SAFETY EVALUATION BY THE OFFICE OF NEW REACTORS
"TRACG APPLICATION FOR ESBWR
ANTICIPATED TRANSIENT WITHOUT SCRAM ANALYSES,"
NEDE-33083P, SUPPLEMENT 2, REVISION 2

1.0 INTRODUCTION

GE-Hitachi Nuclear Energy (GEH) submitted for review topical report NEDE-33083P, Supplement 2, Revision 2, "TRACG Application for ESBWR Anticipated Transient Without Scram Analyses," issued September 2009 (Reference 1), in support of the economic simplified boiling-water reactor (ESBWR) advanced passive design. This safety evaluation report (SER) documents the staff's review of NEDE-33083P, Supplement 2, Revision 2, as it relates to the ability of TRACG04 to model ESBWR anticipated transients without scram (ATWS) analyses.

This SER builds on the conclusions and analyses of related reviews of the TRACG code, including the following:

- the generic applicability of TRACG for ESBWR analyses, NEDC-33083P-A (Reference 2)
- the applicability of TRACG to ATWS analyses for operating reactors, NEDE-32906P, Supplement 1,(References 3) and Supplement 3, (Reference 4)
- the applicability of TRACG to ESBWR stability analyses, NEDE-33083P, Supplement 1, (Reference 5)
- the applicability of TRACG to ESBWR anticipated operational occurrences (AOOs), NEDE-33083P, Supplement 3, (Reference 6)
- the applicability of TRACG to AOO transient analysis for operating reactors, NEDE-32906P-A, Revision 2, (Reference 7)
- a technical evaluation by a staff contractor of the applicability of TRACG to ESBWR ATWS events (Reference 8)

2.0 REGULATORY BASIS

As defined in NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants" (hereafter referred to as the SRP), Section 15.8, Revision 2, "Anticipated Transients Without Scram," issued March 2007 (Reference 9), the ATWS acceptance criteria are based on meeting the relevant requirements of the following Commission regulations:

Enclosure 1

- Title 10 of the *Code of Federal Regulations* (10 CFR) 50.62, “Requirements for Reduction of Risk from Anticipated Transients Without Scram (ATWS) Events for Light-Water-Cooled Nuclear Power Plants” (known as the ATWS rule), as it relates to the acceptable reduction of risk from ATWS events via (1) inclusion of prescribed design features and (2) demonstration of their adequacy

- 10 CFR 50.46, “Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors,” as it relates to maximum allowable peak cladding temperatures (PCTs), maximum cladding oxidation, and coolable geometry

- General Design Criterion (GDC) 12, “Suppression of Reactor Power Oscillations,” as it relates to ensuring that oscillations are either not possible or can be reliably and readily detected and suppressed

- GDC 14, “Reactor Coolant Pressure Boundary,” as it relates to ensuring an extremely low probability of failure of the coolant pressure boundary

- GDC 16, “Containment Design,” as it relates to ensuring that containment design conditions important to safety are not exceeded as a result of postulated accidents

- GDC 35, “Emergency Core Cooling,” as it relates to ensuring that fuel and clad damage, should it occur, will not interfere with continued effective core cooling and that clad metal-water reaction will be limited to negligible amounts

- GDC 38, “Containment Heat Removal,” as it relates to ensuring that the containment pressure and temperature are maintained at acceptably low levels following any accident that deposits reactor coolant in the containment

- GDC 50, “Containment Design Basis,” as it relates to ensuring that the containment does not exceed the design leakage rate when subjected to the calculated pressure and temperature conditions resulting from any accident that deposits reactor coolant in the containment

For boiling-water reactors (BWRs), the following specific criteria apply:

- Equipment shall be provided to initiate an automatic trip of the reactor coolant recirculation pumps under conditions indicative of an ATWS.

- An alternate rod injection system is provided that is independent and diverse from the reactor trip system sensor output to the final actuation device. The system shall have an independent scram air header exhaust valve.

- A standby liquid control system (SLCS) shall be provided that is capable of initiating reactivity control equivalent to injection of 326 liters per minute (or 86 gallons per minute) of 13 weight-percent sodium pentaborate decahydrate solution of boron-10 into a 638-centimeter (251-inch) inside diameter reactor pressure vessel (RPV) operating at a power density consistent with the original licensed thermal power.

- The SLCS initiation is automatic for the plants specified in 10 CFR 50.62(c)(4).

- For BWRs, reactor coolant system pressures should not exceed American Society of Mechanical Engineers (ASME) Service Level C limits (approximately 10.3 megapascals (MPa) (1,500 pounds per square inch (psig)).

- 10 CFR 50.34 (f), TMI-2 Action Item No. 1.C.9, requires a program which includes emergency procedures. Each plant emergency operating procedure or emergency operating instruction to implement the ATWS/stability mitigation actions, as described in References 8 and 10 of SRP Section 15.8. The two main mitigation actions are the following:

  (1) Following a failure to scram, the reactor vessel water level must be lowered to a level below the feedwater spargers that will allow vessel steam to preheat the cold feedwater.

  (2) If unstable power oscillations are detected following a failure to scram, boron injection through the SLCS must be initiated manually.

For evolutionary plants (e.g., the ESBWR), SRP Section 15.8 specifies that some of the equipment required to satisfy the rule may not apply. For example, passive BWRs do not have recirculation pumps; therefore, these designs cannot provide equipment to trip them, as required by the rule. For these designs, provision of an equivalent action, such as reducing the vessel water level, may be acceptable.

The ATWS rule (10 CFR 50.62) prescribes hardware requirements, rather than acceptance criteria because, during the rulemaking process, BWR performance with the required hardware was shown to meet specific acceptance criteria. SRP Section 15.8 specifies that, for evolutionary plants, the applicant's design shall ensure the following:

- <u>Maintain coolable geometry for the reactor core</u>. If fuel and clad damage were to occur following a failure to scram, GDC 35 requires that this condition should not interfere with continued effective core cooling. The regulation in 10 CFR 50.46 defines three specific core-coolability criteria: (1) PCT shall not exceed 2,200 degrees Fahrenheit (F), (2) the calculated total oxidation of the cladding shall nowhere exceed 0.17 times the total cladding thickness before oxidation, and (3) the calculated total amount of hydrogen generated from the chemical reaction with water or steam shall not exceed 0.01 times the hypothetical amount that would be generated if all of the metal in the cladding cylinders surrounding the plenum volume, were to react.

- <u>Maintain reactor coolant pressure boundary integrity</u>. The calculated reactor coolant system transient pressure should be limited such that the maximum primary stress anywhere in the system boundary is less than that of the "emergency conditions" as defined in the ASME Nuclear Power Plant Components Code, Section III. The acceptance criterion for reactor coolant pressure, based on the ASME Service Level C limits, is 10.3 MPa (1,500 pounds per square inch gauge (psig)).

- <u>Maintain containment integrity</u>. Following a failure to scram, the containment pressure and temperature must be maintained at acceptably low levels based on GDC 16 and 38. The containment pressure and temperature limits are design dependent, but to satisfy GDC 50, those limits must ensure that containment design values are not exceeded when the containment is subjected to the calculated pressure and temperature conditions resulting from any ATWS event.

In the design control document (DCD) application, GEH used the TRACG04 code to ensure that acceptance criteria are met during an ATWS event. This SER documents the staff evaluation of the ability of the TRACG04 code to perform ATWS calculations to ensure ESBWR compliance with the above regulatory requirements.

3.0 TECHNICAL EVALUATION

In the following sections, the staff addresses the scope of the review; the technical evaluation based on the code scaling, applicability, and uncertainty (CSAU) methodology; and confirmatory calculations performed in support of this review.

3.1 SCOPE OF REVIEW

The scope of this SER is limited to the capability of the TRACG04 code to perform ATWS analyses for the ESBWR. Section 15.5.4 of the SER on ESBWR design certification (Ref. 38) discusses the adequacy of the ESBWR ATWS systems (e.g., SLCS) and evaluation of the ATWS event as it pertains to regulatory criteria. This review builds on the evaluation of the ability of TRACG to perform AOO analysis for the ESBWR (Reference 6) and on the evaluation of the ability of TRACG to perform ATWS analyses in operating reactors (Reference 4).

3.2 TECHNICAL EVALUATION BASED ON THE CODE SCALING, APPLICABILITY, AND UNCERTAINTY APPROACH

GEH has chosen to follow the basic CSAU approach outlined in NUREG/CR-5249, "Quantifying Reactor Safety Margins: Application of Code Scaling, Applicability, and Uncertainty Evaluation Methodology to a Large-Break, Loss-of-Coolant Accident," issued December 1989 (Reference 10), for evaluating total model and plant parameter uncertainty in ESBWR ATWS calculations. [[ ]] The staff review has also followed the methodology described in Reference 10, and the staff conclusions are organized based on the steps required in the CSAU methodology and the ability of TRACG04 to implement them.

The CSAU methodology consists of 14 steps contained within 3 elements (Reference 10). The first element includes Steps 1 through 6 and determines the requirements and code capabilities. The scenario modeling requirements are identified and compared against code capabilities to determine the applicability of the code to the specific plant and accident scenario. Element 1 notes code limitations.

The second element in the methodology includes Steps 7 through 10 and assesses the capabilities of the code by comparison of calculations against experimental data to determine code accuracy and scaleup capability and to determine appropriate ranges over which parameter variations must be considered in sensitivity studies.

The third element in the methodology consists of Steps 11 through 14, in which individual contributors to uncertainty, such as plant input parameters, states, and sensitivities, are calculated, collected, and combined with biases and uncertainties into a total uncertainty.

3.2.1 Element 1—Requirements and Code Capability

3.2.1.1 Step 1—Scenario Selection

The processes and phenomena that can occur during an accident or transient vary considerably depending on the specific event being analyzed. GEH has identified the ATWS scenarios applicable to the ESBWR that can be analyzed using TRACG and the associated methodology described in Reference 3. These correspond to SRP Section 15.8.

More detail on the specific events for which this methodology is applicable appears in Section 2.0 of "Technical Evaluation Review of TRACG Applications to ESBWR ATWS," issued January 2007 (Reference 8).

GEH is consistent with Step 1 in the CSAU approach.

3.2.1.2 Step 2—Nuclear Power Plant Selection

The dominant phenomena and timing for an event can vary significantly from one nuclear power plant design to another. GEH has specified that the methodology applies to the ESBWR natural circulation, passive design. The staff evaluated the methodology as it applies to the 4,500-megawatt thermal (MWt) ESBWR design described in the ESBWR DCD.

GEH is consistent with Step 2 in the CSAU approach.

3.2.1.3 Step 3—Phenomena Identification and Ranking

All phenomena that occur during an accident or transient do not equally influence the behavior of the nuclear power plant undergoing the event. A determination must be made to establish those phenomena that are important for each event and various phases within an event. Development of a phenomena identification and ranking table (PIRT) establishes those phases and phenomena that are significant to the progress of the event being evaluated.

GEH identified important phenomena for ATWS events in the ESBWR in a PIRT, which appears in Table 3-1 of NEDE-33083P, Supplement 2, Revision 2, (Reference 1). NEDC-33079P, Revision 1, Supplement 1, "ESBWR Test and Analysis Program Description, Discussion of PIRT Parameters," issued March 2005 (Reference 11), discusses the parameters. The phenomena are identified as having an impact on three critical safety parameters: (1) suppression pool temperature, (2) vessel pressure, and (3) fuel clad temperature.

In ranking the phenomena, GEH divided the limiting scenarios into five phases:

(1) short-term pressurization, neutron flux increase, and fuel heatup
(2) feedwater runback and water level reduction
(3) boron injection, mixing, and negative reactivity insertion
(4) post shutdown suppression pool heatup
(5) depressurization of the reactor

GEH states that emergency operating procedures may direct an operator to depressurize the reactor during an ATWS, but these procedures have not been established at this time. In Request for Additional Information (RAI) 21.6-4, the staff asked GEH to address depressurization during an ATWS event. In the RAI response (Reference 12), GEH described its procedure for developing a PIRT for ATWS depressurization. This procedure was nearly identical to that used when developing the PIRT for loss-of-coolant accident (LOCA) events, with some differences noted by GEH. The staff finds that GEH has addressed the differences between a depressurization resulting from a LOCA and one resulting from a controlled depressurization during an ATWS. However, the staff noted in its supplemental RAI that GEH has not provided demonstration calculations or the procedures for depressurization during an ATWS, and therefore the staff cannot thoroughly review the application of TRACG to depressurization. In response to RAI 21.6-4 S01, the applicant provided TRACG depressurization analysis results for the limiting ATWS event with respect to suppression pool heatup, the main steam isolation valve closure (MSIVC) ATWS event. The results shown in Figure 21.6-4 S01-1 indicate that the final suppression pool temperature is consistent with containment pressure limits. This indicates that, as designed, the ESBWR suppression pool can adequately handle an operator-initiated depressurization during an ATWS event. In addition, this simulation shows that TRACG is capable of simulating the depressurization of the reactor in an ATWS MSIVC event. Based on the applicant's response, RAI 21.6-4 is resolved.

The following PIRT parameters were introduced specifically for ESBWR ATWS evaluation:

- ATW1—boron mixing/entrainment between the jets downstream of the injection nozzle
- ATW2—boron settling in the guide tubes or lower plenum
- ATW3—boron transport and distribution through the vessel, particularly in the core bypass region
- ATW5—boron reactivity

The staff concludes that this PIRT is comprehensive and gives the appropriate rating to ESBWR ATWS phenomena. GEH is consistent with Step 3 in the CSAU approach.

3.2.1.4 Step 4—Frozen Code Version Selection

The version of a code, or codes, reviewed for acceptance must be "frozen" to ensure that after an evaluation has been completed, changes to the code do not impact the conclusions and that changes occur in an auditable and traceable manner. GEH has specified that the TRACG04 code be used for the ESBWR AOO applications. TRACG04 contains PANAC11 three-dimensional neutronic methods. PANAC11 and TGBLA06 are used to generate ESBWR cross section data for input into TRACG04.

On October 14 through 19, 2006, and October 30 through November 3, 2006, the staff performed an audit of PANAC11 and TGBLA06 as they are applied to the ESBWR. During the audit, the staff reviewed the most current versions of PANAC11 and TGBLA06 codes for their applicability to the ESBWR. Even though GEH regularly issues new versions of its code to correct errors, the staff considers these codes frozen, along with future revisions to the codes, as long as changes to the codes are within the conditions and limitations specified in its SER for NEDE-33239P, "GE14 for ESBWR Nuclear Design Report" (Reference 13).

The ATWS methodology documented in NEDE-33083P, Supplement 2, Revision 2, (Reference 1), restricts changes to the reference code (TRACG04). Thus, changes to the models documented in NEDE-32176P, Revision 3, "TRACG Model Description," issued

April 2006 (Reference 15), may not be made without NRC review and approval. However, the methodology does allow programming changes in numerical methods to improve code convergence or code enhancements or corrections of programming errors. These changes must be tested and auditable records kept in accordance with Appendix B, “Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants,” to 10 CFR Part 50. As part of the testing process, the calculated TRACG results must be compared against the results documented in the most recent version of the qualification test document NEDE-32177P, “TRACG Qualification” (References 16 and 17). If the differences are larger than the one-sigma uncertainty in that assessment, the methodology documented in NEDE-33083P, Supplement 2, Revision 2, (Reference 1), requires that GEH submit the changes for staff review. New models or features, other than input enhancements that do not affect calculated results significantly, may not be implemented without prior NRC review and approval.

In RAI 21.6-92, the staff asked GEH to provide the exact version and revision number for all analyses performed in the ESBWR DCD (Reference 18). In addition, GEH has two versions of the TRACG04 code—TRACG04A runs on an Alpha Virtual Memory System (VMS) platform, and TRACG04P runs on a Personal Computer (PC) platform. The staff asked GEH to state which of these two codes is used to perform the analyses for which this methodology will be applied. In its response, GEH provided a list of the code versions used for each calculation in the DCD, which the staff finds sufficient. Based on the applicant’s response, RAI 21.6-92 is resolved.

GEH is consistent with Step 4 in the CSAU approach.

3.2.1.5 Step 5—Provision of Complete Code Documentation

This step requires the applicant to provide documentation on the frozen code version such that evaluation of the code’s applicability to postulated transient or accident scenarios for a specific plant design can be performed through a traceable record. GEH has provided the documentation through the submittal of ESBWR ATWS specific documentation in References 1, 11, and 19, and code documentation in References 11 and 15.

The staff concludes that the code documentation is adequate, and GEH is consistent with Step 5 in the CSAU approach.

3.2.1.6 Step 6—Determination of Code Applicability

TRACG04 is based on two-fluid models capable of one-dimensional and three-dimensional thermal-hydraulic representation, along with three-dimensional neutronic representation. The code is designed to simulate reactor transients as best estimates. Conservatism is added, where appropriate, via input specifications. An analysis code used to calculate a transient scenario in a nuclear power plant should use many models to represent the thermal-hydraulics and components. These models should include the following four elements:

(1) field equations—provide code capability to address global processes

(2) closure equations—provide code capability to model and scale particular processes

(3) numerics—provide code capability to perform efficient and reliable calculations

(4) structure and nodalization—address code capability to model plant geometry and perform efficient and accurate plant calculations

The staff performed an extensive review of the thermal-hydraulics models and their applicability to the ESBWR for LOCA events and containment analysis (Reference 20) and the application to AOO and ATWS overpressure events in BWR/2–6 as described in the staff evaluation report included in the topical report (Reference 3). The staff also reviewed TRACG as applied to ESBWR AOO/infrequent event analysis (Reference 4). The current safety evaluation (SE) of the TRACG applicability for ATWS builds on these previous reviews.

3.2.1.6.1 Thermal-Hydraulic Modeling

The SER for NEDE-33083P, Supplement 3, (Reference 6), contains a review of the TRACG thermal-hydraulic modeling as applied to ESBWR AOOs. In addition, Reference 8 documents a technical evaluation by a staff contractor of the TRACG thermal-hydraulic models related to ATWS phenomena. Some of the phenomena unique to ATWS events include those related to high heat flux and boron mixing and transport. The following sections in this SER discuss other phenomena that are unique to modeling ESBWR ATWS events.

3.2.1.6.2 Minimum Stable Film Boiling Temperature

For the minimum stable film boiling temperature, GEH uses the Iloeje correlation for ESBWR applications. TRACG has the option of using the Shumway correlation, which, according to GEH, better captures the flow and pressure dependence. The staff has not reviewed the Shumway correlation, which was an option provided by GEH, and finds the use of the Iloeje correlation acceptable for ESBWR ATWS applications. For ATWS events where the core does go into film boiling, the minimum stable film boiling temperature is used to determine when the core will quench and has no effect on the value of the maximum PCT.

3.2.1.6.3 Standby Liquid Control System Modeling

GEH modeled the SLCS using a [[ ]] component. In RAI 21.6-12 (Reference 21), the staff asked GEH to justify its selection of the velocity for this component. GEH responded to this RAI in Reference 12. The velocity profile assumed in TRACG04 is based on a simple model of adiabatic expansion of the standby liquid control (SLC) accumulator nitrogen gas, and it assumes a constant reactor pressure of 8.72 MPa (1260 psi). The adiabatic assumption is conservative because, in real life, some heat will be transferred from the environment to the nitrogen gas, resulting in increased SLC velocity. The constant reactor pressure assumption is conservative because 8.72 MPa (1260 psi) is higher than the safety/relief valve actuation pressure; thus, the reactor pressure is expected to be reduced when the safety/relief valves actuate. Since both assumptions are conservative, the TRACG model results in slower boron injection rates than in the real case. In addition, GEH performed a sensitivity calculation assuming 90 percent of the injection velocity table. The results indicate that this 10-percent reduction in SLC injection velocity had [[ ]].

The staff concludes that the SLC injection models documented in NEDE-33083P, Supplement 2, Revision 2 (Reference 1), are conservative. Based on the applicant's response, RAI 21.6-12 is resolved.

3.2.1.6.4 Boron Mixing and Transport

The ESBWR uses the SLCS to shut down the reactor in the event of an ATWS. This system injects soluble boron, a strong neutron absorber, into the peripheral bypass of the core. GEH has included a mass-continuity equation in TRACG for boron transport, in a method similar to that for the treatment of noncondensable gas, which assumes that all noncondensable gases are in thermal equilibrium with the liquid that is present and move with the same velocity as the liquid. GEH has also incorporated single- and two-phase fluid mixing models to account for mixing resulting from molecular and turbulent diffusion. GEH made the following assumptions in modeling turbulent mixing and molecular diffusion:

- Equal volumes of two-phase mixture are exchanged among adjacent regions.
- In each computational cell, the properties of the incoming fluid volume and the resident fluids are perfectly mixed.
- Both vapor and liquid travel with the same lateral mixing velocity.

Even though the boron model is simplistic, it has produced sufficient results for a number of applications. However, empirical confirmation is still required at different scales. As a result of the assumption that there is perfect mixing in each computational cell in the boron mixing model, the model is highly dependent on nodalization because the boron is transported instantaneously to the whole node; very large nodes would result in nonconservative fast boron transport. Section 3.2.2.2 of this report discusses the adequacy of the GEH TRACG nodalization for performing ATWS evaluations. In RAI 21.6-41 (Reference 32), the staff requested that GEH justify its position that the uniform mixing assumption of the boron in the bypass will be conservative. The information requested in RAI 21.6-41 was also listed in RAI 21.6-44, which included a request for GEH to address computational fluid dynamics (CFD) calculations. The response to RAIs 21.6-44 and RAI 21.6-44 S01 are documented in References 39, 40 which shows a comparison of TRACG-predicted boron concentrations against experimental data from NEDE-22267, “Test Report Three-Dimensional Boron Mixing Model,” issued October 1982 (Reference 23). The results of this benchmark indicate that TRACG calculations [[

]]. The staff performed CFD confirmatory calculations (see Section 3.3.2 of this report) and reached similar conclusions. Thus, the staff concludes that the overall TRACG boron mixing models result in a lower reactivity worth and, thus, are conservative.

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]] The ESBWR ATWS analysis does not use this model; therefore, the staff did not review it. Based on the applicant’s response, RAI 21.6-41 is resolved.

3.2.1.6.5 Boron Settling

Boron may be lost to the system because of settling in the control rod guide tubes and the lower plenum. Since TRACG assumes that boron is uniformly mixed in each cell, TRACG is not able to calculate the effects of boron settling. Therefore, the effects of potential removal of boron from the system because of settling can be controlled using nodalization and input assumptions. GEH did not adjust the nodalization to account for this settling. In Reference 1 (Section 5.0), by calculating a critical velocity based on a critical Froude number, GEH concluded that the boron will not settle. GEH estimated that the critical velocity is much less than the velocity being calculated by TRACG, and thus, settling will not occur. In RAIs 21.6-9 (Ref. 24), 21.6-27, and 21.6-28 (Reference 12), the staff asked GEH to justify the assumptions about the settling of boron. In response to RAI 21.6-27 (Reference 12), GEH provided the velocity calculated by TRACG for the duration of the transient to demonstrate that it is mostly upward and that boron is not likely to settle in the guide tubes. During some time periods, the velocity is slightly negative, and in response to RAI 21.6-9 (Reference 24) and 21.6-28 (Reference 12), GEH performed sensitivity studies on the amount of boron settling in the guide tubes and found its effect on maximum suppression pool temperature to be negligible. The staff technical evaluation in Reference 8 discusses this issue and reaches similar conclusions. Based on the applicant's responses, RAIs 21.6-9, 21.6-27, and 21.6-28 are resolved.

The sensitivity studies performed by GEH are based on the MSIVC ATWS. The results may be different for different ATWS events since the flow field will be different. In a supplement to RAI 21.6-39, the staff asked GEH to address the flow field for ATWS events that may be different than MSIVC. In addition, the results of the CFD analyses discussed in Section 3.3.1 have provided additional insight into the settling of the boron. The staff evaluation of RAI 21.6-39 is included in Section 3.2.2.2 of this report.

3.2.1.6.6 Channel Leakage Model

Following SLCS activation, the injected boron will fill or settle in the bottom of the bypass region and enter the channels through the leakage paths because the bypass flow is downwards during ATWS events. The staff reviewed the channel leakage model in TRACG. The staff issued RAI 21.6-100 (Reference 25) requesting justification for the applicability to ATWS of the TRACG channel leakage correlations. In response to RAI 21.6-100 S02 (Reference 27), the applicant stated that the hardware used to design the ESBWR core, including lower tie-plate and fuel bundle leakage path geometry, is similar to that of the operating BWRs. Therefore, the staff agreed that using the same forward and reverse channel leakage flow coefficients as for the current operating BWRs is appropriate for the ESBWR. Based on the applicant's response, RAI 21.6-100 is resolved.

3.2.1.6.7 Fuel Thermal Conductivity and Gap Conductance

During the review of NEDE-33083P, Supplement 3 (Reference 6), the staff found a number of inconsistencies in the TRACG04 treatment of fuel thermal conductivity and gap conductance. These inconsistencies are also covered by a related 10 CFR Part 21, "Reporting of Defects and Notification". Sensitivity analyses were performed in the response to RAI 6.3-54 (Reference 28) and showed [[ ]]. The AOO and ATWS sensitivity study results documented in the response to RAI 6.3-54 S01 provide the staff with reasonable assurance that the transient event analyses shown in NEDE-33083P do not exceed acceptance criteria, and therefore, RAI 6.3-54 is resolved. The fact remains that the inconsistencies in the TRACG04 thermal conductivity model have not been submitted for ESBWR application with the supporting empirical data. Therefore, the staff SER for NEDE-33083P, Supplement 3 (Reference 6), imposes a condition to use consistent pellet and gap models for future calculations. This condition is also outlined as Condition 10 as identified in Section 4 of this report as it applies to the AOO and ATWS calculations.

3.2.1.6.8 Hot Rod Model

GEH has implemented a hot rod model in its one-dimensional thermal-hydraulic model of the channel component in TRACG04. As described in Section 8.1.1 of NEDE-33083P Supplement 2, Rev 2, GEH calculated a PCT during ATWS events, for the limiting bundle. The hot rod model option is activated for the limiting PCT channels, where the rods are presumed to be near boiling transition or uncovered (as in the case of conventional BWR reflood during LOCA calculations prior to quenching). The model allows for accurate modeling of the peak cladding temperature (PCT) in conditions where the rods may dry out. In addition, a bundle power peaking is applied to one of the hot channels to operate at a Critical Power Ratio (CPR) lower than the expected Operating Limit CPR (which results in earlier dryout of the fuel bundle).

A detailed description of the hot rod model option is provided in Section 7.5.7 of the TRACG Model Description Topical Report, NEDE-32176P (Reference 15). Reference 31, NEDE-32177P, provides qualification of the hot rod model option by comparison to separate effects tests at several LOCA test facilities. The Core Spray Heat Transfer Test (CSHT) data indicate close agreement between measured PCT values and the TRACG hot rod model-predicted PCT for a core spray reflood test. The Two-Loop Test Apparatus (TLTA) data was also compared against TRACG predictions using the hot rod model, with good agreement. The Thermal Hydraulic Test Facility (THTF) PCT data was also generally well-predicted by TRACG, [[ ]], as noted in Section 3.2.1.3 of Reference 31.

In general, the LOCA tests show that TRACG, with the hot rod model option implemented, adequately predicts PCT based on average hydraulic conditions. However, localized variations in the test hydraulic conditions could lead to underprediction of PCT, considering measurement uncertainty, at some rod locations. This is particularly the case for transients with significant radial or azimuthal variation in void fraction from the bundle average value. Since the ESBWR core is never uncovered during LOCA, the hot rod model option is not utilized for LOCA analyses.

In Reference 41, GEH provided supplemental supporting information for ATWS application of the hot rod model option. As indicated in the reference, the above LOCA tests' comparisons are not fully representative of the rod conditions which would exist for ATWS scenarios, [[ ]] These tests are described in Section 3.6.1 of Reference 31, the TRACG Qualification Report. [[ ]] The TRACG-calculated and measured cladding surface temperatures are compared for two of the ATLAS tests (Figures 3.6-5 and 3.6-6). The calculated temperatures conservatively overpredict the test measurements by [[ ]].

GEH noted in Reference 41 that the hot rod model option was not used for the ATLAS qualification benchmarks, [[ ]]. The staff agrees with the applicant's explanation that, for the ATLAS tests, as well as for expected ATWS scenarios, [[ ]].

NEDE-33083P, Supplement 2, identifies the Main Steam Line Isolation Valve Closure (MSIVC), Loss of Feedwater Heating, and Loss of Condenser Vacuum as limiting scenarios for ATWS overpressure and PCT. The supplemental information provided in Reference 41 further states that the results for the ESBWR ATWS bounding MSIVC calculation in NEDE-33083, Supplement 2 included a hot channel rod in which the hot rod model option was applied, and [[

]] Only the maximum PCT of all rods is reported. [[

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The staff reviewed the limiting cases for ATWS PCT presented in NEDE-33083P, Supplement 2, and all ATWS cases presented in DCD, Tier 2, Chapter 15. In all cases, substantial margin to the 10CFR 50.46 limit (2200°F or 1204°C) is calculated. The TRACG hot rod model option was utilized for all of the ATWS analyses. Therefore, the staff finds the TRACG hot rod model option acceptable for use in ESBWR design and reload ATWS applications with GE14E fuel.

GEH stated, and the staff agrees, that it is not expected that incremental design differences in replacement ESBWR fuel would significantly alter the PCT margin. However, it is possible that a shift in timing for prediction of the occurrence of boiling transition beyond the statistical uncertainty could result. For this reason, if replacement fuel different from GE14E is utilized, the limiting ATWS analyses should be submitted for staff review. This would already be necessary if any fuel design parameters specified in the fuel design topical reports designated as Tier 2* documents are altered.

3.2.1.6.9 Three-Dimensional Neutron Kinetics Modeling

The SER for NEDE-33083P, Supplement 3 (Reference 6), discusses the staff's review of the three-dimensional neutron kinetics in TRACG. In addition, Reference 8 provides a technical evaluation of the three-dimensional neutronic models in TRACG.

GEH has successfully benchmarked TRACG three-dimensional neutronic capabilities against experimental data, including the following:

- Peach Bottom turbine trip tests
- Hatch MSIVC tests
- Nine Mile Point pump upshift tests
- Leibstadt loss of feedwater with high-pressure core spray (HPCS) unavailable tests

Even though these operating BWR events are not expected to be the same as the AOOs in the ESBWR, similar phenomena must be modeled accurately to simulate the three-dimensional neutron fluxes during these transients in operating plants as well as in the ESBWR (i.e., power response to void collapse, pressure response to Turbine Control Valve (TCV) closure or MSIVC, among others). Therefore, the staff concludes that the three-dimensional neutronic models in TRACG04 are adequate to model ATWS events in the ESBWR.

3.2.1.6.10 Xenon Reactivity

TRACG accounts for negative reactivity from xenon by adjusting the thermal absorption cross section at each node. The PANAC11 wrapup file includes the xenon number density and the microscopic absorption cross section. For TRACG calculations, the xenon concentrations are held constant throughout the transient. Since the timeframe of concern for ATWS is on the order of seconds or minutes, and xenon concentrations change over the course of hours, the staff finds that the constant xenon assumption is reasonable.

3.2.1.6.11 Boron Reactivity

Section 9.5 of References 13 and 15 describes the boron reactivity model in TRACG04. TRACG04 models the negative reactivity from boron by adjusting the absorption cross section for other preexisting neutron removal mechanisms already modeled in TRACG04. The SLCS shutdown margin is evaluated with PANACEA; therefore, cross sections could be provided for TRACG through PANACEA. However, GEH considers this method to result in cumbersome calculations and instead used the absorption cross section adjustment.

Since the boron is introduced into the core only during the ATWS event, there are no direct exposure effects on the boron or the reactivity. The reactivity worth of the boron can be accurately captured if the absorption cross section is increased to account for the neutron absorption in boron. This is most accurately done when the thermal cross section is adjusted. The boron absorption cross section depends on the local flux spectrum. The thermal spectrum is precollapsed in one group by TGBLA before being included in the PANACEA wrapup file; therefore, the GEH methodology adjusts the boron microscopic cross section to account for local perturbations to the thermal spectrum using a 1/v (velocity) energy dependence of the boron cross section.

In RAIs 21.6-34 and 21.6-35 (Reference 29), the staff asked GEH to provide additional information on the boron reactivity model and justify some of the assumptions used in the development of the model. GEH provided these details in Reference 29 by propagating the lattice values into PANAC11 for purposes of model development and testing.

In the responses to RAIs 21.6-34 and 21.6-35 (Reference 29), GEH showed the PANAC11 lattice evaluations of the boron reactivity model as a function of exposure for a large number of lattice types and lattice conditions, such as void fraction, boron concentration, and gadolinium content. The trends with exposure depend on factors such as enrichment, gadolinium content, and lattice design. GEH did not explicitly account for the change in neutron spectrum resulting from exposure of the fuel in its boron cross section model; however, it did explain that the TRACG model accounts for the trends seen with features via the 1/v dependence of the cross section and the exposure-dependent PANAC11 reference values provided to TRACG by the wrapup file. For two representative lattices, GEH showed that the boron cross section values as a function of exposure calculated by TRACG and PANAC11 are comparable.

TRACG also has an empirical correction for moderator temperature. GEH provided in Reference 29 a comparison of the TRACG model to PANAC11 for different moderator temperatures and demonstrated that they are comparable and that the trend in the cross section with moderator temperature is appropriate.

The analyses provided in Reference 29 did not account for the effect of void history on the boron cross section. Void history may have an effect through the neutron spectrum of the lattice. However, GEH showed through PANAC11 lattice evaluations that the effect of void history on the boron cross section is [[ ]]. The GEH evaluation indicates that at the higher void history, the TRACG model [[ ]], which is nonconservative. However, the [[

]]; therefore, the overall error in boron reactivity is expected to be significantly lower when realistic exposures and core-average void levels are used.

GEH accounted for self-shielding by reducing the boron cross section by empirically determined factors as the boron number density increases. GEH showed the self-shielding effect based on PANAC11 lattice evaluations and then stated that TRACG calculates a comparable reduction in the boron cross section for the same conditions.

GEH showed comparisons of the calculated eigenvalue versus boron concentration for PANAC11 and TRACG04. Since PANAC11 interpolates using boron concentrations of [[ ]], the two codes did not match exactly but did match where expected at the midpoint of the PANAC11 interpolation and for larger boron concentrations.

Since GEH uses empirical models to develop the boron reactivity model, the staff asked GEH to justify this model when applying it to other fuel designs not encompassed by those on page 5-15 of Reference 3 (or page 9-40 in Section 9.5.2 of Reference 15).

Even though the only validation available for staff review is a code-to-code comparison to PANAC11, the staff believes that GEH stated all of the factors affecting boron reactivity in the development and testing of its empirical model. Based on the applicant's responses, RAIs 21.6-34 and 21.6-35 are resolved.

To confirm GEH's assertions, the staff performed confirmatory calculations using the Monte Carlo MCNP code (Reference 30). Input decks representative of the ESBWR lattices were developed to support steady-state physics calculations. The staff added boron to these lattices to compare the resulting cross sections with the ones used in TRACG using the theoretical 1/v boron model. The results of these analyses are documented in a technical evaluation report (Reference 29). The results of the staff technical evaluation confirmed the validity of the TRACG boron model.

The staff finds that GEH is consistent with Step 6 in the CSAU approach, and each step in Element 1 is consistent with the CSAU approach and, therefore, acceptable.

3.2.2 Element 2—Assessment and Ranging of Parameters

3.2.2.1 Step 7—Establish Assessment Matrix

The staff's review of the assessment of TRACG as applied to ESBWR AOOs appears in Reference 6. This review is also applicable to ESBWR ATWS events. In Table 4.2-1 of Reference 1, GEH identified the qualification basis for each of the high-ranked phenomena identified in the ATWS PIRT by citing the quantitative assessment performed for separate effects qualification, component performance qualification, integral system qualification, and plant data. The assessment descriptions cover the test facility, where applicable, the test results, TRACG sensitivity studies, and nodalization studies, where applicable. All high-ranked phenomena have been assessed.

In RAI 21.6-75, the staff asked GEH to provide an update to the TRACG qualification report (Reference 16) that is consistent with the current version of TRACG used in ESBWR licensing analyses (TRACG04). In response, GEH submitted Revision 3 of the TRACG qualification report, NEDE-32177P (Reference 30), in August 2007, and this RAI and the associated concern are resolved.

GEH is consistent with Step 7 in the CSAU approach.

3.2.2.2 Step 8—Nuclear Power Plant Nodalization Definition

The nodalization for ATWS events is similar to that used for ESBWR AOO and stability analysis. Reference 6 discusses the adequacy of this nodalization for simulating transient thermal-hydraulic neutronic behavior in an ESBWR. The only ATWS-specific nodalization issue relates to the bypass region nodalization because it affects the boron transport.

As stated in Section 3.2.1.6.4 of this report, boron mixing is highly dependent on the nodalization scheme, especially in the bypass region. Section 5.1 of NEDE-33083P, Supplement 2, Revision 2 (Reference 1), presents the GEH justification for its vessel bypass nodalization in relation to boron mixing and transport. This justification is based on the qualitative discussion of postulated jet and plume characteristics of the SLCS liquid after injection. In addition, in RAI 21.6-42 staff requested (Reference 12) that GEH provide the boron concentrations and mass flow rates through the core bypass and channels for the MSIVC transient. In response, GEH provided the boron concentrations and mass flow rates in support of staff's review. Therefore, RAI 21.6-42 is resolved.

GEH also performed CFD calculations to help justify the selected TRACG nodalization. Separately, the NRC staff has completed independent confirmatory CFD calculations.

In addition to the CFD calculations, the staff requested in RAI 21.6-8 that GEH perform nodalization studies of the vessel to illustrate the sensitivity of the TRACG-calculated safety parameters to nodalization. [[

]] GEH submitted the results of its radial and azimuthal sensitivity studies in the response to RAI 21.6-8 (Reference 32). GEH performed a series of sensitivity studies that [[

]]

GEH showed that, when it injects boron into the two smaller sectors versus the four large sectors, the shutdown time [[ ]]. This was because, in both cases, [[

]]

GEH repeated this study with the blocking removed. The results for both the small- and large-sector injection cases [[

]]

GEH compared the results of just the large-sector injection cases (with and without blocking) to demonstrate that the case with blocking has a [[

]]. Despite the more conservative results, GEH proposed to maintain the size of the third outer ring and inject the boron into this ring [[

]]

The staff was concerned that, in the current GEH modeling approach, the outer ring into which boron is injected is the largest ring in the TRACG model and contains several rows of bundles. The staff was concerned that this is nonconservative because these bundles, which constitute a substantial portion of the bundles in the core [[ ]], would see boron immediately. To resolve this problem, the staff requested that GEH perform CFD calculations of boron mixing in the bypass. In addition, the staff performed its own confirmatory calculations. Both the staff and GEH CFD calculations appear to indicate that the SLCS injection of boron into the core bypass region is effective in getting boron to the inner parts of the core. Penetration of the boron into the inner bundles is more effective than the TRACG modeling approach which puts an [[

]] radial boron mixing. Based on the staff's confirmatory CFD calculations, RAI 21.6-8 is resolved.

In RAI 21.6-83 (Reference 33), the staff requested that GEH perform sensitivity studies for the axial nodalization of the bypass. In the response to RAI 21.6-83 (Reference 33), GEH supplied a study of boron mixing under different axial nodalization schemes. The staff concurred that key ATWS figures of merit like peak suppression pool temperature and shutdown time were not affected significantly by changes in the nodalization, which indicates that the reference solution is sufficiently converged. Based on the applicant's response, RAI 21.6-83 is resolved.

The staff was also concerned that the nodalization studies by GEH and the CFD analyses were performed for the limiting ATWS event (MSIVC), where the core flow and associated core pressure drop are reduced significantly, resulting in reverse (downward) flow in the bypass region. In RAI 21.6-39, the staff requested that GEH evaluate the adequacy of this nodalization for nonisolation ATWS events, where the core flow and associated core pressure drop may remain high enough to maintain upward flow in the bypass during the boron injection time. In the response to RAI 21.6-39 S01 (Reference 24), GEH performed calculations for nonisolation ATWS events where the initial bypass flow was upwards. The calculations show that the shutdown time is achieved only a few seconds later than in the isolation ATWS event (with downwards bypass flow), and key ATWS parameters do not change significantly. The primary reason for these results is that, even for nonisolation ATWS events, the ESBWR initiates a feedwater flow runback to lower the downcomer water level and reduce the core flow and power. This feedwater flow runback eventually forces flow reversal on the bypass region, which enhances the core boron concentration.

The staff concludes that the bypass region nodalization documented in NEDE-33083P, Supplement 2, Revision 2, (Reference 1), is adequate to model the boron mixing effect in ESBWR ATWS events. Therefore, GEH is consistent with Step 8 in the CSAU approach, and RAI 21.6-39 is resolved.

3.2.2.3 Step 9—Definition of Code and Experimental Accuracy

Simulation of experiments developed from Step 7 (discussed in Section 3.2.2.1), using the nuclear power plant nodalization from Step 8 (discussed in Section 3.2.2.2), provides checks to determine code accuracy. The differences between the code-calculated results and the test data provide bias and deviation information. Code scaleup capability can also be evaluated from separate effects data, full-scale component tests data, plant test data, and plant operating data where available. Overall code capabilities are assessed from integral systems test data and plant operational data. References 16 and 34 document the assessments of TRACG. Since the ESBWR is a new design, no operating plant data are available. However, many of the key parameters and phenomena for analyzing ATWS in the ESBWR are not significantly different from those in operating reactors.

GEH used TRACG to simulate separate effects tests, component performance tests, integral systems tests, and operating BWR plant data. GEH was able to determine an uncertainty between the code-calculated results and the test data. Sections 4.0 and 5.0 of Reference 8 include discussion of the uncertainties associated with various qualification tests.

3.2.2.3.1 Boron Mixing Qualification

To qualify and determine the uncertainty in the boron mixing model, GEH used data from three-dimensional boron mixing tests (Reference 23) conducted in a [[ ]] (BWR/5 and BWR/6), RPV using the HPCS spargers as the primary location for injection of the simulated boron solution. In the response to RAI 21.6-44 (References 39 and 40), GEH provided additional details of the boron mixing and transport tests used to qualify the TRACG boron model and its applicability to the ESBWR given its unique injection location (in the core bypass). GEH provided additional information about the test used to qualify the boron mixing model in Reference 22. The test used to qualify TRACG for ESBWR ATWS applications has simulated boron injection through the HPCS spargers. GEH stated that it expects the behavior of the boron to be similar to that of the ESBWR SLCS injection in the core bypass because of the downward flow conditions.

GEH defined a figure of merit, the boron "mixing coefficient," as the ratio of the local concentration of boron to the global average concentration of boron. With this definition, large mixing coefficient values indicate bad or incomplete mixing. GEH showed plots of the mixing coefficient in various elevations in the core and bypass for three tests. GEH also provided the conditions of the three tests. These three tests indicate that the mixing coefficient is [[ ]].

GEH developed scale factors between the test model and the ESBWR based on the dimensions of the ESBWR for the radial and axial directions. Using these scale factors, GEH then compared the mixing coefficients calculated by TRACG during the ESBWR MSIVC ATWS simulation and that of the test for various locations in the vessel. [[ ]] and therefore is conservative.

During the review, the staff was concerned about the applicability of a direct comparison between the BWR tests (Reference 23) and ESBWR TRACG results because the boron injection points are different. Boron injection in BWR is through the HPCS. Boron injection for the ESBWR design is by direct injection to the lower bypass region. However, in one of the tests (Case 345), the bypass water level was held at approximately [[ ]], so that the HPCS boron injection would flow freely down to the bypass region and the boron flow paths would propagate from that level, which is similar to the ESBWR case. In addition, the TRACG mixing models are conservative by a significant factor, and TRACG predicts significantly higher mixing coefficients (greater than 200 percent in most cases) than in the experiment. Based on these two observations, the staff concludes that the TRACG boron mixing models with the input parameters recommended in NEDE-33083P, Supplement 2, Revision 2, (Reference 1), are conservative and result in conservative shutdown times. Based on the applicant's response, RAI 21.6-44 is resolved.

The staff concludes that GEH is consistent with Step 9 in the CSAU approach.

3.2.2.4 Step 10—Determination of Effect of Scale

Various physical processes may give different results as components or facilities vary in scale from small to full size. The effect of scale must be included in the quantification of bias and deviation to determine the potential for scaleup effects. The key parameters and phenomena for analyzing ATWS events in the ESBWR do not have significantly different scales than in operating reactors. The staff discusses scaling of tests performed to qualify TRACG for ESBWR-specific components in Section 21.5 of the SER for ESBWR design certification (Ref. 38).

The staff concludes that GEH is consistent with Step 10 in the CSAU approach.

The staff finds each step in Element 2 to be consistent with the CSAU approach and therefore acceptable.

3.2.3 Element 3—Sensitivity and Uncertainty Analysis

3.2.3.1 Step 11—Determination of the Effect of Reactor Input Parameters and States

The purpose of this step is to determine the effect that variations in the plant operating parameters have on the uncertainty analysis. This evaluation has been performed in the SER for TRACG ESBWR AOOs (Reference 6), and it applies to ATWS calculations. The application methodology described in Section 2.7.2 in Reference 1 controls changes to the uncertainty values used for the model inputs. New data with which the specific model uncertainties may be reassessed may become available. If the reassessment results in a need to change specific model uncertainty, the specific model uncertainty may be revised for ESBWR ATWS licensing calculations without NRC review and approval as long as the process for determining the uncertainty is unchanged. In all cases, changes made to model uncertainties without review and approval will be transmitted to the NRC to keep the agency informed.

The treatment of initial conditions is slightly different for the TRACG ESBWR ATWS analyses than for the TRACG ESBWR AOO analyses discussed in Reference 6. The ATWS events will be initiated from the limiting point in the allowed operating domain. Initial conditions will not be adjusted to account for instrumentation and simulation uncertainties. Section 8.2.1.1 in Reference 1 describes the sensitivity studies on initial conditions performed by GEH. Since ATWS is a low-probability event, the NRC has accepted this approach in the past for TRACG ATWS analyses as applied to BWR/2–6 (Reference 3). The staff finds this approach acceptable for ESBWR ATWS analyses.

The treatment of plant parameters is slightly different for the TRACG ESBWR ATWS analyses than for the TRACG ESBWR AOO analyses discussed in Reference 6. GEH applied the analytical limit (often the same as the technical specification limit) for the plant parameters unless it determined that the safety parameters are not sensitive to that plant parameter. GEH performed a study investigating the effect of plant parameters on the MSIVC ATWS event. Section 8.2.2.1 in Reference 1 describes this study. Since ATWS is a low-probability event, the

NRC has accepted this approach in the past for TRACG ATWS analyses as applied to BWR/2-6 (Reference 3). The staff finds this approach acceptable for ESBWR ATWS analyses.

GEH is consistent with Step 11 in the CSAU approach.

3.2.3.2 Step 12—Performance of Nuclear Power Plant Sensitivity Calculations

Sensitivity calculations are performed to evaluate methodology sensitivity to various operating conditions that arise from uncertainties in the reactor state at the initiation of the transient, in addition to sensitivity to plant configuration. The safety-related quantities of importance in the ATWS analysis are peak vessel pressure, PCT, peak suppression pool temperature, and peak power. In RAI 21.6-77 (Reference 35) staff requested that the applicant provide additional information to support the staff's CFD modeling of the boron flow paths during an ATWS event. Using TRACG, GEH's response calculated representative ATWS events to demonstrate ESBWR plant behavior. In a subsequent supplement to its response to RAI 21.6-77, GEH identified and corrected an error associated with the channel leakage flow rates in its ATWS analysis that could affect the safety analysis results in this topical report. Staff was satisfied with GEH's response as compared to its CFD modeling and therefore, RAI 21.6-77 is resolved.

GEH is consistent with Step 12 in the CSAU approach.

3.2.3.3 Step 13—Determination of Combined Bias and Uncertainty

GEH chose the [[

]]

GEH is consistent with Step 13 in the CSAU approach.

3.2.3.4 Step 14—Determination of Total Uncertainty

GEH provides the uncertainty analysis in Section 8.0 of Reference 1. GEH provided clarifying information on this process in Reference 12 in response to RAI 21.6-36. GEH set each of the initial conditions and the highly ranked parameters in the PIRT at both the +1 sigma and the -1 sigma level and performed analyses to determine the impact on the calculated safety parameters.

[[

]] Following the uncertainty analysis, GEH added another set of conservatisms in the initial condition uncertainties, listed in Table 8.3-1 of Reference 1.

GEH provided the calculated peak RPV pressure, peak power, PCT, and peak suppression pool temperature for the nominal and bounding cases, and the uncertainty associated with each, in Tables 8.3-2 and 8.3-3 of Reference 1. Section 3.2.2.1 of this report discusses this issue.

The staff finds the GEH total uncertainty analysis acceptable, and GEH is consistent with Step 14 in the CSAU approach. Based on the applicant's response, RAI 21.6-36 is resolved. The staff finds each step in Element 3 to be consistent with the CSAU approach and therefore acceptable.

3.3 STAFF CONFIRMATORY CALCULATIONS

The staff performed independent CFD calculations using the FLUENT code to verify the GEH boron mixing and transport models and vessel bypass nodalization. In addition, the staff used MCNP to verify the TRACG04 boron reactivity models. The following sections discuss each modeled event.

3.3.1 Computational Fluid Dynamics Calculations of Boron Mixing and Transport

The NRC staff conducted confirmatory CFD calculations to confirm the boron mixing and transport models used by GEH and then issued a technical evaluation report summarizing the analyses and major conclusions (Reference 36). The major conclusions from this report are described below.

The NRC has completed a confirmatory set of CFD predictions to judge the applicability of a set of GEH CFD predictions used to support the TRACG predictions of the ESBWR ATWS scenarios. The GEH CFD predictions indicate that the SLCS injection of boron into the core bypass region is effective in moving boron to the inner parts of the core. Penetration of the boron into the inner bundles is more effective than the TRACG modeling approach, which puts [[

]].

The series of steady-state predictions that were completed to look for potential sensitivities to boundary conditions or other non-conservative modeling assumptions uncovered no significant issues. Variations in the upper surface mass inlet condition had little or no impact on the movement of boron into the inner regions of the core. The neglect of the increased specific gravity of the injected solution was also not a significant factor. The only factors that impacted the amount of boron penetrating into and building up in the core bypass were direct changes in the incoming boron mass flow or the exit mass flows from the bypass. These results are not unexpected.

The transient CFD predictions completed by the NRC agree reasonably well with the GEH predictions even though the approaches were quite different. The NRC CFD model used different material properties, geometry, turbulence modeling, wall treatments, and computational mesh along with a completely different code. The NRC predictions indicate a similar penetration rate for boron into the inner regions of the core bypass and differ only in the rate of boron accumulation and the rate of boron leakage from the GEH CFD predictions. These differences can be attributed partially to the geometric differences between the models and are not significant in light of the differences between the CFD and TRACG results, which are the ultimate subject of the GEH analyses. The principal conclusion is that the GEH CFD model is appropriate for demonstrating that the TRACG modeling approach, with the [[

]], is conservative with respect to boron mixing and penetration from the SLCS into the core bypass region.

3.3.2 Boron Reactivity Calculations

The staff developed MCNP input decks representative of the ESBWR lattices in support of steady-state physics calculations. The staff added boron to these lattices to compare the resulting cross sections with the ones used in TRACG using the theoretical 1/v boron model. The results of these analyses are documented in a technical evaluation report (Reference 29). The results of the staff technical evaluation confirm the validity of the TRACG boron model.

The technical evaluation (Reference 29) performed a series of MCNP calculations as an independent check of the TRACG boron model by calculating the effective microscopic boron-10 cross section and the average neutron velocity for several configurations. These calculations were carried out for the appropriate assembly type (depending on axial height), for the void fraction and boron concentrations, and for four burnup levels. This resulted in a total of sixty combinations of assembly type, burnup, void fraction, and boron concentration. Based on the relationships between cross section and velocity, it is clear that the microscopic cross section should decrease with increasing average velocity. This decrease should vary inversely with velocity, but it could be modified by non-1/v effects. This dependence might be closer to linear, since any variation of the boron cross section will be small compared to the variation in boron number density for this particular transient.

The average cross section and velocity were calculated over both (1) the thermal range (less than 0.625 electronvolts (eV)), and (2) the total range (0–20.0 megaelectronvolts (MeV)). The results show that, for all cases, at each height, the thermal range microscopic cross section is essentially linearly proportional to the average neutron velocity, regardless of burnup level, boron concentration, or height (implies assembly type). However, this was not the case for the cross sections averaged over the entire energy range. In this case, there were four distinct “straight” lines for each burnup level at each height. The correlation is still largely linear, but there are burnup effects that separate the lines. In addition, an effect due to height (neutron spectral effect) is evident in the cross section magnitude. The staff noted that these conclusions are valid only for the conditions encountered in the evaluated transient; thus, any possible self-shielding effects caused by significantly higher boron concentrations were not explored because they are not likely in an ESBWR ATWS event. The fast range (above 0.625 eV) microscopic cross section has essentially no correlation with average neutron velocity. The cross section values group themselves into distinct groups (as a function of burnup) with no easily identifiable correlation.

Furthermore, the average macroscopic thermal range cross section can be determined by multiplying the microscopic cross section by the boron number density at the time of interest. The variation of the macroscopic cross section with average velocity for the thermal range shows an increasing cross section with increasing boron concentration (and time into the transient), regardless of height or burnup. The increase is essentially linear, with a slightly different slope, depending on burnup.

4.0 CONDITIONS AND LIMITATIONS

The staff has identified the following specific conditions that will be applied to NEDE-33083P, Supplement 2, Revision 2, (Reference 1):

(1) The staff evaluated the methodology for analyzing ESBWR ATWS events using TRACG, described in NEDE-33083P, Supplement 2, Revision 2, (Reference 1), as it applies to the 4,500-MWt ESBWR design presented in the approved ESBWR DCD. If GEH or an applicant referencing the methodology in Reference 1 wishes to use this methodology for an ESBWR design not completely consistent with the approved ESBWR DCD, GEH or the applicant must provide a summary of the design changes and justification for NRC staff review and approval of the applicability of the methodology.

(2) Changes to the TRACG models as described in NEDE-32176P, Revision 3, (Reference 15), may not be made without NRC review and approval. The NRC must review and approve any changes to the method described in NEDE-33083P, Supplement 2, Revision 2, (Reference 1).

(3) Changes in numerical methods to improve code convergence, or code enhancements, or error corrections must be tested and auditable records kept in accordance with Appendix B to 10 CFR Part 50. As part of the testing process, the calculated TRACG results must be compared against the results documented in the most recent version of the qualification tests document, NEDE-32177P, Revision 2, (Reference 16). If the differences are larger than the 1-sigma uncertainty in that assessment, the methodology documented in NEDE-33083P, Supplement 2, Revision 2, (Reference 1), requires that GEH submit the changes for staff review.

(4) New models or features, other than input enhancements that do not affect calculated results significantly, may not be implemented without prior NRC review and approval.

(5) Since GEH used empirical models to develop the boron reactivity model, GEH shall justify this model when applying it to other fuel designs not encompassed by those shown on page 5-15 of NEDE-33083P, Supplement 2, Revision 2, (Reference 1) or page 9-40 in Section 9.5.2 of NEDE-32176P, Revision 3, (Reference 15).

(6) The application methodology described in Section 2.7.2 of NEDE-33083P, Supplement 2, Revision 2, (Reference 1) controls changes to the uncertainty values used for the model inputs. New data with which the specific model uncertainties may be reassessed may become available. If the reassessment results in a need to change specific model uncertainty, this uncertainty may be revised for ESBWR ATWS licensing calculations without NRC review and approval as long as the process for determining the uncertainty is unchanged. In all cases, changes made to model uncertainties performed without review and approval will be transmitted to the NRC for its information.

(7) [[

]], and that model is not approved for use in ESBWR ATWS events.

(8) Use of TGBLA or PANAC11 codes must be within the conditions and limitations stated in Section 4.3.3.2.5 of Reference 37

(9) Conditions and limitations from the staff review of TRACG application to AOOs (NEDE-33083P, Supplement 3, (Reference 6)) are applicable to TRACG ATWS analyses.

(10) The staff accepts the use of the GSTRM model for both gap conductance and thermal conductivity in the ESBWR design certification. The conclusions and limitations for

ESBWR TRACG ATWS analyses (including the 350-psi (2413 Kilopascal) critical pressure penalty) contained in the NRC staff evaluation of GEH's 10 CFR Part 21 report (Appendix F to the SE for NEDC-33173P (Agencywide Documents Access and Management System (ADAMS) Accession No. ML073340214) are applicable to this SE. The NRC must approve the use of other methods or analysis strategies for the ESBWR design.

5.0 CONCLUSIONS

The staff concludes that the ATWS analysis methodology documented in NEDE-33083P, Supplement 2, Revision 2, (Reference 1), is an acceptable way to employ the TRACG04 code to demonstrate compliance with the regulatory requirements for ESBWR ATWS events. The staff finds that the ATWS methodology and the TRACG04 code comply with all three elements of the CSAU methodology to calculate best-estimate results and estimate their uncertainty.

6.0 REFERENCES

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2. NEDC-33083P-A, MFN 05-017, "TRACG Application for ESBWR," March 2005. (ADAMS Accession No. ML051390265)

3. NEDE-32906P, Supplement 1-A, "TRACG Application for Anticipated Transient Without Scram Overpressure Transient Analysis," November 2003. (ADAMS Accession No. ML033381102)

4. Final Safety Evaluation Report By the Office of NRR Licensing Topical Report NEDE-32906P, Supplement 3, "Migration To TRACG04/PANAC11 From TRACG02/PANAC10 For TRACG AOO And ATWS Overpressure Transients General Electric Hitachi Nuclear Energy Americas, LLC, July 10, 2009(ADAMS Accession No. ML0917511021), GE Hitachi Letter MFN 10-137, Add NEDE-32906P, Supplement 3, "Migration To TRACG04/PANAC11 From TRACG02/PANAC10 For TRACG AOO And ATWS Overpressure Transients, " to ESBWR Docket, dated March 31, 2010 (ADAMS Accession No. ML100900085)

5. NEDE-33083P, Supplement 1, "Safety Evaluation Report Regarding the Application of General Electric's Topical Report, 'TRACG Application for ESBWR Stability Analysis'" (TAC MC3288). (ADAMS Accession Nos. ML060890075 and ML061000463)

6. Safety Evaluation Report for NEDE-33083P, Supplement 3, "Application of the TRACG Computer Code to the Transient Analysis for the Economic Simplified Boiling Water Reactor Design", July 2010. (ADAMS Accession No. ML100270024)

7. NEDE-32906P-A, Revision 2, MFN 06-046, "TRACG Application for Anticipated Operational Occurrences (AOO) Transient Analysis," February 28, 2006. (ADAMS Accession Nos. ML060530571 and ML060530575)

8. J. Spore (ISL), Information Systems Lab (ISL), ISL-NSAD-TR-07-02, “Technical Evaluation Review of TRACG Applications to ESBWR ATWS,” January 2007 (ADAMS Accession No. ML080040449).

9. NUREG-0800, Revision 2 “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants, LWR Edition,” Section 15.8, March 2007 (ADAMS Accession No. ML070570008).

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