ENCLOSURE 4

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"Topical Report on ASME Section III Piping and Component Fatigue Analysis Utilizing the WESTEMS™ Computer Code"

(Non-Proprietary)

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1 INTRODUCTION

The purpose of this report is to document the use of the WESTEMS™ computer program, developed and maintained by Westinghouse Electric Company, for performing ASME Section III fatigue analysis on Class 1 piping and components for the AP1000® Nuclear Power Plant. Westinghouse is seeking US Nuclear Regulatory Commission (NRC) review and approval for application of the NB-3600 and NB-3200 modules of the program to perform the fatigue analysis required by Section III of the ASME Code in order to complete the piping and component design for the AP1000 Nuclear Power Plant. The scope of this topical report submittal to the NRC is limited to the NB-3200 and NB-3600 design analysis modules of the WESTEMS computer program for application to AP1000 class 1 piping and component design. The on-line monitoring module of WESTEMS is not in the scope of this report. The content within this report serves to demonstrate that:

- ASME Section III Fatigue analyses performed using the WESTEMS analysis software meet the requirements of the ASME Code [29].
- The WESTEMS computer program complies with ASME NQA-1-1994 [28] regarding the ability of the WESTEMS™ computer program to produce a valid solution to a physical problem;
- The WESTEMS™ program produces repeatable results for a specific input.
- Westinghouse has released a new program version, and has created and updated user guidance documentation in response to NRC documented concerns with the program in order to simplify the approach to performing fatigue analysis.
- WESTEMS™ users are fully trained and qualified in the use of the WESTEMS™ analysis software.

Additionally, Revisions 1 and 2 of this report include additional information in order to address comments from the NRC on specific content lacking in Revision 0 of the report that is needed in making a safety determination.

Computer codes implemented across the nuclear industry have historically required a high level of scrutiny by the software developer, regulatory organizations, nuclear plant operators, and individuals performing ASME Code evaluations. Many controls exist that ensure that Code and regulatory requirements are met. These controls include quality assurance policies for the development and validation of software, procedures for utilizing the software and documenting the analysis process, training and qualification requirements for individuals, and benchmarking of the analysis process.

This report presents an overview of the WESTEMS software and a demonstration of how the specific controls in place ensure proper utilization and valid analytical results. The fatigue analysis process was assessed and determined to be acceptable by the Design Centered Working Group (DCWG) as reported in [31].

1.1 BACKGROUND

The WESTEMS computer program is used to perform the Class 1 piping and component fatigue analysis of the AP1000 reactor coolant loop, auxiliary lines, and equipment. Following NRC audit and published concerns about the program, this topical report is provided to describe the fatigue analysis process and address NRC concerns in using the WESTEMS computer program to demonstrate how ASME Code Section III fatigue requirements are met using the WESTEMS computer program. This report describes the WESTEMS computer program, the Westinghouse quality assurance program for control and use of computer programs, the program validation process and application, the user procedure created to enhance repeatability of fatigue analysis results, and the user training and qualification program.

Separate regulatory audits were performed to review the WESTEMS NB-3600 and NB-3200 fatigue analysis modules and fatigue analysis processes. Items identified during both audits resulted in requests for additional information (RAI) issued by the NRC and responses provided by Westinghouse. Additionally, a regulatory issue summary (RIS) was released regarding metal fatigue analysis performed by computer software. This report also summarizes the audits, identifies actions taken to resolve auditor concerns identified in [17 and 18], and addresses concerns identified in RIS 2011-14 [24].

The WESTEMS computer program provides a versatile range of capabilities to enable engineers to evaluate components according to the Class 1 design analysis requirements of the ASME Code, Section III, Subsections NB-3600 and NB-3200. These include limits on stress and fatigue using linear elastic analysis methods as well as simplified elastic-plastic analysis specified for use with elastically calculated stresses. It utilizes different model types for the user to be able to choose the types of inputs and the rules to use for analysis. The WESTEMS software also provides supporting tools that allow users to perform heat transfer and stress analyses and process time history data, [ ]^{a,c}.

The design analysis capabilities were first developed for NB-3200 evaluations that utilize stress tensor history inputs generated using [ ]^{a,c}, which is required for stress range calculations per subsection NB-3216 of the Code. The process developed was modeled after manual methods classically used by design engineers and is primarily based on processing of the stress intensity time history of individual transients. The approach is described in PVP2010-25891 [22].

Piping fatigue analysis is required as part of the design basis for all Class 1 piping system designs (greater than 1 inch nominal outside diameter) that are governed by the ASME Code. A majority of these Class 1 piping systems do not require detailed NB-3200 analysis methods and will be analyzed with the rules and guidelines of ASME Code, Section III, NB-3600. The NB-3600 piping fatigue analysis capability was first incorporated in version 4.5 of the WESTEMS computer program, released in 2007, to replace older software packages previously used to perform NB-3600 fatigue analyses. The integration of NB-3600 fatigue analysis capability into the existing WESTEMS software utilized some of the existing WESTEMS program functionality, but it was also modeled after processes previously used by Westinghouse engineers for piping fatigue analysis. Some of these previous processes were manual, and others were part of older software algorithms. [ ]^{a,c}

Also mirroring the approach used in the NB-3200 module of the program, the peak and valley time selection algorithm was designed as a tool to assist the user in selection of the peak and valley times. However, due to the nature of the NB-3600 evaluation, more user controls over the process were incorporated. Proper incorporation of the user controls and related inputs has been the subject of NRC audit concerns raised with the WESTEMS NB-3600 analysis feature. To address these concerns, Westinghouse has modified the NB-3600 peak and valley selection process and related moment load input methodology to significantly reduce the need for user controls. The revised methodologies with respect to NB-3600 peak and valley selection and related moment input capabilities are described in this report.

The WESTEMS program is designed to provide qualified fatigue analysts the necessary tools to perform fatigue analyses commensurate with the degree of conservatism required to demonstrate qualifications to ASME Code limits. This includes versatility in inputs, availability of intermediate and final outputs to understand the problem and support qualification documentation, and efficiency of the iterative process that could be required for more complex problems. The selection of peak times is a major step in the fatigue analysis process. Westinghouse chose to design the program such that the peak time inputs to the fatigue analysis are ultimately user controlled for the following reasons:

1. The degree of automation of the fatigue evaluation process is not a function of ASME Code requirements. Therefore, quality assurance requirements for program development and engineering evaluations together provide the basis for demonstrating ASME Code compliance.

2. While it might be possible to program all typically user-controlled decisions for the peak selection, it is understood that many parts of the decision-making process are dependent upon each specific problem. As a result, this is not an optimum solution for reasons such as the following:

    a. The effort to develop algorithms to cover all possibly conceived problem dependencies is not practically justified compared to the effort for analysts to make reasonable engineering decisions about the inputs for known problems.

    b. The complexity of such algorithms would require a much broader range of program validation with minimal return, since most cases can be solved more readily with inputs determined by the qualified analyst.

    c. The development and inclusion of such algorithms would tend to reduce the computer program to more of a "black box" in the view of users, and discourage complete understanding of the physical problem.

3. Westinghouse Quality Policies and Procedures for computer program development require user elicitation for program functional requirements. Predominant user feedback supports the need for user cognizance and supervision of the peak selection process.

1.2 RECENT HISTORY OF REGULATORY AUDIT OF THE WESTEMS COMPUTER PROGRAM

The initial NRC audit of the WESTEMS NB-3600 fatigue analysis software occurred in May 2009 at the Westinghouse offices. The audit resulted in a number of RAIs and additional interaction between the NRC staff and Westinghouse to provide supporting information. The audit report summary is detailed in [18]. The following is a summary of questions posed by the regulatory auditors concerning the software and analysis process:

- RAI-SRP3.9.1-EMB-04, Revision 0 (became open item OI-SRP3.9.1-EMB-04)
  - Provide technical justification for the variation of material properties when applying the unit step transfer function database in a wide range of temperatures, and document guidelines/criteria for developing/benchmarking transfer function stress databases.
- RAI-SRP3.9.1-EMB-05, Revision 0 (became open item OI-SRP3.9.1-EMB-05)
  - Provide technical justification for the option "algebraic summation of orthogonal moment vectors" in selecting peak and valley times for the fatigue evaluation.
  - Follow-up question: Discuss the technical basis that the use of the algebraic summation of three orthogonal vectors would not lead to erroneous moment stresses that is misleading for the selection of the peaks and valleys.
  - Revision 1:

    The staff requests Westinghouse to define proper and improper use of the algebraic summation of three orthogonal vectors and provide above mentioned instruction.
  - Revision 2:

    Follow-up question #1: Westinghouse failed to address the staff's RAI regarding the use of the algebraic summation of three orthogonal vectors.

    Follow-up question #2: The WESTEMS™ methodology for stress combination is not correct as it adds the thermal stresses absolutely.

    Follow-up question #3: Provide justification to ensure that WESTEMS™ method using negative sign for this item (Snalg, Spalg, S13alg) meets ASME Code requirements.

    Follow-up question #4: Justify the difference between how ASME Code and WESTEMS™ defines Mi.

- Revision 3:

  Provide user's manual markups to caution users that SRSS should be selected when individual moments are input.

- RAI-SRP3.9.1-EMB-06, Revision 0 (became open item OI-SRP3.9.1-EMB-06)

  - Provide benchmark acceptance criteria to validate computer code calculation.

  - Revision 1:

    Inside surface for temperature cooldown (in benchmark calculation) must be under tension based on system conditions – it cannot be in compression as indicated.

  - Revision 2:

    Response provided to address staff comments at the audit concerning coding of thermal stress equations for the pipe OD.

- RAI-SRP3.9.1-EMB-07, Revision 0 (became open item OI-SRP3.9.1-EMB-07)

  - Provide the configuration control and limitation of the program for the available analysis options (eliminating peak/valley points during calculation) allowing the user to alter results.

  - Follow-up question: Discuss how the interactive WESTEMS™ allowing the user to manually modify the peak and valley time/stresses without the configuration control and documentation changes record to satisfy the quality assurance requirements in accordance with 10 CFR 50, Appendix B and ASME NQA-1.

  - Revision 1:

    The staff requests Westinghouse to discuss why peak editor is required to modify the peak/valley stresses calculated by WESTEMS™.

  - Revision 2:

    Follow-up question #1: The manual provides no control over peak removal so that the results obtained are not predictable and repeatable.

    Follow-up question #2: The WESTEMS™ NB-3600 analysis heavily relies on user determined options and manual selection of the stress peaks and valleys.

– Revision 3:

Staff comment at audit – The staff believes that a comprehensive training program should be in place for WESTEMS™ along with procedures for ensuring that outputs are correct and repeatable.

As a result of the RAIs associated with the WESTEMS NB-3600 audit, a subsequent regulatory audit was initiated to review the process and applicability for a WESTEMS NB-3200 fatigue analysis for license renewal. Westinghouse was requested to conduct benchmarking evaluations of a representative WESTEMS NB-3200 fatigue analysis. The audit objectives were to review the benchmark NB-3200 analyses in accordance with Section III requirements of the ASME Code, review the ability of the user to edit peak and valley sets, and confirm that concerns identified with the WESTEMS NB-3600 module did not apply to the operation of the WESTEMS NB-3200 module. The audit associated with the WESTEMS NB-3200 module has been completed and all concerns have been suitably resolved, as detailed in the safety evaluation report (SER) [23].

Subsequent to the audits, a RIS was released by the NRC to formally communicate the concerns with algebraic summation of moment load terms and user interaction with the peak and valley sets without sufficient control and documentation. These points provided an additional emphasis on OI-SRP3.9.1-EMB-05 and OI-SRP3.9.1-EMB-07. Actions taken by Westinghouse to directly address these concerns and improve the fatigue analysis process are detailed in Section 2.1 of this report.

Following the submittal of Revision 0 of this topical report to the NRC in February 2012 for acceptance review [33], the NRC staff indicated the existence of gaps in the technical details of the report that would preclude further assessment of the WESTEMS software and use, as indicated in the topical report withdrawal acknowledgement letter [34]. At this juncture, Westinghouse decided to revise the WESTEMS software, with the intention of eliminating the concerns identified by the NRC staff. While Revision 0 of this report was intended to justify the methods of WESTEMS software and the controls in place for its use, this revision of the report describes the changes made within the software to simplify the analysis process, eliminate the need for a number of user controls, and address all concerns with the proper application of the WESTEMS program for ASME Section III fatigue analysis.

1.3 GLOSSARY

Functional Test – Software test case developed to ensure operation of a specific function within a maintenance version of the software package.

Installation Test – Software testing intended to verify that a new installation of the program on a new hardware system or under a new software operating system produces expected results that are valid and consistent with results produced on other hardware systems or software operating systems.

Load Excursion – Time variation of the load to some relative maximum or minimum value; a single transient event may include multiple load excursions.

Moment History – Time dependent [ ]^{a,c} or moment component load used as input to a stress and fatigue analysis.

[ ]a,c

Redundant Peaks – [

]a,c

Regression Test – Software validation intended to demonstrate that no unintended side effects were introduced while modifying the program.

Sn – Primary plus secondary stress intensity range, equivalent to Equation 10 stress for an NB-3600 fatigue analysis.

Sp – Total stress intensity range, equivalent to Equation 11 stress for an NB-3600 fatigue analysis.

Tagname – WESTEMS program label assigned to a transient data point used to link the data input history to the component model loads and boundary conditions.

Validation – Software test case developed to ensure that the program meets the functional requirements defined in the software requirements specification.

Terms Applicable to the Legacy Versions of WESTEMS (Prior to Version 4.5.6)

Numerical Peak – [

]a,c

1.4 ACRONYMS

ASN	Analysis Section Number, NB-3200 design analysis model
ASME	American Society of Mechanical Engineers
B&PV	boiler and pressure vessel
BIT	boron injection tank
BWR	boiling water reactor
CAPs	Corrective Actions Process
CUF	cumulative usage fatigue
DCWG	Design Centered Working Group
EAF	environmentally assisted fatigue
FSER	final safety evaluation report
GUI	graphical user interface
LRA	license renewal application
MSR	moment stress range
NRC	Nuclear Regulatory Commission
OD	outer diameter
PWR	pressurized water reactor

QMS	Quality Management System
RAI	request for additional information
RIS	regulatory issue summary
SER	Safety Evaluation Report
SRSS	square room of the sum of the squares
TSR	thermal stress ratchet

1.5 SUMMARY

This report describes the actions taken by Westinghouse to improve the WESTEMS fatigue analysis process and provide supporting information on the revised functionality of the software and methods in place for controlled use of the program to perform safety-related fatigue evaluations. Specific aspects addressed are the resolution of regulatory concerns, quality control attributes of the software development and application process, technical functionality of the program, and review and validation of the program and fatigue analysis process. This report demonstrates that the application of the WESTEMS computer program, in accordance with procedural guidelines, produces a valid fatigue evaluation that meets the criteria of the ASME Boiler and Pressure Vessel Code, Section III, and quality control requirements, as specified in 10 CFR 50, Appendix B [30] and NQA-1.

A significant action initially taken to resolve NRC concerns with the WESTEMS software and fatigue evaluation process was the enhancement of the WESTEMS NB-3600 fatigue analysis procedure to provide more detailed guidelines for the application of the WESTEMS computer program and define quality control measures to prevent the potential misuse of the program. These measures include documentation requirements, process flowchart, and verification checklists designed to bring focus on various aspects of the fatigue evaluation process that require additional consideration. The enhancements made to the fatigue analysis procedure were also reflected in an update to the WESTEMS User Manual to clarify program functionality and related aspects of the fatigue analysis process. Additional improvements included a modification of the WESTEMS program and the development of training and qualification criteria for analysts utilizing the WESTEMS computer program for fatigue evaluation. With the significant revisions of version 4.5.6 of the WESTEMS program, the WESTEMS NB-3600 fatigue analysis procedure has also been revised to reflect the reduction of user controls and considerations accomplished by the revised algorithms.

The development of safety-related computer software and the requirements for performing design analysis are governed by Westinghouse quality policies and procedures that ensure compliance with NQA-1 quality controls. This report describes the development of the WESTEMS computer program for fatigue analysis and identifies the requirements for software specifications, verification and validation, configuration control, maintenance, and the process for software problem identification and resolution.

An overview of the technical process internal to the WESTEMS computer program for evaluating fatigue based on defined user input is discussed in this report to demonstrate the compliance with ASME Code Section III, Subsections NB-3600 and NB-3200. The WESTEMS computer program evaluates stresses due to thermal, pressure, and moment load inputs for a given component configuration to determine extreme stress conditions (peaks and valleys) that result in fatigue stress ranges. The differences between these peak and valley states (ranges) are used to determine alternating stresses in the components and resulting fatigue usage factors. Aspects of the peak and valley selection process are described to provide a more complete understanding of the software functionality.

Application of the WESTEMS computer program for NB-3600 fatigue evaluation is controlled through a fatigue analysis procedure [7] that provides requirements and guidelines to be followed by the analyst and verifier. The fatigue analysis procedure describes the phased analysis approach considering:

[

]a,c

The procedure provides supporting information for performing each phase of the analysis, including developing inputs, assigning appropriate analysis options, reviewing outputs, reducing conservatisms, and providing sufficient documentation. These features of the procedure are reinforced through process flowcharts and verification checklists to ensure correct application of the WESTEMS computer program for fatigue analysis.

Key changes to the NB-3600 fatigue analysis methodology made in WESTEMS version 4.5.6 to simplify the procedure and address the NRC staff's concerns are:

[

]a,c

Advantages of the new analysis methodology include the following:

[

]a,c

[

]a,c

User controls retained in version 4.5.6 of the WESTEMS software include [

]a,c The NB-3600 fatigue analysis procedure contains sufficient detail for the user to perform each of these operations and provide sufficient justification in the analysis documentation to support the decisions made.

2 RESOLUTION OF REGULATORY CONCERNS WITH FATIGUE ANALYSIS SOFTWARE AND PROCESS

The NRC audit and review process for both the NB-3600 and NB-3200 WESTEMS fatigue analysis modules involved multiple on-site and off-site sessions that included face-to-face interaction between the NRC staff and Westinghouse personnel responsible for the WESTEMS software. These interactions included independent review by the NRC staff of documentation supporting the development and use of the WESTEMS computer program and detailed presentations demonstrating examples of the software functionality. The NRC staff provided several rounds of comments and requests for additional information to Westinghouse for clarification and resolution. This section of the report summarizes these concerns and the actions taken by Westinghouse for resolution. The actions taken to resolve the concerns may be grouped in the following major categories: program changes, user manual revision, NB-3600 user application procedure and qualification, and user training improvements.

2.1 WESTEMS NB-3600 AUDIT

Open items OI-SRP3.9.1-EMB-04 and OI-SRP3.9.1-EMB-06 from the NB-3600 audit have been resolved based on information provided to the auditors by Westinghouse and closed by the NRC staff in the final safety evaluation report (FSER). The remaining items are addressed below.

OI-SRP3.9.1-EMB-05

WESTEMS users may incorrectly apply the SRSS option resulting in the algebraic summation of orthogonal moment components for the stress history calculations used for the selection of peak and valley times.

<u>Resolution</u>

This user control on peak selection options has been eliminated in version 4.5.6 of the WESTEMS software. The modified peak selection process, which is based explicitly on stress ranges using ASME Section III equations 10, 11, and 14, always uses the SRSS of ranged orthogonal moment components as follows:

$$Mi = [(Mx_k - Mx_j)^\wedge 2 + (My_k - My_j)^\wedge 2 + (Mz_k - Mz_j)^\wedge 2]^\wedge 0.5$$

where:

- Mi = the resultant moment range between load sets j and k
- M = moment load, for each direction as designated by subscripts x, y, z
- j = designates the value of the subscripted parameter for time j
- k = designates the value of the subscripted parameter for time k

[ ][a,c] A more detailed explanation of the moment stress range calculations is included in subsection 4.1.4.

OI-SRP3.9.1-EMB-07

The software functionality allowing the user to edit the set of peak and valley stress states input in the final fatigue evaluation requires additional quality control requirements to ensure that the process and results are valid and repeatable.

Resolution

There are two primary aspects of this concern that are addressed separately. The first is with respect to NQA-1 requirements that the results of safety-related computer software are valid and repeatable. The second aspect focuses on quality control of the analyst performing the fatigue evaluation with specific regard to the editing of the input peak and valley set in a restart file.

With respect to the first aspect, the Westinghouse software development process implemented in the development and maintenance of the WESTEMS computer program is fully in compliance with NQA-1 requirements, and the validation and verification of the WESTEMS computer program [10] shows that the software produces valid and repeatable results for a given set of inputs.

To further ensure that the WESTEMS computer program meets the requirements of NQA-1, an assessment of the WESTEMS program was performed by an AP1000 Design Centered Working Group (DCWG) comprised of Westinghouse customer representatives. The review concluded that the WESTEMS computer program meets NQA-1 requirements. However, the technical team made a recommendation to enhance the analysis documentation to reflect the two-phase process of the WESTEMS fatigue analysis. The first phase is an initial analysis, where the program performs stress history calculations, selects peak and valley times, and calculates fatigue results from the parameters associated with the initial peak and valley times selected. The first phase includes user review of results and validation of the peak and valley set. The second phase includes an optional step for editing of the input peak and valley set based on identified conservatisms. If the input peak and valley set is modified to reduce conservatism, then a final analysis is performed in the second phase of the fatigue evaluation. As such, if a final analysis is performed, the edited set of stress peaks is considered new user input as provided in a restart file. It is therefore expected that the initial and final analyses would yield different results. Each phase is an independent analysis that produces consistent output for a given set of inputs. The complete fatigue analysis including inputs, methodology, results of the initial and final evaluation phases, and associated engineering justification are fully reviewed by an independent verifier.

By this separation of the fatigue analysis process into two distinct phases, it is clarified that the user "interaction" to edit the input peak and valley set does not constitute producing different outputs for the same analysis inputs. The initial analysis has one set of inputs and always produces consistent and repeatable outputs. The final analysis is based on the initial analysis, but also considers an independent set of revised user inputs. The final analysis phase will also produce consistent and repeatable results for its set of inputs.

To establish the concept of a two-phase NB-3600 fatigue analysis, the procedure developed for performing a WESTEMS NB 3600 analysis [7] was organized to clearly describe the separate phases and the process involved for each phase. Similarly, the procedure provides a recommended template for documenting the fatigue analysis that also clearly describes the two-phase approach, with specific documentation required for the input and output considered for each phase. The User Manual [13] was also modified to include the description of the two-phased fatigue analysis process to further reduce the potential for misusing the WESTEMS program features. However, the revised WESTEMS 4.5.6 computer program substantially reduced the number of user controlled features and related instructions in the procedure and manual.

The second aspect of this assessment, provided by the DCWG NQA-1 expert, focused on quality control of the analyst performing the fatigue evaluation with specific regard to the editing of the input peak and valley set between the two phases of WESTEMS evaluations. Since this is not an aspect of the software, it cannot be controlled through software specifications and validation analyses. The WESTEMS NB-3600 fatigue analysis procedure is intended to serve as the quality control to ensure that the decisions made by the analyst are justified, documented, verified, and repeatable. Both the procedure and User Manual provide discussion of the potential causes for conservative peaks and valleys that may be included in the initial fatigue evaluation. The procedure also provides the analyst with guidelines for identifying instances of these non-controlling redundant peak and valley times that are considered conservative and unnecessary. The procedure also specifies documentation requirements for the analyst to provide detailed justification for modifications made to the initial phase peak and valley set and identification of the WESTEMS input and output files associated with both analysis phases.

The procedure provides significant detail for developing and performing an NB-3600 analysis and also provides many of the quality control requirements for the analysis process, documentation, and verification of a fatigue evaluation. All analysts intending to utilize the WESTEMS computer program for the application of NB-3600 are required to review the procedure in detail and document this review in their training record in accordance with the Westinghouse training process. Review of the procedure does not qualify an individual to perform fatigue evaluation, but rather is a supplement to mentoring, training, and past experience with NB-3600 fatigue analysis.

The modifications made in version 4.5.6 of the WESTEMS software were also intended to further address the NRC staff's concern about user interaction with the peak and valley set input to the optional second phase of the WESTEMS fatigue analysis process. While it is not practical to completely remove any need for the elimination of conservative inputs, the updated peak selection algorithm based on maximum stress intensity ranges is shown to be effective in removing most instances of redundant peak stress states. Also, the new method of calculating moment stresses, especially in the case of branches and tees, eliminates the peak selection option that contributed to the identification of "numerical peaks" in past versions of the software. Overall, these changes greatly reduce the number of instances that peak editing may need to be implemented for fatigue analysis qualification.

2.2 WESTEMS NB-3200 AUDIT

As a result of the NRC concerns in the NB-3600 audit, the NRC also requested additional information and performed an audit of license renewal NB-3200 evaluations applying the WESTEMS computer program. For the audit that reviewed NB-3200 calculations, Westinghouse was requested to conduct alternative evaluations to benchmark WESTEMS NB-3200 fatigue analyses to demonstrate application of ASME Code rules, provide justification of the process for determining critical analysis locations, provide an example of the peak editing process with respect to the WESTEMS NB-3200 module, and address any other aspects of the WESTEMS NB-3600 audit that may also apply to the WESTEMS NB-3200 module.

The benchmark analyses were provided and reviewed, and the staff determined the WESTEMS analyses to be in compliance with the ASME Code. The peak editing process was also found to be acceptable, with the recommendation that additional documentation would support compliance with NQA-1 requirements and more suitably satisfy Westinghouse procedures to ensure analysis repeatability. In response to this recommendation and the related RIS concerning metal fatigue analysis performed by computer software [24], Westinghouse issued documentation requirements for peak editing in WESTEMS fatigue analysis [21]. These were also subsequently included in expanded instructions in the NB-3200 section of the user's manual [13]. Apart from the peak editing process, the WESTEMS software concerns raised by the NRC in the NB-3600 audit do not apply to WESTEMS NB-3200 analysis.

3 GENERAL SOFTWARE REQUIREMENTS

Computer software developed for safety-related design and analysis must meet a series of requirements defined in Westinghouse quality policy and procedure documents that ensure the software is in compliance with ASME NQA-1 quality assurance standards. These documents identify the responsibilities for developing a computer code, validating the software functionality, maintaining configuration control, documenting errors and their resolution, and updating controlled software.

In line with the policies pertaining to software development are Westinghouse policies and procedures governing the design and analysis process. While these policies are higher level, the requirements defined are applicable to all safety-related analyses performed, including those utilizing engineering tools and computer software.

3.1 DEVELOPMENT AND VALIDATION OF COMPUTER CODES

Activities affecting the quality of items and services are performed at Westinghouse in accordance with the Quality Management System (QMS) [35]. The QMS serves as a directive for all functions in establishing necessary policies and procedures that comply with the requirements of ISO 9001; and in addition, as applicable for safety-related activities, 10 CFR 50, Appendix B; ASME NQA-1. Software development at Westinghouse is performed in accordance with documented policies and procedures that implement the QMS and conform to NQA-1. These procedures explicitly apply to safety-related software (e.g., plant operational control), and software used in the design and analysis of safety-related systems structures, and components (e.g., the WESTEMS analysis software). The specific sections of NQA-1 that relate to software and are implemented by the Westinghouse Level 2 Policies and Procedures are as follows:

- Part I, Requirement 3, Supplement 3S-1, Supplementary Requirements for Design Control – Verification of software is explicitly mentioned in Section 3.1, (a).
- Part I, Requirement 11, Supplement 11S-2, Supplementary Requirements for Computer Program Testing – Verification testing of software is described in Section 2.1.
- Part II, Subpart 2.7, Quality Assurance Requirements of Computer Software for Nuclear Facility Applications – Testing is described in Section 3.4; verification and validation of software is described in Section 4.

As adapted from QMS Section 4.2.9.1: The life cycle models used encompass the activities associated with requirements definition, design, code implementation and testing, installation, operation and maintenance, and retirement. Functional requirements, design documents, test requirements, and test results are verified in accordance with written procedures. Verification is performed at the completion of each phase to ensure that the output of a given phase fulfills the requirements established by previous phases (NQA-1, Subpart 2.7, Section 4.1). Validation is performed upon completion of software development to ensure that the code satisfies all identified requirements and produces correct results. Software testing is the primary method of software validation (NQA-1, Subpart 2.7, Section 4.2).

The development of the WESTEMS program has been performed and documented in accordance with Westinghouse policies and procedures, which implement the Westinghouse QMS. The QMS specifies that these policies and procedures comply with NQA-1. The current edition of the QMS has been accepted by the NRC as a method of meeting the 10 CFR 50 Appendix B requirements for quality assurance programs.

The Westinghouse software development process is defined in WEC 3.6.1 [1]. This document outlines the software development cycle, which includes software project planning, defining software requirements, preparing and verifying a software design specification, writing the software code, establishing configuration control, and establishing an authorized user list. Specific requirements for each element described in WEC 3.6.1 [1] comply with ASME NQA-1. For instances where it is necessary to modify, update, or otherwise revise configured software, the policy NSNP 3.6.7 [5] defines requirements to prepare and verify a software change specification in accordance with meeting the requirements of WEC 3.6.1. WEC 3.6.1 provides for verification activities at the end of each development phase. For example, Step 8.2.6 addresses verification of the software requirements, and Step 8.2.12 provides for the verification of the software design.

The WESTEMS NB-3600 fatigue analysis module was originally introduced in version 4.5 under software change specification CN-PAFM-06-159 [8]. Requirements for version 4.5.6 of the WESTEMS computer program addressed in this report are documented in software change specification CN-PAFM-12-56 [9]. Note that the NRC audit discussed in this report reviewed version 4.5.2 of the WESTEMS computer program. A summary of the modifications made to create version4.5.6, including changes in version 4.5.3 through 4.5.5, is provided later in this section of the report.

Once a computer code has been produced in compliance with the software design specification, it is necessary to validate the software against all identified requirements in the specifications according to WEC 3.6.1 [1]. The Westinghouse policy for validation of computer software is defined in NSNP 3.6.2 [2]. NSNP 3.6.2 discusses preparation and execution of test cases intended to validate the computer program (Step 8.2, 8.3, and Appendix A). In practice, the tests performed are also "verification tests" as described in NQA-1, Supplement 11S-2; that is, they "demonstrate the capability of the computer program to produce valid results for test problems encompassing the range of permitted usage defined by the program documentation." Acceptable methods for validation are given in NSNP 3.6.2, Appendix A, and include comparisons with hand calculations, exact analytical solutions, experimental results, known solutions for similar or standard problems, alternate verified calculation methods, etc. This is consistent with NQA-1, Supplement 11S-2, Section 2.1. When testing is complete and the validation documentation package is prepared, it is independently verified in accordance with Westinghouse procedure NSNP 3.3.3 [27] to ensure that test cases are correct, and that they have been executed correctly.

Validation testing of the NB-3600 module was performed for the initial implementation of the NB-3600 module in version 4.5 of the WESTEMS computer program, and functional and regression testing has been performed for maintenance versions (4.5.1 through 4.5.6) to validate modifications made to the NB-3600 module. The validation of version 4.5.2 of the WESTEMS computer program, which had been audited by the NRC [17], is documented in calculation note CN-PAFM-08-119, Revision 1 [20], and presents several validation and functional tests, including a test case and associated hand calculations, to validate a complete stress and fatigue calculation using the NB-3600 module (Appendix A of [20]) in response to an NRC request for a more detailed and representative validation case.

The focus of this report now considers version 4.5.6 of the WESTEMS computer program that was most recently developed and released. Changes made to version 4.5.6 are documented in [9]. Changes made through version 4.5.6 impacting WESTEMS NB-3600 piping fatigue analysis since the NRC audit of version 4.5.2 are summarized as follows:

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Validation of the WESTEMS version 4.5.6 NB-3600 analysis module, including functional testing of these modifications and regression testing in accordance with WEC 3.6.1, is documented in calculation note CN-PAFM-12-20 [10] and summarized in Section 5 of this report.

For safety-related software, it is required to maintain configuration control of the computer code in accordance with Westinghouse policy NSNP 3.6.3 [3]. This includes the development of an installation test process and documentation of the program configuration for release to the software user group. The release letter includes the program information, configuration location, and documents supporting the configuration (software specification, validation, user manual, etc.). The configuration control of version 4.5.6 of the WESTEMS computer program is included in the release letter LTR-PAFM-12-111 [11], and an updated User Manual for version 4.5.6 is provided in [13].

A final consideration for software development is the process to document and address any problems identified in the program operation. It is the responsibility of any individual utilizing a computer code to report any issues encountered in the software to the cognizant organization responsible for the software, according to NSNP 3.6.4 [4]. In the event that the software problem could impact safety-related aspects of the software, it is required that the cognizant organization initiate a Corrective Actions Process (CAPs) and distribute a software problem report to the user group detailing the extent of the error, requirement to review past use of the software, and potential workaround until the error is corrected. The individuals utilizing the software are responsible for assessing the impact of any software problem reports that may affect past use of the software, as required.

3.2 USE OF COMPUTER CODES AND DOCUMENTATION

According to the Westinghouse quality policy WEC 2.6 [26], the principal requirement placed on the individual fatigue analyst is a documented record of qualification to perform the design analysis. Qualification for applying the type of analysis performed by most computer programs is determined by management based on mentoring, training, and past experience with the analysis type. Qualification documentation is maintained by each Westinghouse organization. An individual's qualification to use a specific computer program or engineering tool is typically not documented; therefore, it is the responsibility of management to ensure that the analysts are qualified to perform the related engineering calculations. For the piping fatigue analysis group, qualification to use the WESTEMS fatigue analysis methods is documented in a new qualification matrix. Subsection 4.1.7 of this report further discusses the user qualification requirements for WESTEMS NB-3600 analysis.

Beyond qualification and regardless of software and engineering tools utilized, the analyst is required to satisfy all requirements identified in Westinghouse policy NSNP 3.2.6 [6] in performing and documenting a design analysis. This is intended to ensure that the design analysis meets all defined acceptance criteria. In general, complete documentation of the design analysis must include background information, design requirements, detailed inputs and applicable references, review of assumptions, discussion of the analysis methodology, and results. For application of a computer code, it is also required to provide sufficient documentation in order for the results to be independently reproduced. This includes the software name, version, inputs, options, and outputs, as well as referencing to documentation supporting the software configuration and validation (i.e., software release letter [11]). In addition, all calculations performed with or without a computer code are independently verified in compliance with NSNP 3.3.3 [27].

3.3 APPLICABILITY LIMITS OF THE WESTEMS SOFTWARE

The WESTEMS User Manual [13] discusses the limits of applicability on the type of physical or mathematical problems that can be solved by the program, according to the requirements of Westinghouse quality policies and procedures.

With respect to stress and fatigue analyses, the physical problems to be solved by the WESTEMS program represent power plant components designed to the ASME Code, Section III, Subsection NB [29]. Components meeting the ASME Code fabrication requirements can be analyzed using the program according to the rules in NB-3200 and NB-3600, including the following considerations:

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4 OVERVIEW OF WESTEMS FATIGUE ANALYSIS

The WESTEMS design analysis modules calculate the stresses required by the ASME Boiler and Pressure Vessel (B&PV) Code Section III, Subsections NB-3200 and NB-3600, and provide a comparison of calculated results to Code allowables. [

]^{a,c} The general steps followed in the fatigue usage factor calculation are as follows:

1. Primary plus Secondary Stress Intensity ranges for all possible pairs [ ]^{a,c}.

2. Simplified Elastic-Plastic penalty factors, Ke, corresponding to each stress range pair are determined.

3. The range of Total Stress Intensity is calculated for all possible pairs [ ]^{a,c}.

4. Alternating Stress, Sa, is calculated for each pair, including correction factors required by the Code.

5. Fatigue usage factors are calculated using the Sa values and corresponding cycles of each pair, determined according to NB-3222.4(e)(5).

6. Stress ranges corresponding to Simplified Elastic-Plastic Analysis and Thermal Stress Ratchet requirements for each associated range pair are calculated.

4.1 NB-3600 ANALYSIS OVERVIEW

NB-3600 thermal stress analyses are based on one dimensional time history temperature solutions and stress formulas. Temperature solutions are calculated using finite difference techniques. Material and geometric discontinuities are accounted for through the ASME Code simplified formulas and stress indices applied to appropriate terms of the stress solution. The one-dimensional thermal model has an "a" side and a "b" side to allow input of different materials and wall thicknesses related to discontinuities, as required by the Code equations.

A flowchart detailing the WESTEMS NB-3600 analysis process is provided in Figure 4-1, with supporting flowcharts addressing the peak time selection process (Figure 4-2), as modified in version 4.5.6, and the user peak review and editing process (Figure 4-5).

a,c

Figure 4-1 Process Flowchart for a WESTEMS NB-3600 Fatigue Analysis

4.1.1 Software Analysis Process

The WESTEMS NB-3600 fatigue analysis processes a set of user-defined input parameters describing the piping component being analyzed and the loading conditions prescribed by the design specification. The piping component is represented by the [

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Version 4.5.6 of the WESTEMS program incorporated two primary changes within the overall fatigue analysis process depicted in Figure 4-1. The first change [

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The fundamental change to the algorithm eliminates the previous method of creating [

]^{a,c} The equations used are those defined in ASME Section III, NB-3653, for Total stress (Sp, or Equation 11), Primary plus Secondary stress (Sn, or Equation 10), Equation 13 stress, and Thermal Stress Ratchet, which all represent a range of stress, or associated temperature difference, between different times in the component transient history. The logic is based on ASME Section III, Subsection NB-3216 methodology prescribed for selection of maximum stress differences (ranges) in the fatigue evaluation.

The general logic of NB-3216 (either NB-3216.1 or NB-3216.2) is summarized as follows:

- Select one time known to be an extreme stress state (i.e., peak or valley) in a stress cycle
- Calculate the range of stress from that stress state time with all other times in the cycle until the range of stress is a maximum magnitude
- Use the maximum range of stress found in the fatigue calculation; the alternating stress is half the range found (generally, as modified by other parameters in the balance of the fatigue evaluation such as elastic modulus correction and Ke penalty if applicable)

The NB-3216 process refers to stress component and principal stress differences in the context of NB-3200. This process is applied for piping components in NB-3600 by calculating the stress ranges using formulas based on the load input ranges, as prescribed in NB-3653. NB-3600 piping stress formulas represent conservative stress intensity ranges based on the constant principal stress directions in piping geometries.

The NB-3216 process is then extended for application to multiple transient stress cycles in NB-3222.4(e), which describes consideration of fatigue stress ranges formed from extreme stress states originating from different transient stress cycles. This is the same procedure invoked directly by NB-3653.5 for piping fatigue usage calculation (satisfaction of Equation 11 "Peak Stress" requirement), and implied for application to "all pairs of load sets" for Equations 10 and 13 and for TSR.

The application of [ ]a,c is described below in subsection 4.1.2. The peak selection is performed in the context of the overall NB-3600 fatigue evaluation process, which is outlined below.

WESTEMS Fatigue Evaluation Steps

Step 1, User Inputs

- Piping component section and material properties required by Code equations
- Stress indices applicable to the component
- Transient temperature, heat transfer coefficient input, and pressure histories
- [

]a,c

Step 5, Stress Range and Fatigue Usage Calculations

- Using the peak times selected, all possible fatigue pairs are determined, and the following applicable stress ranges and factors are calculated: Equation 10, Ke (based on the Sm allowable option selected), Equation 11, elastic modulus correction (Ky in the WESTEMS computer program), and Equation 14 (Sa).
- All fatigue usage pairs are arranged in order of descending Sa. In this order, allowable cycles from the ASME fatigue curve are determined, and cycles associated with each pair are used up to calculate the individual usage Ui, for each pair (per NB-3222.4(e)(5)).
- Cumulative usage factors are calculated as the sum of the Ui for all fatigue pairs.

[

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4.1.2 Peak Time Selection for Fatigue Usage Factor Calculation

The basis for the peak and valley time selection approach is that design transients are defined by arbitrary "breaks" in the component transient history. A completely general application of the intent of NB-3216 would be to check all ranges for all times in all transients. This would be limited by the computer hardware capacity and reasonable run time requirements, as well as requirements for additional user "bookkeeping" of transient inputs. The WESTEMS algorithm applies [

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Another significant consideration is that the algorithm also [

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[

]a,c

The approach applied for each design transient (see Figure 4-2) is described as a two-stage process:

[

]a,c

The Sa value is based on the values of Sn, Sp, and Ke for the times in the pair, as follows:

$$Sn = C1 \cdot Do/(2 \cdot t) \cdot |P_i - P_j| + C2 \cdot Do/(2 \cdot I) \cdot [(Mx_i - Mx_j)^2 + (My_i - My_j)^2 + (Mz_i - Mz_j)^2]^{0.5} + C3 \cdot E_{ab} \cdot |\alpha a(Ta_i - Ta_j) - \alpha b(Tb_i - Tb_j)|$$

$$Sp = K1 \cdot C1 \cdot Do/(2 \cdot t) \cdot |P_i - P_j| + K2r \cdot C2 \cdot Do/(2 \cdot I) \cdot [(Mx_i - Mx_j)^2 + (My_i - My_j)^2 + (Mz_i - Mz_j)^2]^{0.5} + K3 \cdot E \cdot \alpha/(2 \cdot (1-\nu))|\Delta T1_i - \Delta T1_j| + K3 \cdot C3 \cdot E_{ab} \cdot |\alpha a(Ta_i - Ta_j) - \alpha b(Tb_i - Tb_j)| + E \cdot \alpha/(1-\nu)|\Delta T2|$$

$$\Delta T2 = \max[\ |(To_i - To_j) - (Ta_i - Ta_j)| - 1/2|\Delta T1_i - \Delta T1_j|,\ |(Ti_i - Ti_j) - (Ta_i - Ta_j)| - 1/2|\Delta T1_i - \Delta T1_j|,\ 0]$$

$$\begin{aligned} Ke &= 1 \text{ for } Sn \le 3Sm \\ &= 1.0 + [(1 - n)/n(m - 1)](Sn/3 \cdot Sm - 1), \text{ for } 3\,Sm < Sn < 3mSm \\ &= 1/n, \text{ for } Sn \ge 3mSm \end{aligned}$$

$$Sa = Ke \cdot Sp/2$$

where:

P	=	pressure load
Do, t, I	=	diameter, thickness, and moment of inertia inputs
M	=	moment load, for each direction as designated by subscripts x, y, z
subscript i	=	[ ]^{a,c}
subscript j	=	[ ]^{a,c}
Ti	=	temperature at the inside surface
To	=	temperature at the outside surface
Ta	=	average temperature for the a-side, used for (T) in ΔT2 calculation

C1, C2, C3, K1, K2, K3 = User input stress index values per NB-3680

All other terms are as described in NB-3653. [

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]a,c

- The program performs this selection process on all transients considered in the evaluation.

The revised algorithm includes [

]a,c These options, described in subsection 4.1.5, are procedurally controlled and default to the most conservative input. A flowchart detailing the internal WESTEMS NB-3600 peak selection process is provided in Figure 4-2. Processing of the [ ]a,c is detailed in the Figure 4-4 flowchart.

a,c

Figure 4-2 Process Flowchart for WESTEMS NB-3600 Peak Selection

a,c

Figure 4-3 NB-3600 Equations Supporting Flowcharts Shown in Figure 4-1 and Figure 4-2

For peak selection and qualification of Equation 13 and TSR, see subsection 4.1.3. Moment stress terms for consideration of run-side and branch-side moment loads applied to a branch or tee piping component is discussed.in subsection 4.1.4.

a,c

Figure 4-4 Process Flowchart for WESTEMS NB-3600 Peak Selection Options

Subsection 5.1.1 provides a more detailed review of the redesigned peak selection process applied to a sample problem (Figure 5-1 and Figure 5-2) considered for the validation of version 4.5.6 of the WESTEMS software. This summary includes [

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4.1.3 Peak Time Selection for NB-3600 Range Qualifications

In the process of modifying the WESTEMS peak time selection algorithm to account for stress ranges consistent with the ASME Code equation for alternating stress for the qualification of cumulative usage, similar peak selection processes were established for independent qualifications of Equation 10, Equation 13, and TSR.

Equation 10 Peak Selection and Qualification

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Sn for each pair is calculated as follows:

$$Sn = C1 \cdot Do/(2 \cdot t) \cdot |P_i - P_j| + C2 \cdot Do/(2 \cdot I) \cdot [(Mx_i - Mx_j)\text{^}2 + (My_i - My_j)\text{^}2 + (Mz_i - Mz_j)\text{^}2]\text{^}0.5 + C3 \cdot E_{ab} \cdot |\alpha a(Ta_i - Ta_j) - \alpha b(Tb_i - Tb_j)|$$

where:

P	=	pressure load
Do, t, I	=	diameter, thickness, and moment of inertia inputs
M	=	moment load, for each direction as designated by subscripts x, y, z
subscript i	=	[ ]^{a,c}
subscript j	=	[ ]^{a,c}
C1, C2, C3	=	User input stress index values per NB-3680

All other terms are as described in NB-3653. [

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[

]^{a,c}

Equation 13 Peak Selection and Qualification

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EQ13 for each pair is calculated as follows:

$$EQ13 = C1 \cdot Do/(2 \cdot t) \cdot |P_i - P_j| + C2 \cdot Do/(2 \cdot I) \cdot [(Mx_i - Mx_j)^2 + (My_i - My_j)^2 + (Mz_i - Mz_j)^2]^{0.5} + C3' \cdot E_{ab} \cdot |\alpha a(Ta_i - Ta_j) - \alpha b(Tb_i - Tb_j)|$$

where:

P	=	pressure load
Do, t, I	=	diameter, thickness, and moment of inertia inputs
M	=	Equation 13 moment load, for each direction as designated by subscripts x, y, z (input separate from moment terms used in Sn, Sp, and Sa calculations)
subscript i	=	[ ]^{a,c}
subscript j	=	[ ]^{a,c}
C1, C2, C3		User input stress index values per NB-3680

All other terms are as described in NB-3653. [

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ΔT1 range is calculated according to NB-3653.7 as follows:

$\Delta T1 = |\Delta T1_i - \Delta T1_j|$

[

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Equation 12 Qualification

Equation 12 stress is calculated separate from the WESTEMS NB-3600 evaluation based on moment stress range determined from the piping stress analysis.

4.1.4 Processing of Moment Relationships

The WESTEMS NB-3600 fatigue calculation has been expanded to accommodate the explicit calculation of run and branch side moment stresses for branch and tee components using additional user inputs while retaining the moment stress calculation as previously included [

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1. Branches and tees

   For branch and tee connections, the program calculates the moment stress ranges between any two times as follows:

   Secondary moment stress range:

$$C2r/Zr \cdot [(Mx_{Bj} - Mx_{Ai})r\text{^}2 + (My_{Bj} - My_{Ai})r\text{^}2 + (Mz_{Bj} - Mz_{Ai})r\text{^}2]\text{^}0.5$$
$$+ C2b/Zb \cdot [(Mx_{Bj} - Mx_{Ai})b\text{^}2 + (My_{Bj} - My_{Ai})b\text{^}2 + (Mz_{Bj} - Mz_{Ai})b\text{^}2]\text{^}0.5$$

   Total moment stress range:

$$K2r \cdot C2r/Zr \cdot [(Mx_{Bj} - Mx_{Ai})r\text{^}2 + (My_{Bj} - My_{Ai})r\text{^}2 + (Mz_{Bj} - Mz_{Ai})r\text{^}2]\text{^}0.5$$
$$+ K2b \cdot C2b/Zb \cdot [(Mx_{Bj} - Mx_{Ai})b\text{^}2 + (My_{Bj} - My_{Ai})b\text{^}2 + (Mz_{Bj} - Mz_{Ai})b\text{^}2]\text{^}0.5$$

where:

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2. Other piping components

For other piping components, when individual moments are input for each transient, the moment stress range is calculated using the Diameter and thickness input for the moment stress calculation for the component, as represented below:

Secondary moment stress range:

$$C2/Z \cdot [(Mx_{Bj} - Mx_{Ai})\wedge 2 + (My_{Bj} - My_{Ai})\wedge 2 + (Mz_{Bj} - Mz_{Ai})\wedge 2]\wedge 0.5$$

Total moment stress range:

$$K2 \cdot C2/Z \cdot [(Mx_{Bj} - Mx_{Ai})\wedge 2 + (My_{Bj} - My_{Ai})\wedge 2 + (Mz_{Bj} - Mz_{Ai})\wedge 2]\wedge 0.5$$

where:

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All other terms are as described in NB-3653.

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4.1.5 Peak Selection and Analyst Control

The WESTEMS peak and valley selection algorithm is designed to [

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The user configurable peak selection controls provided by the program include:

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Figure 4-5 Process Flowchart for WESTEMS NB-3600 Peak Review and Editing

4.1.6 Application of the WESTEMS NB-3600 Analysis Feature

The fatigue analysis of a piping system component is performed by the analyst using the following typical steps, which correspond to the user operations depicted in Figure 4-1.

1. Define the problem fixed and transient inputs, and enter them in the NB-3600 user interface and transient history input files. The initial fixed inputs include:

   a. [

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2. Execute an initial analysis run. [

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3. [

   ]^{a,c}

4. If conservatism needs to be removed to demonstrate qualification, revise the inputs to remove conservatism and perform a re-analysis.

   a. If transient history or stress calculation input parameters need to be changed, revise the inputs and perform a complete re-analysis. For example,

   [

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5. Document the results of the initial analysis and any re-analysis performed, along with justification for the revised inputs used in the re-analysis.

4.1.7 Qualification and Procedure for Application of WESTEMS NB-3600 Software

Utilization of the WESTEMS NB-3600 analysis software is controlled by a series of requirements applicable to any analyst using the program for safety-related fatigue analysis of Class 1 piping components. The first requirement is general qualification to perform ASME Code fatigue evaluations regardless of computer programs and engineering tools used during the analysis process. Qualification is determined by management based on mentoring, training, and past experience. A documented list is maintained by each Westinghouse organization that identifies an individual's level of ability to perform or verify Class 1 piping fatigue analysis. For the Westinghouse organization responsible for Class 1 piping fatigue analysis, an example of this qualification is identified in [12, 32].

A Westinghouse Level 3 quality procedure has been developed as an additional level of control specific to the application of WESTEMS software for performing an NB-3600 fatigue analysis. This procedure, PSDR-QP-4.7 [7], provides the steps for performing and verifying an ASME NB-3600 fatigue analysis using the WESTEMS software. It also provides supporting guidelines to perform each step. These include developing an NB-3600 analysis model, defining the appropriate input and analysis options, and clarifying the various methods for NB-3600 analysis that can be implemented during the overall analysis process, as it becomes necessary to eliminate conservatisms. This procedure also provides guidance for the analyst and verifier to review the results of a given fatigue analysis with respect to the chosen inputs and options.

The WESTEMS NB-3600 analysis procedure further delineates the fatigue evaluation process into separate stages:

[

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This process is captured in the body of the procedure and summarized in the procedure appendix as the fatigue analysis flowchart shown in Figure 4-6 of this report. Requirements and guidelines are included in the procedure for the documentation of an NB-3600 fatigue evaluation using the WESTEMS program, and a general calculation note template is provided for analysts to document required pertinent information. The procedure also identifies requirements and guidelines to be followed for verification of the fatigue analysis inputs, outputs, interpretation of results, and documentation. These verification requirements are captured in a checklist that is included in the documentation for an NB-3600 fatigue analysis. An example of this checklist is shown in Figure 4-7.

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Note: Numbers identified in parentheses for each step correlate to the respective Sections of the procedure [7].

Figure 4-6 NB-3600 Fatigue Analysis Process Flowchart from [7]

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Figure 4-7 Fatigue Analysis Verification Checklist

4.2 NB-3200 ANALYSIS OVERVIEW

The structural stresses determined according to NB-3200 are based on stress intensity and stress intensity range due to mechanical loads (e.g., pressure and moment) and thermal transient loads. The stress component histories are calculated by [

]a,c The transient stress histories are evaluated to determine the stress peaks and valleys, which are in turn used to calculate the applicable stresses and ranges of stress intensity required for the Code equations.

The ASME Code limits total stress by requiring that the cumulative usage factor from fatigue associated with these stresses be less than or equal to 1.0. Fatigue analysis is performed using the stress peaks selected from the stress time histories produced for each transient.

The general WESTEMS peak and valley selection algorithm is designed to [

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Justification for elimination of conservative peak times is limited to the sources of conservatism discussed above, which are summarized as follows:

[

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No other sources of conservative peak times can be cited without prior NRC approval.

A flowchart detailing the internal WESTEMS NB-3200 analysis process is provided in Figure 4-8.

4.2.1 NB-3200 Analysis Process

The steps in the NB-3200 fatigue evaluation are summarized below.

Step 1: Prepare Model Fixed Inputs

The user registers the NB-3200 model in the WESTEMS project database and supplies the required fixed inputs. Fixed inputs include material properties, water properties as required by the model, unit load stress inputs, and ASME Code inputs. The ASME Code inputs include stress intensification, stress classification, radius correction input to stress linearization (if required), and elastic modulus correction input.

Step 2: Prepare Transient Inputs

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Step 3: Select Analysis Options and Perform Initial Evaluation

The initial analysis is performed according to the user manual instructions, observing guidelines for analysis options and settings, including:

- [

]a,c (see Section 4.2.2)

The output files from the initial run are documented and attached to the calculation.

Step 4: Results Review

The analyst must review all levels of analysis output files to perform self-checking and confirm proper inputs and outputs. The review includes the following considerations:

- Transient Stress histories reflect inputs
- Peaks and Valleys account for transient stress histories
- Fatigue stress range and usage results
- Initial Results Documentation and need for further analysis

Step 5: Peak Revisions and Final Analysis

If conservatism needs to be removed to demonstrate qualification to ASME requirements, the inputs are revised to remove conservatism and perform re-analysis.

Identification of redundant peaks

The criteria and guidelines provided in the user manual are used to identify sources of conservatism with respect to redundant peak times in the fatigue evaluation. Redundancies justified to be removed must be documented in the calculation note, and a re-analysis is performed with the conservatism removed.

Final Analysis

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If the fatigue analysis results exceed allowable limits using the procedures described above, alternative methods, such as those described in ASME Code Section III Subparagraph NB-3228, may be investigated.

Documentation

In all cases where peak editing is implemented, the user must document in the calculation note the justification for all peaks edited/removed. The final documentation must also include output files for the initial run and the final run. This provides for comparison and verification of any peak editing performed.

Step 6: Verification

Verification of NB-3200 analyses must include, as a minimum, checking of the following items in the documentation and analysis output files.

1. Echoed Inputs
   - Fixed
   - Transient
2. Outputs
   - Stress histories
   - Review peaks
   - Peak edits and justification documented
   - Fatigue stresses and usage results

4.2.2 Peak and Valley Selection and Peak Editing

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Users may employ any or all of these in a particular analysis. The influence of each and guidance for their use are discussed in the user manual. These are summarized below.

Transient Load Histories

The transient definitions may inherently include redundant extreme stress states, such that a final stress state for one transient may represent an initial stress state of another transient (e.g., heatup and cooldown design transients where cooldown begins at the same state that heatup ends and heatup begins at the same state that cooldown ends). [

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Stress Filter Input

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Time Constant Input

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ASME fatigue usage is based on alternating stress, Sa, which is determined from the Total stress range and the Ke penalty factor. The Ke penalty factor is based on the Primary plus Secondary stress range.

[

]a,c the thermal stress contributions to Sn and Sp can be separated by a period of time. For example, the thermal discontinuity stress will typically maximize later than the peak surface stress due to a given temperature load excursion. Both types of thermal stress are included in Sp, but only thermal discontinuity stress is included in Sn. Therefore the Sn peak time can lag the Sp peak time in response to the same load excursion. This phasing of the Sn and Sp stress histories can result in different Sn and Sp peak times being selected in response to the same transient load excursion.

General guidelines and limitations for use of the time constant are provided in the user manual. [

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Analysis Options Peak Selection Control

[

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In most cases, both of these options are selected by the user to minimize unnecessary peak retention by the algorithm, unless the user has particular transient cases for which either option is not applicable. Final review and documentation of final peaks used in the analysis must provide justification for the analysis options settings used.

Peak Editing

[

]a,c

When the final run is completed, the user must again review the results and save and document the results files and input files needed for the method used. All original and final files must be archived with the analysis documentation.

4.2.3 NB-3200 Benchmarking for License Renewal

An audit was performed by the NRC to review the license renewal application (LRA) for an operating plant, which incorporated WESTEMS NB-3200 analysis in environmentally assisted fatigue (EAF) evaluations, and also implemented the WESTEMS program for online fatigue usage monitoring. Westinghouse was requested to conduct benchmarking evaluations of two locations of the associated WESTEMS NB-3200 fatigue analyses. The audit objectives were to review the benchmark NB-3200 analyses in accordance with Section III requirements of the ASME Code, review the ability of the user to edit peak and valley sets, and confirm that concerns identified with WESTEMS NB-3600 did not apply to the plant LRA. The benchmark evaluations for WESTEMS NB-3200 were provided in Westinghouse calculation notes CN-PAFM-10-98 [15] and CN-PAFM-10-101 [16] and the audit report is USNRC docket numbers 50-272 and 50-311 [17].

The intent of the benchmarking evaluations was to confirm that the results of the WESTEMS models and analyses, including any analyst judgments, are acceptable and comparable to traditional ASME Code, Section III, NB-3200 analyses for the selected monitored locations. The benchmarks considered two limiting locations of the WESTEMS NB-3200 fatigue analysis: the pressurizer surge nozzle [15] and the boron injection tank (BIT) nozzle [16]. The benchmark documentation includes the following information:

- A summary of the WESTEMS NB-3200 evaluation methodology

- Reference to the WESTEMS computer program validation according to Westinghouse Quality Policies and Procedures, meeting the requirements of 10 CFR 50, Appendix B

- A comparison of the calculated stresses and cumulative usage factor (CUF) using WESTEMS software to the same results from alternative traditional ASME Code, Section III, NB-3200 stress and CUF calculations for all transient pairs representing at least 75 percent of the total CUF for the component

- The differences in the results between the WESTEMS evaluation and the alternative ASME Code, Section III, CUF calculations, and justification for acceptability of the differences

- A comparison of a fatigue usage factor calculated in the WESTEMS "design" analysis with a fatigue usage factor calculated using the WESTEMS "online monitoring" analysis mode. This comparison demonstrates that the use of the same WESTEMS stress model in the program's monitoring mode will result in a conservative CUF compared to the design analysis mode.

The summary of the WESTEMS NB-3200 audit [16] concludes that the software provides calculations of stresses and cumulative usage factors that are consistent with a traditional ASME Code Section III analysis, and that the analyst judgment in choosing to delete or add stress peak and valley times in these calculations is reasonable and can be appropriately justified and documented. The audit report also recommended that additional documentation of the peak editing process be provided in future calculations. This recommendation has been implemented in Westinghouse through user correspondence [21].

a,c

Figure 4-8 Process Flowchart for a WESTEMS NB-3200 Fatigue Analysis

a,c

Note: The WESTEMS User Manual [13] further details NB-3200 evaluation method and terminology used in Figure 4-9.

Figure 4-9 NB-3200 Equations Supporting Flowchart Shown in Figure 4-8

5 VALIDATION OF THE REVISED WESTEMS PROGRAM

Program validation followed the Westinghouse quality policies and procedures as described in Section 3.1. The modifications to the program functional requirements and related program design were documented in a software change specification. The validation test plan includes problems designed to test that the program performs according to the requirements specified, using alternate calculation methods. The test plan includes specific problems to test the new functional changes, as well as regression test problems performed for previous versions, to verify that the program changes have not impacted other features of the program that were not intended to be changed.

The modifications implemented in version 4.5.6 of the WESTEMS software focused on revision of the NB-3600 peak selection process and related input definitions. Accordingly, the validation of version 4.5.6 focused on reviewing various iterations of these new features and confirming that they function as specified and produce correct results for various input conditions that are representative of an NB-3600 analysis. A series of tests cases was established to fully exercise the updated program functionalities identified in the change specification for version 4.5.6 [9]. The validation process and results, which have been fully documented in [10], also include regression testing of the remaining unchanged NB-3600 functionalities and the balance of WESTEMS functions, to ensure that the changes implemented in version 4.5.6 did not cause any adverse impact. Table 5-1 summarizes the test cases considered in the validation of the WESTEMS 4:5.6 software, correlated to the report subsections describing each test case.

Table 5-1 WESTEMS Software Validation Summary for Version 4.5.6

a,c

Table 5-1 (cont.) WESTEMS Software Validation Summary for Version 4.5.6

a,c

Table 5-1 (cont.) WESTEMS Software Validation Summary for Version 4.5.6

a,c

5.1 MAJOR NB-3600 FUNCTIONAL MODIFICATION: UPDATES TO NB-3600 PEAK SELECTION ALGORITHM

The peak selection algorithm was revised in version 4.5.6 of the WESTEMS program per the software change specification [9] as described in subsections 4.1.2 and 4.1.3. A butt welded tapered transition piping component representing a weld to a 3-inch valve was considered for the test problem with geometry inputs consistent with Table 5-2. This allowed testing of the full set of inputs, including thermal discontinuity impact, on the results of the algorithm. Multiple test cases were considered in order to represent variations in transient conditions that would generally be considered in NB-3600 design analysis, for varying degrees of detail in the input loads. Table 5-3 lists the various test run transient inputs considered to validate the revised peak selection algorithm.

Table 5-2 Peak Selection Test Case – Model Geometry

a,c

[

]a,c

Table 5-3 Summary of Peak Selection Algorithm Test Cases

a,c

[

]a,c

a,c

Note: The WESTEMS User Manual [13] further details NB-3600 model inputs and labels shown in Figure 5-1.

Figure 5-1 NB-3600 Peak Selection Testing Model Inputs Sample Excerpt

5.1.1 Example Test Case Review – Severe Step Transient, Temperature + Pressure + Moment (In-Phase)

[

]a,c

Test Case Loading Description

[

]a,c

[

]a,c

a,c

[ ]

Figure 5-2 Example Test Case – Transient Conditions

Test Case Results

[

]a,c

a,c

Figure 5-3 Example Test Case – Maximum Stress Ranges by Time (ksi)

[

]a,c

Table 5-4 Example Test Case – Peak Selection Basetimes

a,c

[

]a,c

[

]a,c

a,c

Table 5-5 Example Test Case – Peak Selection		

a,c

[ ]

Figure 5-4 Example Test Case – Sub-cycle Peak Selection from Basetime Sa Ranges (ksi)

[

]a,c

a,c

[ ]

Figure 5-5 Example Test Case – Sub-cycle Peak Selection from Basetime Sn Ranges (ksi)

[

]a,c

a,c

Figure 5-6 Example Test Case Peak Selection from Basetime Eq. 13 Ranges (ksi)

[

]a,c

a,c

[ ]

Figure 5-7 Example Test Case Peak Selection from Basetime TSR Ranges (°F)

[

]a,c

5.1.2 Validation Review of Remaining Peak Selection Test Cases

The peak selection validation method described and illustrated in subsection 5.1.1 was completed for each test case identified in Table 5-3. Details of the comparisons are included in the validation calculation note [10]. Results from these other cases are summarized as follows:

[

]a,c

a,c

Figure 5-8 **Transient Inputs and Sub-cycle Sa Peaks for Temperature + Pressure (Out-of-Phase) Peak Selection Test Case**

[

]a,c

a,c

[ ]

Figure 5-9 Transient Inputs and Sub-cycle Sa Peaks for Temperature + Pressure + Moment (Out-of-Phase) Peak Selection Test Case

[ ]a,c

a,c

[ ]

Figure 5-10 Sub-cycle Sa Peaks for Multiple Load Excursion Peak Selection Test Case (ksi)

[

]a,c

a,c

Figure 5-11 Sub-cycle Sa Peaks for Large Step Load Decrease Peak Selection Test Case (ksi)

[

]a,c

5.2 MAJOR NB-3600 FUNCTIONAL MODIFICATION: NB-3600 MOMENT STRESS REVISION AND INDEPENDENT GEOMETRY INPUTS

The WESTEMS NB-3600 model definition was revised to support the explicit input of run-side and branch-side moments and section properties to evaluate the combined moment stress range effects in accordance with the ASME Code, as discussed in subsection 4.1.4. A test case was developed to validate the revised moment definition and the resulting stress range history calculations for a typical branch component. General methodology consistent with the testing done for the peak selection validation, as summarized in subsection 5.1.1, was applied for the branch moment input case.

Test Case Description

[

]a,c

Table 5-6 Branch Moment Loading Test Case – Model Geometry and Moment Load Inputs a,c

a,c

Figure 5-12 NB-3600 Run/Branch Moments Testing – Model Inputs

a,c

[ ]

Figure 5-13 Branch Test Case – Transient Conditions

Test Case Results

Stress Calculation Validation Results:

[

]a,c Therefore, WESTEMS calculation for consideration of branch moment inputs was shown to be acceptable.

a,c

Figure 5-14 Branch Test Case – Maximum Stress Ranges by Time (ksi)

a,c

Figure 5-15 Branch Test Case – Maximum Sa Ranges from Basetimes (ksi)

a,c

Figure 5-16 Branch Test Case – Maximum Sn Ranges from Basetimes (ksi)

a,c

Figure 5-17 Branch Test Case – Maximum Eq. 13 Ranges from Basetimes (ksi)

Independent Geometry Inputs – Moment, Pressure, and Thermal

Version 4.5.6 of the WESTEMS program allows for [

]a,c

[

]a,c

a,c

Table 5-7 Independent Geometry Test Case – Model Geometry Inputs

[

]a,c A plot of the test problem's maximum Sa range in Figure 5-18 shows that hand calculations match the WESTEMS alternating stress calculation, which confirms that WESTEMS software is using the independent inputs correctly. [

]a,c

a,c

[ ]

Figure 5-18 Branch Test Case – Max Sa by Time for A-Side as Run and Branch Geometry (ksi)

5.3 SUPPORTING NB-3600 MODIFICATIONS

In addition to testing the primary modifications made to the WESTEMS NB-3600 analysis method, validation was also performed for a number of program functions that were revised in support of the primary modifications. This testing is briefly described in the following subsections, and is documented in detail in the version 4.5.6 validation calculation note [10].

5.3.1 NB-3600 Stress Filter

The WESTEMS NB-3600 stress filter [

]a,c

[

]a,c This is demonstrated by the results shown in Table 5-8.

Table 5-8 NB-3600 Stress Filter Validation

a,c

[

]a,c

5.3.2 Peak Exclusion Time Constant

[

]a,c

[

]a,c

a,c

Table 5-9 NB-3600 Peak Exclusion Time Constant Validation		

a,c

Figure 5-19 Peak Exclusion Time Constant Test Case – Base Time Sa Ranges (ksi)

5.3.3 Retention of Initial and Final Transient Times as Peak States

[

]a,c

[

]a,c

5.3.4 Peak Editing Capability

The ability to edit peaks in the [

]a,c

5.3.5 NB-3600 Analysis Restart File and Analysis Repeatability

[

]a,c

[

]a,c

5.3.6 Multiple Moment Tagnames

[

]a,c

Table 5-10 Multiple Moment Input Test Case – Model Load Sets		

a,c

Table 5-10 (cont.) Multiple Moment Input Test Case – Model Load Sets

a,c

5.3.7 Use Moment Stress Range Check Box

The functionality of the check box to indicate that the WESTEMS NB-3600 fatigue analysis should consider [

]a,c

5.3.8 Thermal Stress Ratchet Option

A user input was added to the analysis options interface as a check box to indicate whether the thermal stress ratchet qualification will use [

]a,c TSR pairs for TSR peaks were validated using manual calculations shown to match the WESTEMS TSR qualification outputs.

5.3.9 NB-3600 Outputs

The NB-3600 output files were changed to reflect the changes made in other aspects of the fatigue analysis process. The changes validated include:

[

]a,c

[

]a,c

5.4 NB-3600 REGRESSION TESTING VALIDATION

Regression testing of the WESTEMS NB-3600 analysis function was done for the remaining scope of functions that were not affected by the modifications made in version 4.5.6 [

]a,c. The NB-3600 regression testing was performed using the standard test problem developed for the validation of version 4.5.2 (Appendix A of [20]). Values for analysis options that are consistent between version 4.5.2 and 4.5.6 are the same as those used in [20]. The WESTEMS algorithm [ ]a,c.

Analysis allowable values (Sm, Sy) were specified to be selected based on the [ ]a,c. Peak selection options used in [20] are no longer applicable since the peak selection algorithm has changed and is validated separately in Section 5.1. The analysis option to calculate thermal stress ratchet [

]a,c

The following is a summary of the NB-3600 regression test results:

- [

]a,c

5.5 ADDITIONAL REGRESSION TESTING OF REMAINING WESTEMS FUNCTIONS

Regression testing was performed to ensure the continued and consistent operation of WESTEMS functions that were not impacted by the modification made in version 4.5.6. One of the [

]a,c After the update utility was run for the installation test project files, the model was analyzed and the program produced correct results without any errors.

Regression testing also included a stand-alone analysis of the NB-3200 design analysis (ASN) model included in the installation test package. Results from the NB-3200 design fatigue analysis run in version 4.5.6 were compared against the results from the identical analysis run using version 4.5.5. Consistency between the result files for these two runs validated the design analysis function.

6 REFERENCES

1. Westinghouse document WEC 3.6.1, "Computer Software Development Process."

2. Westinghouse document NSNP 3.6.2, "Validation of Computer Software."

3. Westinghouse document NSNP 3.6.3, "Configuration Control of Computer Programs and Systems."

4. Westinghouse document NSNP 3.6.4, "Software Problem Reporting and Resolution."

5. Westinghouse document NSNP 3.6.7, "Maintenance of Configured Computer Programs."

6. Westinghouse document WEC 3.2.6, "Design Analysis."

7. Westinghouse document PSDR-QP-4.7, "WESTEMS™ WESTEMS NB-3600 Fatigue Analysis and Verification Procedure."

8. Westinghouse document CN-PAFM-06-159, Revision 0, "WESTEMS™ Software Change Specification for Version 4.5."

9. Westinghouse document CN-PAFM-12-56, Revision 0, "WESTEMS™ 4.5.6 Software Change Specification."

10. Westinghouse document CN-PAFM-12-20, Revision 0, "WESTEMS™ 4.5.6 Validation and Verification."

11. Westinghouse document LTR-PAFM-12-111, "Software Release Letter for WESTEMS™ Version 4.5.6."

12. Westinghouse document LTR-PAFM-12-105, "Qualification Matrix & Training Needs Assessment for Piping Analysis & Fracture Mechanics (PAFM)."

13. Westinghouse Software Manual, "WESTEMS™ Version 4.5.6 User Manual Volume 2 (Design Analysis)," included as an attachment to LTR-PAFM-13-47

14. Reference Not Used

15. Westinghouse document CN-PAFM-10-98, Revision 1, "Salem Pressurizer Surge Nozzle WESTEMS™ Fatigue Analysis Benchmark."

16. Westinghouse document CN-PAFM-10-101, Revision 0, "Salem Boron Injection Tank (BIT) Nozzle WESTEMS Fatigue Analysis Benchmark."

17. USNRC Docket Nos. 50-272 and 50-311, "Audit Report on the Use of WESTEMS™ Software in the Salem Nuclear Generating Station, Units 1 and 2, License Renewal Application (TAC Nos. ME1834 and ME1836)," March 30, 2011.

18. USNRC Docket No. 52-006, Memorandum To: Eileen McKenna, From: Phyllis Clark, "Summary of the AP1000 Design Certification – Regulatory On Site and Off-Site Reviews of Open Items for the WESTEMS Computer Code," April 1, 2011.

19. Reference Not Used

20. Westinghouse document CN-PAFM-08-119, Revision 1, "WESTEMS™ 4.5.2 Verification and Validation."

21. Westinghouse document LTR-PAFM-11-150, "WESTEMS™ Documentation with Respect to Draft Regulatory Issue Summary."

22. Westinghouse Publication, "Method for Selecting Stress States for Use in an NB-3200 Fatigue Analysis," Meikle, Cranford, and Gray, Proceedings of the ASME 2010 Pressure Vessels & Piping Division/K-PVP Conference, PVP 2010, July 18-22, 2010, Bellevue, Washington, USA, ASME, NY.

23. USNRC Safety Evaluation Report, NUREG-2101, "Safety Evaluation Related to the License Renewal of Salem Nuclear Generating Station," Docket Numbers 50-272 and 50-311, June 2011.

24. USNRC Regulatory Issue Summary, 2011-14, "Metal Fatigue Analysis Performed by Computer Software," December 29, 2011.

25. Reference Not Used

26. Westinghouse document WEC 2.6, "Training."

27. Westinghouse document WEC 3.3.3, "Design Verification by Independent Review or Alternate Calculations."

28. American Society of Mechanical Engineers (ASME) Standard, NQA-1-1994 Edition, "Quality Assurance Requirements for Nuclear Facility Applications."

29. American Society of Mechanical Engineers (ASME) Standard, Boiler and Pressure Vessel Code, 1977 Edition, including Summer 1979 Addenda, or later.

30. NRC Regulations Title 10, Code of Federal Regulations, Part 50 (10 CFR 50), Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants."

31. Southern Nuclear Letter, ND-12-0401, "WESTEMS NB-3600Assessment," archived in EDMS as Westinghouse document SV0_DCP_000024.

32. Westinghouse Letter, LTR-PAFM-12-30, "Qualification Matrix & Training Needs Assessment for WESTEMS™ Fatigue Analysis."

33. Westinghouse Letter, DCP_NRC_003205, "Transmittal of WCAP-17577, "Topical Report on ASME Section III Piping Fatigue Analysis Utilizing the WESTEMS™ Computer Code," for Safety Evaluation," February 29, 2012 (ADAMS Accession No. ML120610676).

34. USNRC Letter, ML12151A221, "Withdrawal Acknowledgement Letter for WCAP-17577, "Topical Report on ASME Section III Piping Fatigue Analysis Utilizing the WESTEMS™ Computer Code" for Safety Evaluation (TAC No. RP8500)," June 1, 2012.

35. Westinghouse Quality Management System.