserted under load; and the stress criteria ensure that full section yielding of the LSCs and LCP do not occur under load. The results show that more than fifty percent of LSCs can lose their load carrying capacity without exceeding the deflection and stress criteria. As mentioned in *Assessment of Change 6* section, the number of failed LSCs represent clusters of failed LSCs. The NRC staff determined that the FEA are acceptable because they are based on the same methodology in PWROG-14048-P, Revision 0.

Assessment of Change 6

Section 6.4 discusses the results of the FEA of three cases of failed LSCs in each LSC design category. In the first case, the failed LSCs are evenly distributed and in the other two cases, the failed LSCs are clustered. These cases are different than those analyzed in PWROG-14048-P, Revision 0. The NRC staff determined that the cases are acceptable because the number of failed LSCs and patterns of failed LSCs analyzed were sufficient to demonstrate the redundancy in the load-carrying function of the LSCs.

Assessment of Change 7

Section 5.2 discusses neutron fluence estimates for CE LSCs, in addition to estimates for Westinghouse LSCs. The neutron fluence estimates in PWROG-14048-P, Revision 0 were only for Westinghouse LSCs. The NRC staff accepts the discussion of the neutron fluence estimates in Section 5.2 because it provides the additional values applicable to CE LSCs.

Assessment of Change 8

The dashed line in Figure 5.3 in Section 5.3 (Figure 5-8 in PWROG-14048-P, Revision 0) represents the IASCC initiation screening curve, which was changed to show a lower neutron exposure threshold for IASCC initiation screening. Figure 5.3 of the report also shows the additional neutron exposure estimates of the LSCs discussed in the assessment of change 7.

The NRC staff determined that the IASCC initiation screening curve in Figure 5.3 is acceptable because the neutron exposure threshold is lower, and thus more conservative, than the previous neutron exposure threshold.

Assessment of Change 9

Section 5.4 included flaw tolerance tables for CE and Westinghouse LSCs of participating plants. These tables included results for two additional stress levels.

The NRC staff reviewed the tables and methodology used to generate the tables. As in PWROG-14048-P, Revision 0, there is a set of results for a straight-front flaw and a thumbnail flaw. The calculation of the critical flaw sizes were based on the same methodology as in PWROG-14048-P, Revision 0. The NRC staff observed that the critical flaw sizes for CE LSCs are smaller because of the smaller LSC diameter.

The NRC staff determined that the addition of two higher stress levels in the flaw tolerance tables is appropriate to reflect the higher stress values for the CE LSCs. As in PWROG-14048-P, Revision 0, the tables show that for the highest stress level, the critical flaw sizes are larger than the maximum acceptable surface indication from fabrication. Therefore, the NRC staff determined that the flaw tolerance tables in Section 5.4 of the report are acceptable, and thus, the likelihood of full-section failure of LSCs is low.

3.0 CONCLUSIONS

The NRC staff has assessed the report and concludes the following:

- The NRC staff concluded in its assessment of PWROG-14048-P, Revision 0 that the conservative flaw tolerance analyses of the LSCs demonstrated that the likelihood of full-section failure of LSCs is low. Similarly, the NRC staff concludes in this report that the flaw tolerance analyses of the four LSC designs representing participating plants demonstrate that the likelihood of full-section failure of LSCs is low.

- The NRC staff concluded in its assessment of PWROG-14048-P, Revision 0 that the approach in evaluating the structural redundancy of the LSS assembly is reasonable; that plant-specific design parameters should be considered in establishing the tilt and deflection criteria; and that clustering of the failed LSCs should be evaluated. The NRC staff concludes in this report that the approach in evaluating structural redundancy of the LSS assembly of the four LSC designs representing participating plants is reasonable, except for the aspect of buckling discussed in the next paragraph; that the four LSC designs adequately addresses the range of plant-specific geometric parameters, loading conditions, and acceptance criteria of participating plants; and that structural redundancy evaluation adequately included the effect of clusters of failed LSCs.

- The NRC staff concluded in its assessment of PWROG-14048-P, Revision 0 that buckling of the LSCs and changes in the modal characteristics of the LSS assembly should be considered in the redundancy analysis. The NRC staff concludes in this report that the discussion of LSC buckling in the redundancy analysis adequately addressed buckling of an LSC subject only to a compressive axial load, but did not address the effect of bending moment in LSC buckling; and the discussion of the LSS assembly dynamic response

- described in the report adequately shows there is little change in the dynamic response of the LSS assembly due to failed LSCs.

4.0 REFERENCES

1. Letter from Jack Stringfellow (Chairman and COO of PWR Owners Group) to NRC, “PWR Owners Group: Submittal of PWROG-14048-P, Revision 1, ‘Functionality Analysis: Lower Support Columns’ to the NRC for Information Only (PA-MSC-1103),” (ADAMS Accession No. ML17066A266).

2. Office of Nuclear Reactor Regulation Staff Assessment, “Summary Assessment of PWROG-14048-P, Revision 0, Functionality Analysis: Lower Support Columns,” December 2015 (ADAMS Accession No. ML15334A462, non-proprietary version).

3. *Materials Reliability Program: Pressurized Water Reactor Internals Inspection and Evaluation Guidelines (MRP-227-A)*. EPRI, Palo Alto, CA: 2011. 1022863 (ADAMS Accession Nos. ML120170453).

Principal Contributor: David Dijamco, NRR/DE/EVIB

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