DRAFT SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT ANP-10332P, REVISION 0

"AURORA-B: AN EVALUATION MODEL FOR BOILING WATER REACTORS;

APPLICATION TO LOSS OF COOLANT ACCIDENT SCENARIOS"

FRAMATOME, INC.

PROJECT NO.: 728/DOCKET NO. 99902041

Enclosure 2

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1.0 INTRODUCTION AND BACKGROUND

This safety evaluation (SE) documents the NRC staff's review of a Framatome Inc. (Framatome, formerly AREVA Inc.) topical report (TR) that describes a methodology for analyzing the complete spectrum of postulated loss-of-coolant accidents (LOCAs) for certain types of boiling-water reactors (BWRs). The methodology proposed by Framatome is intended to conform to conservative requirements prescribed in Appendix K to Title 10 of the *Code of Federal Regulations* Part 50 (10 CFR 50).

The methodology proposed by Framatome is contained in TR ANP-10332P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Loss of Coolant Accident Scenarios" (Reference 1), which was submitted in February 2014. The NRC staff initiated its review of this report in August 2016, held an audit on May 16-18, 2017 (Reference 2), and issued requests for additional information (RAIs) on October 24, 2017 (Reference 3), and January 19, 2018 (Reference 4). Framatome formally responded to the NRC staff's RAIs in a submittal dated April 30, 2018 (Reference 5).

At the time ANP-10332P was submitted, Framatome went by the name AREVA NP. In January 2018, AREVA NP changed its name to Framatome. Since the name change occurred during the course of the review, the AREVA name is used in the incoming submittal, the NRC staff's RAIs, and other relevant documents. For simplicity, with the exception of the references listed in Section 8.0, this SE generally uses the name Framatome, even when describing events and circumstances that occurred prior to the name change.

The NRC staff conducted its review of ANP-10332P with the assistance of consultants from Brookhaven National Laboratory, who provided a technical evaluation report (Reference 35) (withheld for proprietary reasons) that has served as a reference source in the development of this SE. The Brookhaven technical evaluation report focuses in particular on the assessment and validation of the AURORA-B LOCA evaluation model, which is covered primarily in Section 3.4 of this SE.

1.1 The AURORA-B Code System and Evaluation Models

The name "AURORA-B" refers to a code system developed by Framatome to perform safety analysis for BWRs for a wide variety of events specified in Chapter 15 of the Standard Review Plan (SRP) (Reference 6), including anticipated operational occurrences and accidents. In full generality, the AURORA-B code system is composed of three subsidiary components:

- S-RELAP5, a system-level thermal-hydraulic code that is the primary component,

- a subset of routines from the RODEX4 code intended for the prediction of fuel thermal-mechanical performance under transient conditions, and

- MB2-K, a neutron kinetics code developed from MICROBURN-B2.

For each proposed application of AURORA-B to a defined subset of the safety analysis required for a BWR, Framatome has submitted a TR describing relevant aspects of the AURORA-B code system along with the overall framework of assumptions, required code modeling options, initial conditions, figures of merit, and so forth. The collective union of these subjects, as described in summary detail in the associated TR, constitutes an application-specific evaluation model. It should be emphasized that, while the same basic code system may support a number of distinct

applications, for each application necessitating a distinct framework of assumptions, modeling options, system nodalizations, figures of merit, etc., a unique evaluation model is typically defined. As noted above, the present review pertains to the AURORA-B evaluation model for analyzing BWR LOCA events in accordance with the methodology prescribed in Appendix K to 10 CFR 50. Thus, this SE will refer to the methodology described in ANP-10332P as the AURORA-B LOCA evaluation model.

Of the three AURORA-B subsidiary components described above, the LOCA evaluation model makes use of only two: S-RELAP5 and the subset of routines from RODEX4 (hereafter referred to as the RODEX4 kernel). ANP-10332P states that a three-dimensional (3D) neutron kinetics method is unnecessary for analyzing the LOCA event, and, in lieu of MB2-K, the AURORA-B LOCA evaluation model relies upon the S-RELAP5 point kinetics model. Consequently, the present review does not cover the MB2-K code. Furthermore, inasmuch as the RODEX4 kernel has been integrated into S-RELAP5, it is accurate to consider the AURORA-B LOCA evaluation model an S-RELAP5-based methodology.

Although the codes supplying initial conditions are not strictly part of the AURORA-B LOCA evaluation model, the evaluation model depends on receiving accurate inputs from these models to function properly; for example:

- Nodal core simulator and lattice physics codes are used to initialize core thermal-hydraulic conditions for steady-state S-RELAP5 simulations and provide inputs to the S-RELAP5 point kinetics model.

    - Framatome's current nodal core simulator code is MICROBURN-B2, and its current lattice physics code is CASMO-4. These codes provide **[** **]** necessary to initialize S-RELAP5 simulations.

    - The XCOBRA code may also be used **[** **]** for initializing S-RELAP5. XCOBRA **[** **]**

- The full version of the RODEX4 code provides inputs to AURORA-B concerning fuel rod material properties, geometry, and long-term effects associated with burnup.

In response to RAI 44, Framatome clarified that core simulator and lattice physics methods used with the AURORA-B LOCA evaluation model must have received prior approval by the NRC staff. The NRC staff considers the use of approved core simulator methods appropriate for assuring the quality of inputs to the AURORA-B LOCA evaluation model. In addition, since **[** **]** from the lattice physics code (currently CASMO-4) are also required inputs to the AURORA-B LOCA evaluation model, such inputs must likewise be taken from an approved method. The NRC staff's position on the provision of inputs to the AURORA-B LOCA evaluation model from an approved core simulator and lattice physics methodology is captured in Section 5.0 of this SE as Limitation and Condition 1.

Furthermore, because (1) ANP-10332P credits RODEX4 **[** **]** used in the

AURORA-B LOCA evaluation model, and (2) the kernel of fuel thermal-mechanical performance routines in AURORA-B is based on RODEX4 models, the NRC staff's acceptance of the AURORA-B LOCA evaluation model is also contingent upon Framatome using the stand-alone version of the RODEX4 code, in accordance with an approved methodology, to supply the initial conditions necessary for modeling fuel rods in the AURORA-B LOCA evaluation model. Framatome confirmed its acceptance of this position in response to RAI 12. Use of the full, stand-alone version of RODEX4 in accordance with an approved methodology to supply fuel performance inputs is captured in Section 5.0 of this SE as Limitation and Condition 2.

1.2 Scope of Application and NRC Staff Review

As will be described in greater detail in Section 3.3 of this SE, a number of aspects of the AURORA-B code system and its component codes are familiar to the NRC staff in connection with previous reviews. While the NRC staff performed a comprehensive review of the AURORA-B LOCA evaluation model described in ANP-10332P and its numerous references, the review concentrated especially on unique aspects of the AURORA-B LOCA evaluation model that had not been previously reviewed and approved for similar applications. In light of the NRC staff's partial reliance on past reviews for similar applications, a discussion of previous NRC reviews associated with the AURORA-B code system and its subsidiary components is in order.

In addition to the AURORA-B LOCA evaluation model reviewed herein, Framatome has recently received approval for two other application-specific AURORA-B evaluation models:

- ANP-10300P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Transient and Accident Scenarios" (Reference 7), describes an AURORA-B evaluation model applicable to many anticipated operational occurrences and several accidents described in Chapter 15 of the SRP (Reference 6). This evaluation model uses a best-estimate approach with a non-parametric statistical method for quantifying uncertainties. The NRC staff issued its SE for ANP-10300P (Reference 8) on January 5, 2018.

- ANP-10333P, Revision 0, AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Control Rod Drop Accident (CRDA)" (Reference 9), describes an AURORA-B evaluation model applicable to the control rod drop accident. The calculational uncertainty is determined according to a simplified statistical methodology. The NRC staff issued its SE for ANP-10333P (Reference 10) on March 15, 2018.

While S-RELAP5 and a kernel of routines from RODEX4 have been incorporated into the AURORA-B code system, versions of these codes also exist as independent entities that have previously been reviewed by the NRC staff and approved for specific applications. Table 1 summarizes past reviews of TRs relevant to the current review.[1]

As stated in ANP-10332P, the AURORA-B LOCA evaluation model is applicable exclusively to BWR designs that incorporate jet pumps internal to the reactor vessel. Among other design functions, internal jet pumps allow reflooding of the reactor core to approximately two-thirds height following the limiting postulated LOCA. Internal jet pumps were first introduced by the

[1] In instances where TRs have multiple revisions or supplements, for brevity, only the most relevant is reflected.

General Electric Company (GE) in the BWR Type 3 (BWR/3) design, and have been included in subsequent operating BWR designs through the BWR Type 6 (BWR/6). The [ ] the scope of ANP-10332P. Similarly, application of the AURORA-B LOCA evaluation model [ ] the scope of the current review.

Table 1: Previous NRC Staff Reviews Pertaining to Subsidiary Components of AURORA-B

Topical Report	Description	Date of NRC Safety Evaluation
EMF-2103P, Revision 3	Realistic large-break LOCA methodology for pressurized-water reactors (PWRs) using S-RELAP5	6/17/16
EMF-2328P	PWR small-break LOCA evaluation model using S-RELAP5	3/15/01
EMF-2310P	Standard Review Plan Chapter 15 non-LOCA methodology for PWRs using S-RELAP5	5/11/01
BAW-10247P	Realistic thermal-mechanical fuel rod methodology for BWRs using RODEX4	2/12/08
EMF-2158P	Evaluation and validation of CASMO-4/MICROBURN-B2 for application to BWRs	10/18/99

Across [ ] of ANP-10332P, the plant response to postulated LOCA events tends to proceed in a fairly similar manner. However, design differences in the emergency core cooling system (ECCS) and recirculation system are relevant; in particular, incorporation of the high-pressure core spray system and slightly reduced recirculation system piping sizes result in enhanced core cooling performance for later BWR designs (Reference 55).

As stated in ANP-10332P, the AURORA-B LOCA evaluation model is intended to support the licensing basis for [ ]. The NRC staff requested in RAI 1 (Reference 3) that Framatome clarify the intent of this statement. Framatome responded that, while defining a "significant departure" is inherently subjective, the AURORA-B LOCA evaluation model is [ ]. Furthermore, Framatome observed that, inasmuch as a licensee's initial implementation of the AURORA-B LOCA evaluation model is envisioned as necessitating a license amendment request, the NRC staff would have opportunity to review such applicability justifications. The NRC staff agrees that plant-specific implementation reviews are an appropriate vehicle for ensuring sufficient consistency of plant licensing bases with the SRP to support application of the AURORA-B LOCA evaluation model.

As stated in ANP-10332P, the AURORA-B LOCA evaluation model is not intended for containment analysis; in fact, an atmospheric boundary condition is assumed in ANP-10332P in lieu of a mechanistic containment model. Framatome suggested, [

]

Similar to a condition imposed previously on implementation of ANP-10300P, the NRC staff determined that the AURORA-B LOCA evaluation model may not be used to perform analyses that result in any of its constituent components or supporting codes (i.e., S-RELAP5, RODEX4 kernel, RODEX4, core simulator and lattice physics codes) being operated outside limits of approval documented in their respective TRs, SEs, code manuals, and plant-specific licensing applications. This position is documented as Limitation and Condition 3 in Section 5.0 of this SE.

1.3 Evolution of Appendix K LOCA Methodologies

To place the NRC staff's review of the AURORA-B LOCA evaluation model into perspective, it is worth reflecting upon the conservatisms traditionally associated with Appendix K LOCA methods. According to NUREG-1230, which compiles research supporting the 1988 revision to 10 CFR 50.46 to permit realistic LOCA analysis methods, the conservative margin in Appendix K-based methods has traditionally been expected to be quite substantial, with estimates ranging from several hundred to one thousand degrees Fahrenheit (°F) (Reference 13).

The conservatism of previously approved Appendix K LOCA evaluation models has typically arisen from two distinct sources: (1) requirements imposed directly in Appendix K to 10 CFR 50 and (2) discretionary conservatisms not specifically required by Appendix K that were adopted as practical simplifications, for example, due to computational or state-of-knowledge limitations.

In fact, a limited set of key models is directly prescribed in Appendix K as required features, such as the Baker-Just correlation for the metal-water reaction, the Moody model for two-phase critical flow, and the proposed 1971 American Nuclear Society 5.1 standard with a multiplier of 1.2 for decay heat. Whereas, in most other areas of the analysis, including those for which Appendix K defines certain features as acceptable (but not required), vendors are permitted to propose other models they can demonstrate to be acceptable.

Framatome's AURORA-B LOCA evaluation model relies upon a modified version of a thermal-hydraulic code originally developed for best-estimate analysis of PWRs (i.e., S-RELAP5) to perform BWR LOCA calculations according to Appendix K. While all required Appendix K conservatisms would be maintained, the increased sophistication of the AURORA-B LOCA evaluation model would overcome some limitations associated with previous generations of LOCA evaluation models through the use of more complex models and techniques (e.g., a **[** **]**, non-equilibrium thermodynamic modeling, etc.). In addition to reducing conservatism, experience shows that the increased complexity of modern analytical methods may result in increased susceptibility to variations in code output from nominal input changes. On the other hand, in light of NRC staff comments on previous reviews, Framatome has proposed an **[**

[2,3]

[2] The **[**

] LOCA evaluation model for BWRs (e.g., Reference 60).

[3] According to EMF-2361(P)(A) (Reference 16), this pressure is **[** **]**.

].

The net effect of these changes is not obvious *a priori*. Therefore, this SE (e.g., in Section 3.6) will attempt to illustrate the impacts of these countervailing effects by providing an indication of the overall conservatism of the AURORA-B LOCA evaluation model.

2.0 REGULATORY EVALUATION

2.1 Applicable Regulatory Requirements

The AURORA-B LOCA evaluation model is a methodology **[ ]** for demonstrating compliance with specific requirements in 10 CFR 50.46 concerning the core cooling performance of light-water reactors during a postulated LOCA event. Among the requirements of 10 CFR 50.46, several are particularly worthy of mention:

- Each light-water power reactor licensee using uranium oxide fuel clad with certain types of zirconium alloy[4] must perform analysis of core cooling performance under postulated LOCA conditions using an acceptable evaluation model.

- An acceptable LOCA evaluation model must be used that either applies realistic methods with an explicit accounting for uncertainties or follows the prescriptive, conservative requirements of Appendix K to 10 CFR 50.

- Core cooling performance must be analyzed for a number of postulated LOCAs of different sizes, locations, and other characteristics to ensure that the most severe event is calculated.

- According to 10 CFR 50.46(b), for the most severe postulated LOCA event, the calculated performance of the ECCS must demonstrate that

    - the peak cladding temperature does not exceed 2200 °F,

    - the calculated local cladding oxidation does not exceed 17 percent of the cladding thickness prior to oxidation,

    - the total amount of hydrogen generated from the metal-water reaction is limited to 1 percent of the hypothesized theoretical maximum,

    - the reactor core is maintained in a coolable geometry, and

    - sufficient long-term core cooling is provided to maintain an acceptable core temperature.

[4] 10 CFR 50.46(a)(1)(i) strictly applies to each "boiling or pressurized light-water reactor fueled with uranium oxide pellets within cylindrical zircaloy or ZIRLO cladding…." However, by means of exemptions, the requirements of 10 CFR 50.46 are currently in effect for all operating (light-water) power reactors, regardless of the specific (zirconium-based) cladding alloy in use.

In lieu of developing best-estimate physical models and explicitly accounting for uncertainty, Framatome has proposed the AURORA-B-based methodology in ANP-10332P as a LOCA evaluation model for performing calculations to demonstrate compliance with 10 CFR 50.46 according to the prescriptive, conservative requirements of Appendix K to 10 CFR 50. In particular, as described in Section 4.4 of ANP-10332P, the AURORA-B LOCA evaluation model provides calculated results for three figures of merit (peak cladding temperature, maximum local cladding oxidation, and core-wide cladding oxidation) for comparison with the quantified regulatory limits in 10 CFR 50.46(b)(1)-(3). As the Commission stated in its opinion regarding the rulemaking hearing on ECCS acceptance criteria (Reference 14), the purpose of the first two criteria (peak cladding temperature and maximum local cladding oxidation) is to ensure that the fuel cladding would remain sufficiently intact to retain the fuel pellets in a rod array configuration that constitutes a coolable geometry. Thus, the AURORA-B LOCA evaluation model is further capable of determining compliance with the qualitative requirement to maintain the reactor core in a coolable geometry.

With regard to the final criterion from 10 CFR 50.46(b), ANP-10332P states that demonstration of adequate long-term core cooling is beyond the scope of the AURORA-B LOCA evaluation model. ANP-10332P further indicates that adequate long-term core cooling is demonstrated for BWRs **[** **]** via reference to a generic analysis demonstrating that, with two-thirds core coverage, the upper third of the core can be adequately cooled by a combination of core spray and steam cooling. Such demonstration has been previously provided, for instance, in GE TR NEDO-20566A (Reference 15). The NRC staff **[**

].

Appendix K to 10 CFR 50 consists of two parts, the first of which specifies required and acceptable features of LOCA evaluation models, and the second of which specifies documentation required for LOCA evaluation models. In particular, Appendix K specifies requirements for modeling significant physical phenomena throughout all phases of the LOCA event, including relevant heat sources, fuel rod performance, and thermal-hydraulic behavior. Conformance to Appendix K is fundamental to the acceptability of the AURORA-B LOCA evaluation model; as a result, this topic will be addressed at various junctures throughout this SE and summarized in Section 6.2.1.

An additional, fundamental regulatory requirement relevant to ECCS performance that is generally included in the licensing bases of operating power reactors is General Design Criterion (GDC) 35 from Appendix A to 10 CFR 50.[5] The GDC of Appendix A to 10 CFR 50 were finalized in 1971 (approximately three years prior to the issuance of 10 CFR 50.46 and Appendix K), and they outline criteria for the design of nuclear power plants in broad, qualitative terms. In particular, GDC 35 requires abundant core cooling sufficient to (1) prevent fuel and cladding damage that could interfere with effective core cooling and (2) limit the metal-water reaction on the fuel cladding to negligible amounts. GDC 35 further requires suitable redundancy of the ECCS, such that it can accomplish its design functions, assuming a single failure, irrespective of whether its electrical power is supplied from offsite or onsite sources.

[5] Alternatively, some plants may be licensed to a proposed draft or plant-specific criterion with a similar intent.

Finally, Sections 2.5.1 and 4.4 of ANP-10332P indicate that the AURORA-B LOCA evaluation model may be applied, without substantial modification, for demonstrating compliance with proposed rule 10 CFR 50.46c (Reference 61). **[**

]

2.2 Relevant Regulatory Guidance

In its review of the AURORA-B LOCA evaluation model, the NRC staff consulted regulatory guidance relevant to (1) the LOCA event and (2) the development and assessment of analytical evaluation models. Guidance on these topics is provided in both the SRP, which assists the NRC staff in performing consistent and predictable regulatory reviews, and in regulatory guides that provide licensees and vendors recommended approaches for complying with NRC regulations.

The most relevant chapters of the SRP consulted by the NRC staff during its review of ANP-10332P include

- Chapter 15.0, Revision 3, "Introduction – Transient and Accident Analysis,"

- Chapter 15.0.2, Revision 0, "Review of Transient and Accident Analysis Methods," and

- Chapter 15.6.5, Revision 3, "Loss-of-Coolant Accidents Resulting from Spectrum of Postulated Piping Breaks Within the Reactor Coolant Pressure Boundary."

Chapters 15.0 and 15.6.5 of the SRP present guidelines for the review of safety analyses and corresponding analysis methods, affirming the regulations discussed above and generally providing additional recommendations regarding how compliance may be demonstrated. Additional key guidelines from these chapters relevant to the LOCA event that are not specifically mentioned above include

- allowing credit only for safety-related equipment,

- carrying out analyses until the core has been recovered with a two-phase mixture and cladding temperatures have been reduced to near saturation conditions,

- presenting appropriate analyses to support any credit taken for control rod insertion, and

- demonstrating consistency of calculated results with previous calculations performed by the NRC staff or vendors.

In addition, Chapter 15.0.2 of the SRP identifies key review areas for transient and accident analysis methods that are relevant to the current review, namely:

- the documentation for the evaluation model,
- the evaluation model itself, which typically consists of computer codes and the complete framework of inputs and assumptions necessary to perform licensing-basis analyses,
- the identification of the accident or transient sequence, the ranking of relevant phenomena, and determination of modeling requirements,
- the assessment of the evaluation model against applicable experimental data or exact mathematical solutions,
- assurance that calculational uncertainties are bounded, either through an explicit uncertainty analysis (for best-estimate methods), or through the use of a prescriptive method with adequate built-in conservatism (i.e., Appendix K to 10 CFR 50), and
- the quality assurance plan for the evaluation model.

The topical structure of this SE derives from these key review areas from Chapter 15.0.2 of the SRP. However, the sequence has been modified to present information in the most logical and comprehensible order possible.

Relevant regulatory guides consulted by the NRC staff in its review of ANP-10332P include

- Regulatory Guide (RG) 1.157, May 1989, “Best-Estimate Calculations of Emergency Core Cooling System Performance” (Reference 18)
- RG 1.203, December 2005, “Transient and Accident Analysis Methods” (Reference 19)

RG 1.157 provides guidance related to best-estimate analysis of the LOCA event in a format that closely follows Appendix K. Because the AURORA-B LOCA evaluation model is an Appendix K method, RG 1.157 was not directly used in the review.

On the other hand, ANP-10332P identifies that the evaluation model development and assessment process (EMDAP) described in RG 1.203 was followed in developing the AURORA-B LOCA evaluation model. The EMDAP consists of four elements, each with a number of subsidiary steps. Framatome’s rationale that the AURORA-B LOCA evaluation model complies with each element in the EMDAP is documented in ANP-10332P. Inasmuch as ANP-10332P is further structured in accordance with the EMDAP, this process is diagrammed in Figure 1 below, which has been adapted from RG 1.203.

Another relevant aspect of RG 1.203 that deserves emphasis is the graded approach recommended in Appendix B therein for reviewing a proposed new application for a code system that has previously been reviewed in a different context. As discussed above, the AURORA-B code system and its component parts have been the subject of a number of past NRC staff reviews, which has permitted simplification of the present review with focus on novel features and application-specific topics, as discussed further in Section 3.3 of this SE.

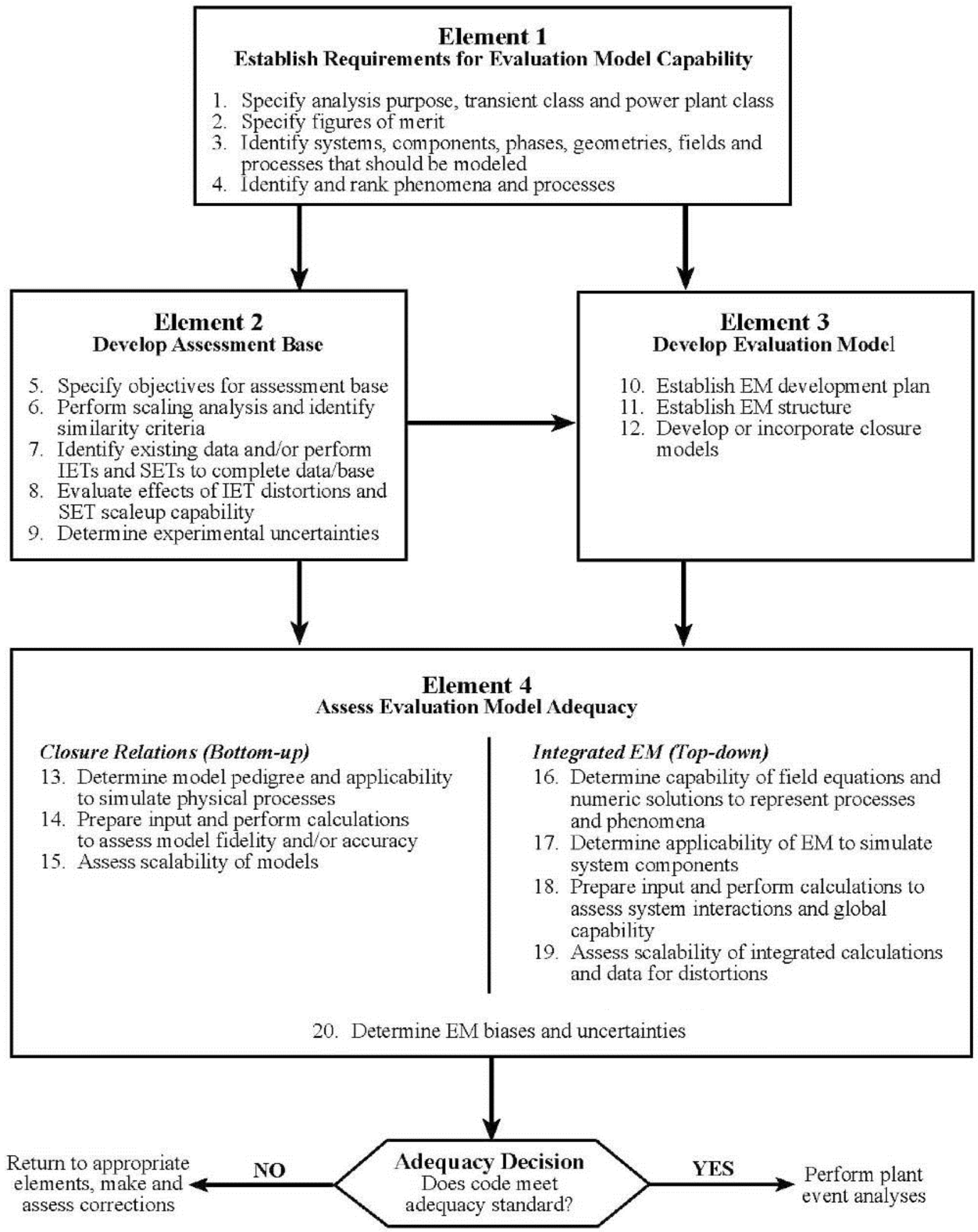

Figure 1: The Evaluation Model Development and Assessment Process[6]

6 Abbreviations in figure:
EM evaluation model
IET integral effects test
SET separate effects test

RG 1.203 further allows that the degree of assessment required for the evaluation model may be reduced if the documented degree of conservatism is large or if the new model can be shown **[ ]** than the previous model. Inasmuch as the AURORA-B LOCA evaluation model was developed to conform to the conservative requirements of Appendix K rather than as a best-estimate model, a reduction in the degree of rigor when assessing against the EMDAP criteria is justified. A comparison of the results of the proposed AURORA-B LOCA evaluation model with those of the currently approved evaluation model (EXEM BWR-2000 (Reference 16)), discussed further in Section 3.6.4 of this SE, **[ ]**.

3.0 TECHNICAL EVALUATION

3.1 Overview of BWR LOCA Event

A LOCA event involves a pressure boundary breach that results in an uncontrolled blowdown of reactor coolant at a rate in excess of the normal makeup capacity. According to 10 CFR 50.46, the maximum postulated size of a LOCA is the double-ended rupture of the largest pipe in the reactor coolant system. Consistent with the nomenclature of Appendix K to 10 CFR 50, a LOCA event is traditionally divided into three phases; for a BWR these phases are typically defined as follows:

- blowdown, which begins when a pressure boundary breach results in a loss of reactor coolant and uncontrolled reactor depressurization,
- refill, which begins when the reactor pressure has **[ ]**, and
- reflood, which begins **[ ]**.[7]

In retrospect, division of the LOCA event into these sequential, neatly defined phases **[ ]**. In particular, **[ ]**.[8] Hence, **[ ]**.

The sequence of events for a given LOCA scenario depends upon the location of the pressure boundary breach and the rate at which reactor coolant is lost. In a BWR, piping ruptures may be postulated on various systems, such as recirculation, feedwater, main steam, and ECCS. Previous analyses typically indicate that ruptures on recirculation piping are among the most

[7] As noted above, the **[ ]** reflooding the reactor core to at least two-thirds core height.

[8] Subsequent to the promulgation of Appendix K, such behavior was demonstrated, for example, by integral testing performed in the Steam Sector Test Facility.

severe postulated events; hence, this scenario is selected as an example for this introductory discussion. With the understanding that the spectrum of postulated LOCA events encompasses conditions other than piping ruptures (e.g., stuck-open, unisolable valves), as a convenience, the spectrum of BWR LOCA events is described conventionally below according to break size categories.

3.1.1 BWR Large-Break LOCA

A double-ended guillotine break on recirculation system piping (e.g., with a maximum total flow area on the order of 5-7 square feet (ft^2)) is typically among the most limiting LOCA events postulated for a BWR. This hypothetical event results in a rapid discharge of coolant through both ends of the ruptured pipe, which can depressurize the reactor from over 1000 pounds per square inch absolute (psia) to less than 100 psia in less than a minute. The analyzed set of large-break LOCA events encompasses large split breaks and double-ended guillotine breaks with an appropriate range of discharge coefficients.[9]

The rapid depressurization of the reactor following a large-break LOCA results in immediate flashing of saturated liquid in the core. This rapid vapor formation, along with the insertion of control rods, terminates the fission chain reaction within seconds of the piping rupture. As the reactor pressure continues to fall, the slightly cooler water in the lower plenum begins to flash, resulting in an updraft of two-phase flow through the reactor core. The consequent reactor power decrease, coupled with high core flow rates and decreasing saturation temperatures induced by the rapid depressurization, initially results in a reduction in fuel cladding temperature. This decrease, however, is short-lived; as the pressure and liquid fraction in the core continue to decrease, heat transfer to the two-phase coolant mixture becomes less efficient, and the fuel cladding begins to heat up. Under the limiting single-failure assumption, heatup of the fuel cladding may continue for a few of minutes in high-powered fuel bundles until it is turned around, typically by the injection of coolant from low-pressure ECCS pumps.

Further discussion and example traces for reactor pressure, cladding temperature, and other key parameters for a BWR large-break LOCA may be found in Sections 7.7.4 and 7.7.6 of ANP-10332P. Section 4.2.5 of NUREG-1230 (Reference 13) provides additional discussion of interest.

3.1.2 BWR Small-Break LOCA

Small split breaks could result in limiting conditions for some BWRs, particularly in the event that a top-peaked axial power distribution is assumed. Compared to the large-break LOCA event discussed above, the greatly reduced flow area for a small-break LOCA (e.g., on the order of 0.1 ft^2) results in the reactor blowing down over a significantly expanded time scale.

For the small-break LOCA event, the timings of the reactor scram and isolation of the main steam system, among other events, depend upon offsite power availability. In the case that a loss of offsite power is assumed, reactor scram and isolation will occur early in the event due to the loss of normal power. With offsite power available, reactor scram and isolation signals would eventually occur after the reactor protection system senses abnormal conditions (e.g., low reactor water level). Unlike the large-break LOCA event discussed above, a

[9] Although the event timescale for such breaks would be mildly dilated due to a reduction in flow area (or effective flow area), at the level of the present discussion, the overall system response is similar.

significant reactor depressurization will not immediately occur for the small-break LOCA. In fact, because the rate of energy removal from a break on the order of 0.1 ft^2 may be less than the post-trip decay heat power, isolation of the main steam system may cause an increase in reactor pressure sufficient to lift safety/relief valves that vent to the suppression pool.

Even if the reactor does not significantly depressurize initially, the loss of coolant from the break will result in a decreasing trend for reactor vessel water level. This decreasing level trend will eventually result in the actuation of a high-pressure ECCS pump that, if available, would typically be capable of mitigating such an event without an extensive cladding temperature excursion. Hence, the single failure assumed for a small-break LOCA generally involves failure of the high-pressure ECCS pump, which results in a further level decrease and actuation of the automatic depressurization system after the expiration of a delay period (e.g., two minutes).

Depending upon the size of the break, the continued loss of reactor coolant during the delay period prior to actuation of the automatic depressurization system may result in partial uncovery and heatup of the reactor core. This initial core temperature rise tends to be mitigated by a significant flashing-induced updraft of the two-phase mixture in the vessel in response to the opening of safety/relief valves by the automatic depressurization system. However, similar to the case of the large-break LOCA scenario discussed above, the pressure and liquid fraction in the reactor vessel continue to fall; as the rate of flashing slows, heat transfer becomes less effective, and a renewed core heatup occurs. As in the large-break LOCA scenario discussed above, core heatup in the limiting small-break LOCA scenario is typically turned around by the injection of coolant from low-pressure ECCS pumps.

Further discussion and example traces for reactor pressure, cladding temperature, and other key parameters may be found in Sections 7.7.4 and 7.7.6 of ANP-10332P.

3.1.3 BWR Intermediate-Break LOCA

The plant response to piping ruptures in a size range between the small- and large-break LOCA scenarios discussed above may be governed by behaviors from either or both of the preceding sections. Hence, additional phenomenological discussion for intermediate breaks is not necessary. The results from the demonstration case scenarios in ANP-10332P generally showed intermediate-break LOCA cladding temperatures below those of the limiting large and small breaks; however, in many cases peak cladding temperatures were of a comparable magnitude. Hence, it is clear that the intermediate region must be analyzed to assure that the globally limiting result has been calculated.

3.2 Identification and Ranking of Relevant Phenomena

According to the EMDAP shown above in Figure 1, prior to undertaking development of the evaluation model itself, phenomena relevant to the event of interest should be ranked according to their expected importance relative to the defined figures of merit. Introductory discussion in foregoing sections of this SE has already established

- accident scenarios and plant types within the intended scope of application (i.e., the entire spectrum of postulated LOCA events for BWR/3-6 plants), and

- figures of merit (i.e., peak cladding temperature, maximum local cladding oxidation, and core-wide cladding oxidation).

Prior to ranking the phenomena relevant to the scenarios of interest, the EMDAP calls for consideration of the systems, components, phases, geometries, fields, and processes that should be included in the model to accomplish the intended objective. Framatome addresses this topic in Section 4.5 of ANP-10332P, as summarized below in Table 2.

Table 2: Summary of Modeling Requirements for the AURORA-B LOCA Evaluation Model

Model Feature	AURORA-B Modeling Capability
Systems, subsystems and modules	The BWR primary system and connected components, including the reactor core and vessel internal geometry and structures, the recirculation system, the ECCS, safety/relief valves, reactor protection system, etc.
Constituent Fluids	Water, noncondensable gas
Fluid Phases	Liquid and vapor phases of water, noncondensable gas
Two-Phase Flow Configurations	Both wet-wall and dry-wall vertical flow regimes are necessary. In addition, wet-wall horizontal flow configurations with stratification must be considered. The specific flow regimes in S-RELAP5 are documented in the code theory manual (Reference 11) and are similar to those of the RELAP5 code.
Field Quantities	S-RELAP5 uses a six-equation, two-fluid formulation for modeling two-phase flow, which includes field equations for mass, momentum, and thermal energy for each fluid phase (i.e., liquid and vapor). In addition, thermal conduction equations are provided to model the temperature of heat structures (e.g., fuel rods and structural metal).
Transport Processes	Numerous process models exist to support the calculation of mass, momentum, and energy transport in S-RELAP5. These processes are summarized in Section 4.5 of ANP-10332P, and discussed further in Section 3.3.1.2 of this SE.

The modeling capabilities discussed above for the AURORA-B LOCA evaluation model do not capture phenomena associated with post-LOCA debris, including its transport, accumulation, and potential for restricting coolant flow to the reactor core. The evaluation model in fact assumes the coolant to be pure water. Consequently, this SE does not review the capability of the AURORA-B LOCA evaluation model for simulating the potential impacts of post-LOCA debris.

As observed in RG 1.203, all phenomena and processes that occur during a transient or accident scenario do not have equal influence on the determination of the intended figures of merit. As such, a systematic method for identifying relevant phenomena and processes and ranking them according to their expected influence promotes the effectiveness and rigor of the code development and assessment processes. To this end, as Framatome has done in support of ANP-10332P, a group of knowledgeable individuals is empaneled to use its collective judgment to identify and qualitatively rank phenomena according to their expected importance (e.g., high, medium, low) for the event of interest. The results of this process are generally tabulated, culminating in a phenomenon identification and ranking table (PIRT).

Framatome presented PIRT results for the AURORA-B LOCA evaluation model in Table 4-1 of ANP-10332P. The PIRT results are intended to characterize **[** **]**. In accordance with RG 1.203, Framatome has broken out its PIRT results according to both space (i.e., specific systems and components, such as the reactor core, core bypass region, and recirculation system) and time (i.e., the three defined phases of the LOCA event,

namely, blowdown, refill, and reflood). Condensed results for Framatome's PIRT exercise showing the maximum ranking for each phenomenon across all three phases of the LOCA event are provided below in Table 3.

Table 3: Condensed PIRT Results for the AURORA-B LOCA Evaluation Model

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	[10]		

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[10] Note that Framatome ranked core power distribution **[**

].

[

1

2

		[11]	

3

4

5

6

7]

[11] As clarified in Framatome’s response to RAI 6, this phenomenon is **[**
].

[

]

According to RG 1.203, PIRT results are intended to guide the uncertainty analysis and assessment of overall evaluation model adequacy. Inasmuch as the AURORA-B LOCA evaluation model is intended to conform to Appendix K, an explicit accounting of calculational uncertainties is not required. However, Framatome does use the PIRT results in its demonstration of overall evaluation model adequacy; in particular, the PIRT results form the basis for determining which phenomena and processes should be validated under the code assessment process. As shown in Table 5-1 of ANP-10332P, Framatome attempted to assess the AURORA-B LOCA evaluation model's predictions for each highly ranked phenomenon using one or more validation comparisons.

As addressed in RAI 5, the NRC staff's review of Framatome's PIRT results in Table 4-1 of ANP-10332P identified several areas where additional justification was necessary regarding the general process used to arrive at the PIRT determinations:

- Framatome provided **[** **]** break locations and sizes.

- Framatome applied **[** **]**

Framatome responded to RAI 5 by affirming that the PIRT **[** **]**. Framatome further stated **[** **]** in the PIRT results presented in ANP-10332P. Additionally, in some cases, Framatome **[** **]**. While the NRC staff considered Framatome's response appropriate, verification of the final, composite PIRT results presented in ANP-10332P was **[** **]**. However, based on comparisons of Framatome's results against other relevant PIRT evaluations for the BWR LOCA event, the NRC staff ultimately concluded that, in general, Framatome's PIRT process has satisfactorily considered the range of postulated breaks and relevant plant design features.

That being said, as pointed out in RAI 7, the NRC staff's detailed review of Framatome's PIRT results identified several potential exceptions to the above generalization, wherein the phenomenon rankings determined by Framatome did not appear to have been sufficiently justified. The additional information provided in response to RAI 7 generally addressed the NRC staff's concerns. **[**

], the NRC staff ultimately concluded that these rankings do not adversely affect the AURORA-B LOCA evaluation model. In particular, as discussed further below, the NRC staff reviewed Framatome's PIRT results only to the degree required to assure adequate validation of the conservative Appendix-K-based method under review. Considering available evidence that the AURORA-B LOCA evaluation model **[** **]**, as well as the demonstrated conservatism of the AURORA-B LOCA evaluation model (as discussed further below in Section 3.6), the NRC staff concluded that the concerns underlying RAI 7 have been addressed.

Framatome specified in Section 4.6 of ANP-10332P that highly ranked PIRT items must be validated against experimental data. **[** **]**. In particular, Appendix K to 10 CFR 50 prescribes in a number of places that certain phenomenological models shall be compared against adequate experimental data.

Furthermore, Appendix K requires that, to the extent practicable, predictions of the evaluation model, or portions thereof, shall be compared with applicable experimental information. Although validation of **[** **]**. Therefore, the NRC staff addressed RAI 8 to Framatome regarding this topic.

Framatome responded by stating that the AURORA-B LOCA evaluation model **[** **]**. Framatome noted that **[** **]**. Framatome's response further listed **[** **]** in the evaluation model and provided additional explanation regarding 3 of the 16 phenomena.

From the NRC staff's perspective, **[** **]**. In evaluating the response to RAI 8, the NRC staff **[** **]**:

- Framatome **[** **]**

- Framatome **[** **]**, the NRC staff concluded that Framatome's overall treatment of these items is appropriate as follows:

    - S-RELAP5 uses **[** **]** similar to RELAP5/MOD2 and /MOD3, and which has been reviewed by the NRC staff in conjunction with previous S-RELAP5 applications.

    - Conservative **[** **]**.

    - The time required for **[** **]** from the plant technical specifications.

In considering Framatome's response to RAI 8, the NRC staff concluded **[** **]** are effectively mitigated for the AURORA-B LOCA evaluation model by several factors, including (1) the **[** **]**, (2) the **[** **]** in Framatome's PIRT (as reflected in the **[** **]**, and (3) the NRC staff's previous review of Framatome's methods for modeling certain phenomena (**[** **]**). Therefore, while the NRC staff **[** **]**, the mitigation described above ensures that the evaluation model treats such phenomena with **[** **]**.

In an overall sense, although the level of detail, justification, and documentation associated with Framatome's PIRT effort for the AURORA-B LOCA evaluation model is **[** **]** provided adequate to support the assessment and validation of the conservative Appendix K-based method under review. Having reached this determination, the NRC staff **[** **]** for the following reasons:

- Although **[** **]**.

- Although the **[** **]**.

- Although the **[** **]**.

Therefore, the NRC staff **[** **]**, Appendix K-based AURORA-B LOCA evaluation model described in ANP-10332P. **[**

].

3.3 Evaluation Model Development

As described in RG 1.203, evaluation model development involves establishing the structure of the supporting code system, temporally and spatially coupling all constituent codes, deriving field equations, selecting compatible closure relationships, applying appropriate numerical solution techniques, and developing control logic and additional supporting capabilities. Section 6.0 of ANP-10332P provides a description of the development of the AURORA-B LOCA evaluation model using the EMDAP format of RG 1.203.

Section 1.1 of this SE introduced the constituent parts of the AURORA-B code system, of which S-RELAP5 and RODEX4 are germane for the LOCA evaluation model. The basic structure of the AURORA-B code system is illustrated schematically below in Figure 2, which is adapted from the S-RELAP5 code theory manual (Reference 11).

Figure 2: Schematic of AURORA-B Code Structure

Previous NRC staff reviews of immediate relevance to the AURORA-B code system and its constituent codes have been noted above in Section 1.2. These previous reviews, as well as additional background information that will be discussed further below regarding the historical development of the S-RELAP5 code, have already established the fundamental soundness of

many aspects of the AURORA-B code system for performing thermal-hydraulic calculations for demonstrating reactor safety. Therefore, while this SE will attempt to touch upon all fundamental aspects of the AURORA-B code system, the main thrust of the NRC staff's present review will be on (1) new or modified parts of the evaluation model and (2) existing models especially significant to the prediction of the figures of merit for a BWR LOCA event.

3.3.1 Overview of S-RELAP5 Models and Correlations

As described in Framatome's S-RELAP5 code theory manual (Reference 11), the ancestry of the current version of the S-RELAP5 code in the AURORA-B LOCA evaluation model can be traced back to **[ ]**. The immediate forerunner to S-RELAP5 was the ANF-RELAP code, which was **[ ]**. The ANF-RELAP code was based on the **[ ]**. Siemens Power Corporation subsequently developed the ANF-RELAP code into S-RELAP5, and, around the turn of the century, submitted S-RELAP5-based methods for PWR LOCA and non-LOCA thermal-hydraulic safety analyses (References 21, 22, 23). The effort to develop S-RELAP5 involved a significant number of improvements to the code structure to **[ ]**. A number of enhancements to physical modeling capabilities were also made, including the adaptation of **[ ]**.

According to ANP-10332P, development of the S-RELAP5 code version employed in AURORA-B began with the version used in the Realistic Large Break LOCA methodology in EMF-2103(P)(A) (Reference 25). Numerous changes were necessary to transform this version of S-RELAP5 into a code capable of performing safety analyses for BWRs under an AURORA-B evaluation model. As described in ANP-10300P, by 2009, Framatome developed a version of S-RELAP5 capable of analyzing BWR non-LOCA events. Significant code modifications associated with this effort are summarized below:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

The NRC staff has previously found these changes to S-RELAP5 acceptable, as applied to the analysis of anticipated operational occurrences and certain non-LOCA accidents for BWRs (Reference 8). In the present review, the NRC staff has reconsidered these models, where appropriate, to ensure model applicability and assessment adequacy under LOCA conditions.

Further modifications were necessary to support modeling the BWR LOCA event according to Appendix K to 10 CFR 50. Listed below is a selection of relevant changes Framatome has implemented in the USEP12 version of S-RELAP5, as discussed in Section 8.2 of ANP-10332P, the S-RELAP5 code theory manual (Reference 11), and Framatome's response to RAI 14 (Reference 5):

1. **[ ]**
2. **[ ]**
3. **[ ]**

4. **[ ]**
5. **[ ]**
6. **[ ]**
7. **[ ]**
8. **[ ]**
9. **[ ]**
10. **[ ]**
11. **[ ]**
12. **[ ]**
13. **[ ]**
14. **[ ]**
15. **[ ]**

According to Chapter 15 of the SRP and RG 1.203, an analytical evaluation model submitted for NRC review should be “frozen” (i.e., placed in a controlled, unchangeable state) during the NRC staff’s review period; **[ ]**. This decision was motivated **[ ]**:

16. **[ ]**
17. **[ ]**

As alluded to in RAI 28, the NRC staff viewed Framatome’s request for approval of the AURORA-B LOCA evaluation model **[ ]**. Therefore, in RAIs 15, 28, 51, and 126, the NRC staff requested that Framatome provide additional descriptions and justification for **[ ]**.

While Framatome was responsive to these requests, the **[ ]** in later sections of this SE covering the evaluation model assessment, sensitivity studies, and demonstration analyses.

The discussion below concerning S-RELAP5 and the RODEX4 kernel is intended to serve as a general review of code modeling practices, with a focus on new models and other models of

significance to the LOCA event. While both the S-RELAP5 field equations and closure relations will be discussed below, the NRC staff's review focus was mainly on the latter. As discussed further below, although S-RELAP5 **[ ]**, the NRC staff expects the basic S-RELAP5 field equations and numerical methods to be sufficiently general to extend to this application. On the other hand, a **[ ]**.

3.3.1.1 S-RELAP5 Field Equations

The S-RELAP5 code employs non-equilibrium, non-homogeneous, "two-fluid" field equations for determining the thermal-hydraulic behavior of the liquid and vapor phases present in the reactor system (Reference 11). The two-fluid formulation, which is commonly used in modern thermal-hydraulic system codes for reactor safety analysis, involves conservation equations for mass, momentum, and energy for each phase, which results in a total of six field equations. In addition, S-RELAP5 incorporates field equations for noncondensable gas and boric acid.[12]

The S-RELAP5 field equations and their numerical solution methods have been subject to NRC staff review on numerous occasions, as attested to above in Section 1.2. Framatome's S-RELAP5 code theory manual further emphasizes the similarity of the formulation of the two-fluid field equations in S-RELAP5 with those in a number of other codes, including RELAP5/MOD2, RELAP5/MOD3, TRAC-PF1/MOD1, and COBRA/TRAC (Reference 11). While acknowledging this point, the NRC staff **[ ]** S-RELAP5 code theory manual (Reference 11). As discussed further below in Section 4.1, the NRC staff **[ ]**; however, considering past approvals discussed above (in particular the NRC staff's 2001 review of EMF-2328, Revision 0 (Reference 34)), additional discussion of this topic in RAI responses in the 2003 review of EMF-2103, Revision 0[13] (Reference 25), as well as continued indication that the S-RELAP5 field equations are performing adequately over a wide range of PWR and BWR applications, the NRC staff found that the existing evidence firmly supports the formulation of the S-RELAP5 field equations. Section 3.4 of this SE describes the code assessment comparisons presented in ANP-10332P, which offer further evidence of adequacy.

3.3.1.2 S-RELAP5 Closure Relations and Process Models

Owing to the temporal and spatial averaging necessary to support derivation of the two-fluid field equations, as well as the relatively coarse noding implemented in thermal-hydraulic system codes such as S-RELAP5, detailed modeling of physical phenomena occurring at the vapor-liquid interface and near walls is not possible. The two-fluid field equations further do not contain models for all physical behavior and processes of relevance to reactor safety analysis. Hence, many relevant behaviors and processes must be modeled using closure relations and process models that typically have semi-empirical bases and comparatively limited ranges of

[12] Boric acid tracking is not a part of the AURORA-B LOCA evaluation model, and the S-RELAP5 modeling of this phenomenon was not assessed in the present review. Modeling of noncondensable gas **[ ]**.

[13] See in particular the responses to RAIs 45-52.

application. Furthermore, due to the complexity of two-phase flow and the significant differences in physical behavior associated with different flow patterns (e.g., bubbly, slug, annular-mist), different closure relations must typically be defined for each specific flow pattern. The situation is complicated further by the need to assure smooth transitions between the closure relations associated with different two-phase flow regimes to promote code stability.

Proper selection of closure relations and process models is vital to the accuracy of a code's predictions. As alluded to above, while all currently approved applications of the S-RELAP5 code rely on the same basic field equations, the closure relations and process models are generally application-specific. For example, S-RELAP5 contains multiple models for addressing many phenomena, such as critical heat flux, heat transfer in a rod array during core reflood, and choked flow. The analyst is required to select the S-RELAP5 model appropriate to a given application, depending on whether the analysis is to be performed for a BWR or PWR, for a LOCA[14] or non-LOCA event, and under an Appendix K or best-estimate evaluation model. As discussed further below in Sections 3.3.4 and 4.1, the analyst is aided in making appropriate selections by a modeling guidelines document (Reference 26) **[ ]**.

Given the large number of closure relations and process models used in thermal-hydraulic system codes such as S-RELAP5, the discussion below organizes these relationships into broad categories. A general description of the closure relations and process models in each category is summarized in tabular form. Additional discussion is provided in supplementary text where appropriate. Detailed review is generally not provided where previous, applicable reviews have already addressed particular code models. Alternative S-RELAP5 code options to those defined by the AURORA-B LOCA evaluation model are omitted from discussion.

[14] For PWRs, a further distinction exists between the modeling options approved for small- and large-break LOCA analysis.

3.3.1.2.1 Hydrodynamic Closure Relations and Process Models

		[15]
		[16]

[15] Note that this model is essentially **[** **]**.
[16] As noted above, while not directly associated **[**
]

Interphase Heat Transfer

Several minor changes relevant to the BWR LOCA event have been made with respect to modeling interphase heat transfer.[17] These changes are discussed further in Section 3.4.10 of the S-RELAP5 code theory manual (Reference 11):

- A simplified model was added to **[** **]**
- A spray **[** **]**.
- Framatome implemented changes to augment interphase heat transfer **[** **]**

The impacts of these changes will be considered in the assessment and validation effort described in Section 3.4 of this SE. In particular, the **[** **]**.

Choked Flow

As required by Appendix K, the Moody critical flow model is applied at potential choking planes where two-phase flow may occur; in particular, **[** **]**. In response to RAI 25, Framatome confirmed that the **[** **]** for all recirculation line breaks (i.e., both discharge and suction breaks). However, at potential choking planes where two-phase flow is not expected, for example the single-phase-vapor choked flow that may occur through safety/relief valves, particularly during small-break LOCA scenarios, Framatome **[** **]**

[17] Note that the original impetus for some of these changes **[** **]**.

3.3.1.2.2 Heat Transfer and Heat Structure Models

The overall heat transfer logic used for the AURORA-B LOCA evaluation model is provided in Figure 6-16 of ANP-10332P, which was reproduced directly from the S-RELAP5 code theory manual. The basic heat transfer logic therein has been previously reviewed and accepted for other applications, and the NRC staff likewise finds it acceptable for the AURORA-B LOCA evaluation model.[18]

[18] Note, however, that Framatome implemented **[**

].

Critical Heat Flux

As discussed in Section 6.4.10 of ANP-10332P, the AURORA-B LOCA evaluation model uses the 2006 version of the Groeneveld CHF lookup table to compute the critical heat flux according to the thermal-hydraulic conditions determined by the S-RELAP5 code at each simulated fuel rod node. Use of this lookup table method in lieu of fuel-specific correlations is necessary for the LOCA event to permit consideration of a wide range of thermal-hydraulic conditions that extend well beyond those typically considered by fuel-specific correlations that are primarily intended for normal operation.

Framatome intends **[**

]

In RAI 16, the NRC staff requested additional information concerning Framatome's implementation of the 2006 Groeneveld CHF look-up table, including

- justification for the fuel-specific correction factors Framatome proposes to apply to the Groeneveld CHF lookup table, and example values for a specific fuel design,

- clarification of a **[** **]**, and

- explanation of the process by which the AURORA-B LOCA evaluation model computes the inputs to the critical heat flux lookup table and **[** **]**.

Framatome's response to RAI 16 explained that the fuel-specific critical heat flux correction factors were derived from Groeneveld (Reference 46) and Lee (Reference 47). The response further provided correction factor values for the ATRIUM 10 fuel design as a function of time during one of the demonstration case analyses included in Section 7.7 of ANP-10332P. Framatome's response also **[** **]**. Finally, Framatome's response **[**

]

Framatome selected fuel-specific critical heat flux correction factors from different sources. In some cases, **[**

], and additional considerations were necessary. The NRC staff considered

- the [ ] the critical heat flux lookup table output,
- the individual justifications for certain correction factors provided in the supporting references, including References 46 and 47, and
- the common usage of a number of the correction factors [ ].

Based on these additional considerations, the NRC staff generally found the correction factors proposed by Framatome acceptable.

However, [ ] As a result, the NRC staff concluded [ ]. In addition, the NRC staff concluded [ ]. The NRC staff has documented these positions as Limitation and Condition 7 in Section 5.0 of this SE.

The NRC staff's review also [[19]] Furthermore, Framatome provided additional data in its response to RAI 16 showing [ ].

Finally, with regard [

[19] Note that the phrase [ ].

]

[

[20]

]

and

[

]

While a [

]

In conclusion, while the NRC staff ultimately agreed with Framatome's approach for computing critical heat flux, review of Framatome's response to RAI 16 indicates that [ ]. In particular, this determination contributed to the NRC staff's decision to impose Limitation and Condition 7.

[20] Note that the [

]

Minimum Stable Film Boiling Temperature

As discussed in Section 6.4.12 of ANP-10332P, the AURORA-B LOCA evaluation model determines the minimum stable film boiling temperature according to the Groeneveld-Stewart correlation, subject to the restriction on rewetting imposed by Appendix K. Namely, during the blowdown phase of the LOCA event, Appendix K effectively establishes the minimum stable film boiling temperature as 300 °F greater than the saturation temperature. Should the cladding temperature exceed this threshold, Appendix K forbids reestablishment of transition boiling for the remainder of the blowdown phase. Hence, the AURORA-B LOCA evaluation model does not use the Groeneveld-Stewart correlation under such circumstances to justify cladding rewet.

The NRC staff identified several areas where additional information was necessary to complete its review and addressed RAIs 19 and 20 to the topics of (1) assessment of the Groeneveld-Stewart correlation in the specific pressure range of interest to the BWR LOCA event post-blowdown, (2) the difference in behavior at low pressure observed in the two datasets Framatome used to assess the Groeneveld-Stewart correlation (i.e., Groeneveld and Stewart, Winfrith), and (3) the apparent variation in accuracy of predictions of the Groeneveld-Stewart correlation, depending upon the degree of liquid subcooling.

Framatome responded to these RAIs by providing a plot to illustrate the performance of the Groeneveld-Stewart correlation against data in the range of interest for the BWR LOCA event. Framatome's responses further discussed several differences in procedure and setup for the tests Framatome used to assess the performance of the Groeneveld-Stewart correlation that could have contributed to differences in behavior between the datasets. Framatome further emphasized the conservatism of the Groeneveld-Stewart correlation, noting in particular how it was developed from testing with Inconel 600 as opposed to Zircaloy or zirconium oxide, for which Peterson and Bajorek observed increased T_{min} values (Reference 39). In view of this demonstrated conservatism, the NRC staff considered Framatome's responses to the first two issues addressed in RAIs 19 and 20 satisfactory.

Regarding the third item, the NRC staff questioned whether the Groeneveld-Stewart correlation would overpredict T_{min} for subcooled conditions at temperatures of interest to the LOCA event (e.g., 400-480 °C / 750-900 °F, in Figure 6-22 of ANP-10332P). Framatome performed a sensitivity study to illustrate the influence of subcooling on the predictions of the correlation. The study considered two sensitivity cases, **[**

]. The first case included both the saturated and subcooled terms of the Groeneveld-Stewart correlation, and the second case biased the calculated T_{min} downward by neglecting the contribution from the subcooled term. The results of the sensitivity calculations **[**

], the NRC staff found Framatome's response acceptable.

While the NRC staff considered the above issues to have been acceptably addressed, during its review of the sensitivity study described in Framatome's response to RAI 20, the NRC staff **[**

] As a means to probe the issue further, the NRC staff **[**

[21]

] Therefore, the NRC staff imposed Limitation and Condition 8 to **[**

]

Film Boiling

Stable film boiling, which is typically associated with the inverted annular flow pattern, is defined by Framatome as occurring at void fractions less than 0.6. Dispersed flow film boiling is defined as occurring at void fractions between 0.9 and 1.0. No heat transfer to liquid is credited in the dispersed flow film boiling region. **[**

].

Framatome calculates film boiling heat transfer to liquid using the modified Bromley correlation. In S-RELAP5, the modified Bromley correlation is formulated using the Taylor characteristic length, as opposed to the Helmholtz criterion used in some other applications. Framatome noted that the Taylor characteristic length was also implemented in RELAP5. Figure 6-24 in ANP-10332P illustrates minor differences in the heat transfer coefficients calculated using the two criteria, but ultimately concludes that both criteria have been adequately validated by test data. The NRC staff found the proposed approach reasonable, and notes that the adequacy of Framatome's post-dryout heat transfer assessments will be evaluated below in Section 3.4.

[21] The use of **[** **]** is stated to be an empirical correction intended to improve agreement with test data.

The modified Bromley correlation has a long history of wide application for computing film boiling heat transfer to liquid. **[** **]** The NRC staff found Framatome's approach reasonable; in particular, as discussed subsequently, the USEP12 version of S-RELAP5 had **[** **]**

As discussed further in response to RAIs 15 and 51, during the NRC staff's review of ANP-10332P, Framatome **[** **]** Per Section 3.2 of the S-RELAP5 code theory manual (Reference 11), **[** **]**. While the NRC staff found Framatome's **[** **]** improved agreement with experimental results and to result in a slight increase in the conservatism of the predictions. **[** **]**

Vapor Convection

The **[** **]**. In the dispersed flow film boiling regime, **[** **]**. Framatome's rationale **[** **]**, as discussed in Section 7.3.11 of ANP-10332P. Furthermore, a two-phase turbulent heat transfer enhancement is added in the dispersed flow film boiling regime based on the formulation by Drucker and Dhir. When the **[** **]**.

Regarding the use of the Drucker-Dhir correlation, in RAI 124, the NRC staff **[** **]**. The NRC staff further requested that Framatome clarify the

implementation of this correlation, [ ]. Framatome responded to RAI 124 by stating [ ] Subject to further discussion of the film boiling/steam cooling transition criterion below in Section 3.6.2.3, the NRC staff generally found Framatome's response to RAI 124 reasonable.

Radiation Heat Transfer

The basic S-RELAP5 code models for calculating wall-to-fluid and rod-to-rod radiation heat transfer are similar to those the NRC staff reviewed for previously approved PWR Realistic Large Break LOCA evaluation models (References 25 and 54). However, as a result of heat sinks afforded by the channeled fuel bundles surrounded by a bypass region, as well as the incorporation of water rods in many modern fuel designs, radiation heat transfer generally plays a more significant role in the BWR LOCA event.

S-RELAP5 models wall-to-fluid radiation heat transfer based on a model developed by Sun, Gonzales, and Tien (Reference 11). In this model, the vapor-droplet mixture is treated as an optically thin medium, and the wall, droplets, and vapor are regarded as three nodes in an electrical network analogy. Wall-to-fluid radiation is [ ]. The general modeling approach for wall-to-fluid radiation heat transfer was included in previously approved Revisions 0 and 3 of the PWR Realistic Large Break LOCA evaluation model (References 25 and 54).

Wall-to-wall radiation is based upon a simplified view-factor approach that considers whether a line of sight or reflection path exists between the two surfaces of interest. Framatome noted that the S-RELAP5 modeling approach for wall-to-wall radiation is based upon that of RELAP5/MOD3.3. The NRC staff's review found that the code theory manual description regarding wall-to-wall radiation heat transfer in S-RELAP5 is essentially identical to those of both RELAP5/MOD3.3 (Reference 48) and RELAP5-3D (Reference 49). The S-RELAP5 modeling approach for wall-to-fluid radiation heat transfer was previously reviewed in as part of Revision 3 of the approved PWR Realistic Large Break LOCA evaluation model (Reference 54).

Based on its review, the NRC staff obtained confidence in the basic S-RELAP5 code models used to determine radiation heat transfer. However, as appropriate for an Appendix-K-based evaluation model, Framatome's implementation of radiation heat transfer modeling in the AURORA-B LOCA evaluation model incorporates a number of conservatisms. These conservatisms include the [ ] discussed below in Section 3.3.4.2.1.

Reflood Solution

The NRC staff reviewed [ ].

Regarding the **[** **]** However, for the AURORA-B LOCA evaluation model, Framatome **[** **]**. The NRC staff considers this change appropriate, **[** **]**

Regarding **[** **]**. Therefore, the NRC staff imposed Limitation and Condition 37, **[** **]**.

3.3.1.2.3 Component and Control Logic Models

[**]**

Jet Pumps

Prior to incorporation into the AURORA-B code system, S-RELAP5 contained a jet mixer model that could be used for BWR jet pumps. However, to support AURORA-B applications, Framatome **[** **]** Furthermore, Framatome performed additional validation comparisons, which the NRC staff has reviewed below in Section 3.4.2.2.

3.3.1.2.4 Reactor Core Power Models

[ ]

Point Kinetics

The AURORA-B LOCA evaluation model relies upon the point kinetics model to determine fission heat. Use of point kinetics modeling is typical for the LOCA event, and the NRC staff considers this approach appropriate since (1) postulated LOCA events are not predominately governed by coupled neutronic-thermal-hydraulic behavior and (2) the spatial dependence of neutronic behavior is not significant.

Framatome stated that approved lattice physics/core simulator methods (e.g., CASMO-4/MICROBURN-B2 (Reference 40)) will be used to provide input to S-RELAP5 to support implementation of the point kinetics model for fission power as well as the determination of decay heat. Regarding the latter, although, as required, decay heat from fission products is determined according to the proposed American Nuclear Society Standard 5.1 from October 1971, Appendix K does not prescribe a method for determining decay heat from actinides. As an input to determining the decay heat contribution from actinides, Framatome would calculate the capture-to-fission ratio using approved lattice physics/core simulator methods.

In response to RAI 44, Framatome summarized inputs necessary to support the point kinetics model implemented in S-RELAP5. The response further stated that **[**

] The topic of licensee verification of the appropriateness of plant-specific analysis parameters is further addressed at a general level in Limitation and Condition 34. Namely, **[**

]

Metal-Water Reaction

During the NRC staff's review of the AURORA-B LOCA evaluation model, Framatome **[** **]**.[22] In RAI 114, the NRC staff requested that Framatome **[** **]**.

Framatome responded that **[** **]** the AURORA-B code system. In response to the NRC staff's **[** **]**.

The NRC staff considered **[** **]**

Framatome's response to RAI 114 further noted **[**

[22] Although the **[** **]** the proposed AURORA-B LOCA evaluation model.

]

3.3.1.2.5 Fuel Rod Transient Behavior

[

]

Fuel Relocation

ANP-10332P discusses the potential for fuel pellets exposed to high burnup to experience fragmentation, with the resulting fragments having the potential to relocate during the LOCA event into space opened up within a swelled region of fuel cladding. Framatome **[**

].[23] During its initial review of ANP-10332P, the NRC staff identified questions **[**

]

Framatome responded to RAI 10 by **[**

]

[23] A reference containing further information concerning these facilities and fuel relocation phenomena in general is NUREG-2121 (Reference 56).

[

]

3.3.1.3 S-RELAP5 Numerical Methods and Code Stability

A semi-implicit numerical solution scheme is used to solve the hydrodynamic field equations, which is similar to that used in RELAP5/MOD2 and /MOD3. However, as noted above, S-RELAP5 uses algebraic manipulation as opposed to the Gaussian elimination approach for solving the finite-difference equations. The NRC staff's review found the general approach used in S-RELAP5 for the AURORA-B LOCA evaluation model to be consistent with that evaluated in previous applicable reviews, one of which is documented in Section 4.2 of the NRC staff's evaluation of EMF-2328, Revision 0 (Reference 34).

The NRC staff's review of ANP-10332P generally did not find concerns with code stability. **[**

]

3.3.2 Overview of RODEX4 Kernel Models and Correlations

The S-RELAP5 code incorporates several fuel rod modeling options, including RODEX2, RODEX3A, COPERNIC, and RODEX4; selection of the proper option is evaluation-model specific. As noted above, the AURORA-B LOCA evaluation model requires selection of the RODEX4 kernel.

Framatome's general strategy for modeling fuel behavior across various S-RELAP5-based evaluation models, **[**

]

According to the S-RELAP5 code theory manual (Reference 11), **[ ]** of the RODEX4 kernel include

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

The **[ ]** of the RODEX4 kernel include

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**[24]

From its review of the S-RELAP5 code theory manual, the NRC staff **[ ]**, which was previously approved by the NRC staff for use in accordance with the methodology described in BAW-10247P (Reference 27). In response to RAI 14.c, Framatome confirmed this understanding, noting that **[ ]**. Framatome's response further clarified that, since the time of its approval by the NRC staff, no changes have been implemented in RODEX4 that would affect the fuel rod physical models used for the AURORA-B LOCA evaluation model.

In RAI 11, the NRC staff requested that Framatome clarify how the fuel pellet thermal conductivity degradation issue discussed in Information Notice 2009-23 was addressed by the models used in RODEX4 and the broader AURORA-B code system. Framatome responded that the RODEX4 code **[ ]** and concluded that the RODEX4 modeling of thermal conductivity was acceptable.

In RAIs 13.b and 13.c, the NRC staff requested that Framatome address how the calculation of effective gap conductance in the AURORA-B LOCA evaluation model accounts for the effects of dimensional changes of the fuel and cladding, as well as non-uniformity in the fuel-cladding gap

[24] As noted above, **[ ]**.

in the axial and azimuthal directions. Framatome responded **[** **]** The NRC staff found these aspects of the gap-conductance calculation reasonable.

Section 6.3.8 of ANP-10332P states that Framatome intends to **[** **]** and clarify whether this method is considered a part of the AURORA-B methodology.

Framatome responded to RAI 42 **[** [25] **]**

The NRC staff considers Framatome's practices **[** **]**

3.3.3 Coupling of S-RELAP5 and RODEX4 Kernel

The basic coupling scheme employed in the AURORA-B LOCA evaluation model has been previously reviewed by the NRC staff in conjunction with AURORA-B-based methods in ANP-10300P (Reference 7) and ANP-10333P (Reference 9). Furthermore, the practice of coupling thermal-hydraulic and fuel thermal-mechanical codes has long been associated with S-RELAP5. For example, a similar coupling scheme to that shown above in Figure 2 was used in the original version of S-RELAP5 submitted for review in 2000, wherein transient models from RODEX2 were brought into S-RELAP5 for the analysis of PWR events.

[25] Framatome's process for performing plant-specific calculations, **[** **]**, is discussed further below in Section 3.3.5.1.

As illustrated in Section 3.3.5 of the NRC staff's SE on ANP-10300P (Reference 8), the S-RELAP5 thermal-hydraulic module and the RODEX4 transient fuel-performance kernel within the AURORA-B code system need not use identical timestep sizes. The NRC staff's review of ANP-10332P **[**

]. The NRC staff requested that Framatome clarify this issue in RAI 13.a. Framatome responded that the AURORA-B LOCA evaluation model **[**

]. The NRC staff considered this response acceptable because it **[**

].

3.3.4 Modeling Options and Nodalization

Section 6.3.7 of ANP-10332P describes the basic modeling and nodalization practices that Framatome has proposed to use with the AURORA-B LOCA evaluation model. Framatome stated that many modeling practices used for the AURORA-B LOCA evaluation model derive from those used for the AURORA-B AOO evaluation model. However, Framatome has made a number of modeling and nodalization changes to support simulation of the LOCA event.

Analysis of the LOCA event brings into consideration a number of different phenomena that do not arise in the course of normal operations and anticipated transients. The basic S-RELAP5 code models for simulating such phenomena have already been discussed (e.g., post-dryout heat transfer, metal-water reaction, and reflood/quench front modeling). The discussion below concentrates upon modeling practices necessary to satisfy Appendix K to 10 CFR 50 and, more broadly, the evaluation model described in ANP-10332P.

The NRC staff's review observed that the S-RELAP5 code has numerous options for modeling various physical processes, which may be activated or deactivated by the analyst. The NRC staff identified that ANP-10332P **[**

] Therefore, the NRC staff issued RAI 27 requesting, **[**

]

Framatome responded to RAI 27 by **[**

],[26] the NRC staff **[**

[26] Note that, in some cases, the NRC staff's agreement is contingent upon the satisfaction of limitations and conditions specified in Section 5.0 of this SE.

]

3.3.4.1 Modeling Options Relevant to Appendix K Requirements

Sections 3.3.1 and 3.3.2 above discuss significant closure models in the S-RELAP5 code and RODEX4 kernel. In some cases, as has already been discussed, these closure models directly address Appendix K requirements. However, in other cases, the requirements of Appendix K focus on input choices that do not directly concern code models and correlations. This section of the SE is intended to address selected input choices of particular relevance to the conformance of the AURORA-B LOCA evaluation model to required and acceptable features specified in Appendix K to 10 CFR 50. A summary of the conformance of the AURORA-B LOCA evaluation model to the full set of Appendix K requirements is provided in tabular form in Section 6.2.1 of this SE.

3.3.4.1.1 Heat Sources

Appendix K defines the heat sources to be considered for BWRs during a LOCA event as the initial stored energy in the fuel, fission heat, decay heat from fission products and actinides, the metal-water reaction from cladding oxidation, and heat transfer from reactor internals. Key issues examined during the NRC staff's review of LOCA heat sources are described below.

<u>Axial Power Profiles</u>

Framatome proposed that the AURORA-B LOCA evaluation model **[**

]

Furthermore, during the May 2017 audit, **[**

] within the scope of the AURORA-B LOCA evaluation model.

Framatome responded **[**

]. Framatome's response to RAI 38 **[**

] Framatome's response further **[**

]

The NRC staff **[**

[27]

]

Meanwhile, as this information came to light, the NRC staff **[**

] In response to RAI 111, Framatome stated **[**

].[28] In particular, **[**

].[29] Framatome stated that, **[**

]. Framatome's response to RAI 111 provided results for a BWR/4 demonstration case that was re-run using the UMAR16 version of S-RELAP5. For the sample case considered in the response, **[**

]

Based upon the discussion above, the NRC staff **[**

[27] See further discussion on this topic in Section 3.6.

[28] This modeling practice is discussed further below in Section 3.3.5.7.

[29] Whereas, the recirculation discharge isolation valves in the BWR/3-4 design are signaled to fully close post-LOCA (1) in the intact recirculation loop for plants with loop-select logic, and (2) in both recirculation loops for plants without loop-select logic.

] Furthermore, in several important assessment and sensitivity analyses [

] This position is documented as Limitation and Condition 10 in Section 5.0 of this SE. [

]

A final note regarding [

]. As specified in Limitation and Condition 34, it remains the responsibility of each licensee to ensure that its safety analyses envelop allowable operating conditions, and furthermore, that its operations remain within analyzed conditions.

In response to RAI 29.k, Framatome further [

]. Hence, the NRC staff imposed Limitation and Condition 11 in Section 5.0 of this SE [

]

<u>Fuel Stored Energy</u>

Input for determining fuel stored energy was obtained [

]

The conservative [ ]. However, once the LOCA [ ]. In RAI 13.d, the NRC staff requested that Framatome discuss the impacts of this variation in thermal conductivity on the timing of the heat transfer to the fuel cladding and its ultimate effect on the conservatism of the calculated results. Framatome responded [ ] The NRC staff concurred [ ] Therefore, the NRC staff designated in Limitation and Condition 12 [ ].

Making a conservative determination of fuel stored energy [ ] Framatome stated that the [ ] Framatome then stated that [ ].

The NRC staff's review found that, while the objective of using a [ ]

Furthermore, in Section 6.2.1 of ANP-10332P, Framatome [

], the NRC staff designated Limitation and Condition 13 to request **[** **]**.

<u>Decay Heat</u>

As already noted, Framatome's approach conforms to the proposed 1971 American Nuclear Society 5.1 standard for fission product decay heat with a multiplier of 1.2, as stipulated in Appendix K. Framatome accounts for actinide decay heat using a model **[** **]**. While the proposed 1971 American Nuclear Society 5.1 standard called for consideration of actinide decay heat, it did not specify a particular calculational method. As such, the NRC staff finds **[** **]** and acceptable for this purpose.

According to Paragraph I.A.4 under Appendix K, some fraction of the gamma energy from radioactive decay is permitted to be deposited outside the fuel, if justified by a suitable calculation. Section 6.2.5 of ANP-10332P states that the assumed distribution of gamma energy between the fuel and coolant in S-RELAP5 will be determined by Framatome's BWR fuel management reactor physics code used for reload licensing analysis. The NRC staff's audit of several demonstration case decks identified **[** **]**. The NRC staff requested in RAI 23 that Framatome provide justification for its approach, particularly under LOCA conditions where the core may be completely voided.

In response to RAI 23, Framatome stated **[** **]** performed using the CASMO-4 lattice physics code. Framatome stated that its calculations **[** **]** for ATRIUM 10 and ATRIUM 11 fuel.

The NRC staff found Framatome's response to RAI 23 reasonable overall; **[** **]** Therefore, the NRC staff imposed Limitation and Condition 14 in Section 5.0 below **]** Furthermore, **[**

]

3.3.4.1.2 Fuel and Cladding Performance

Framatome noted in ANP-10332P that swelling and rupture of fuel rod cladding may occur when cladding temperatures are high and the rod internal pressure exceeds the pressure in the coolant channel. Hence, consideration of cladding swelling and rupture is necessary during a LOCA event. Sections 6.2.9 and 6.4.5 of ANP-10332P state that the fuel rod swelling and rupture models implemented in S-RELAP5 are a modified version of those established in NUREG-0630 (Reference 29). Framatome stated that its implementation of these swelling and rupture models was originally approved by the NRC staff in an Exxon Nuclear Company TR from November 1982 (XN-NF-82-07(P)(A), Revision 1 (Reference 30)), and that these models are currently in use with Framatome's existing Appendix K-based LOCA methodology (Reference 16). However, in view of the significant industrywide evolution of fuel designs since the establishment of these models, the NRC staff questioned the models' applicability to modern fuel types to which Framatome would apply the AURORA-B evaluation model. The NRC staff further observed that the AURORA-B LOCA evaluation model uses the S-RELAP5 code to calculate swelling and rupture, as opposed to the HUXY/BULGEX codes in XN-NF-82-07(P)(A), Revision 1. Consequently, the NRC staff issued RAI 109 to request that Framatome provide justification for the swelling and rupture models used in the AURORA-B LOCA evaluation model.

Framatome's response to RAI 109 **[** **]** Framatome further stated **[** **]**. Performing thermal-hydraulic analysis **[** **]** Thus, Framatome concluded that the AURORA-B LOCA method is consistent with the methodology in XN-NF-82-07(P)(A), Revision 1, as well as the currently approved EXEM BWR-2000 evaluation model documented in EMF-2361(P)(A) (Reference 16).

The NRC staff's review of Framatome's response found it generally reasonable that the currently approved model should continue to apply to modern fuel rods clad with Zircaloy-2. The NRC staff **[** **]**. This comparison increases confidence that application of the swelling and rupture model to modern fuel designed by Framatome should produce expected results. The NRC staff also generally agreed **[** **]** In particular, XN-NF-82-07(P)(A), Revision 1, discusses **[**

] Neither Framatome's response to RAI 109 nor the S-RELAP5 code theory manual appear to address this point. Therefore, the NRC staff designated Limitation and Condition 15 for plant-specific applications implementing the AURORA-B LOCA evaluation model to [ ].

In RAI 13, the NRC staff further questioned Framatome's modeling of cladding rupture. In response, Framatome stated [ ]. Framatome's response to RAI 13.c states [ ]. However, the response to RAI 13.c goes on [ ] A discussion of how [ ]. The NRC staff has designated Limitation and Condition 16 for plant-specific applications referencing the AURORA-B LOCA evaluation model [ ]

In RAI 110, the NRC staff requested that Framatome further describe and justify the modeling of flow blockage due to swelled or ruptured cladding, as described in Section 6.4.5 of ANP-10332P. In particular, the NRC staff [ ].

Framatome's response to RAI 110 indicated [ ].[30] As an example, Framatome stated [

[30] Framatome's response noted [ ]

]

The NRC staff's review of Framatome's response to RAI 110 determined the following:

- **[** **]**
- **[** **]**
- **[** **]**
- **[** **]**

[**]**. Instead, the NRC staff has designated Limitation and Condition 17 for **[** **]**

3.3.4.1.3 Blowdown Phenomena

Following the initial prediction of critical heat flux exceedance at a given location in the core, Appendix K stipulates that use of nucleate boiling heat transfer correlations be discontinued at that location for the remainder of the blowdown phase, even if local conditions would apparently justify rewetting. As described above, the AURORA-B LOCA evaluation model would determine the critical heat flux according to the 2006 version of the critical heat flux tables compiled by Groeneveld (Reference 17). **[** **]**

In RAI 17, the NRC staff requested additional information concerning Framatome's approach, with focus on the following issues:

- In Section 6.4.9 of ANP-10332P (and as reiterated in response to RAI 14), Framatome stated **[**

]

- The NRC staff [ ]

- The NRC staff [ ]

Framatome's response to RAI 17 [ ].[31] Framatome stated that [ ]. Framatome's response [ ]

The NRC staff reviewed Framatome's response to RAI 17 and found that

- [

[31] Note that Framatome cited the fourth edition of this reference, whereas the NRC staff referenced the fifth edition available in the NRC library.

]

- Justification was **[**

]

- Framatome **[**

]

- Available evidence from a historical review of precedent applications **[**

]

- The duration of **[**

]

Based upon its review of the response to RAI 17, the NRC staff **[**

]

Appendix K further requires progressive reduction of the discharge coefficient used with the Moody critical flow model to ensure that the maximum cladding temperature has been achieved. While variations in split break flow area are considered down through the entire range of potentially limiting postulated small-break scenarios, with regard to the discharge coefficient applied to double-ended guillotine breaks, Framatome proposed to **[**

]

Framatome's response stated that the calculations in Section 7.3.16 of ANP-10332P (e.g., Figures 7-159 and 7-160) were performed with **[** **]**. Visual inspection of Figures 7-159 and 7-160 from ANP-10332P indicates that **[** **]**

Also in RAI 24, the NRC staff questioned whether Framatome intends to **[** **]**. Framatome responded **[** **]** Therefore, the NRC staff considers Framatome's approach acceptable.

In RAI 9, the NRC staff requested that Framatome address recirculation pump pressure drop, including the assessment of sensitivity to pump operation or locking discussed in Item II.3 from Appendix K to 10 CFR 50. In response, Framatome characterized the S-RELAP5 pump model as a modified version of the RELAP5/MOD3 model that uses two-phase pump performance data from the Electric Power Research Institute. Framatome stated that the AURORA-B LOCA evaluation model **[** **]**

The NRC staff considered Framatome's response plausible, **[** **]** Therefore, as a check on the reasonability of the response provided by Framatome, the NRC staff **[** **]** However, the NRC staff also observed that the impact **[**

]. Based upon the discussion above, [ ] for the AURORA-B LOCA evaluation model.

3.3.4.1.4 Refill and Reflood Phenomena

As noted above, in the BWR LOCA event, [ ]. This behavior occurs as the result of several factors, [ ]

[ ], the NRC staff issued RAI 18 to request that Framatome clarify how the heat transfer lockouts have been implemented and justify that the AURORA-B LOCA evaluation model conforms to Appendix K.

Framatome's response clarified that the Appendix K heat transfer lockouts [ ]

On the other hand, in the case of the [ ]

While the issue observed by the NRC staff resulted [ ].[32] Therefore, the NRC staff [ ].

[32] Examples of plant-specific delay times are discussed in response to RAI 87.

3.3.4.2 Additional Relevant Modeling Features

Beyond the modeling options required by Appendix K, ANP-10332P specifies additional features that are essential for calculations performed under the AURORA-B LOCA evaluation model. This section of the NRC staff's SE describes several such modeling features the NRC staff deems worthy of discussion.

3.3.4.2.1 Hot Channel Model

As described in Section 6.3.8 of ANP-10332P, the AURORA-B LOCA evaluation model incorporates a hot channel model **[**

].[33] Defined hot channels **[**

]

The hot channel model also incorporates **[**

]

Another salient feature of the hot channel model in the AURORA-B LOCA evaluation model, **[**

]

Because the AURORA-B LOCA evaluation model nodalizes **[**

]. During the NRC staff's review, Framatome stated **[**

] The NRC staff designated this position as Limitation and Condition 20.

[33] Note that the **[**

].

In RAI 39, the NRC staff requested that Framatome explain how the hot channel model [ ]. Framatome's response [ ] Framatome's response further clarified [ ] The NRC staff found Framatome's response to RAI 39 acceptable because it provided [ ] that the NRC staff found necessary to supplement the discussion in Section 6.3.8 of ANP-10332P.

Framatome proposed [ ]. The NRC staff issued RAI 40 on this topic, [ ] The NRC staff has designated this position as Limitation and Condition 21 in Section 5.0 of this SE.

Defined hot channels are expected to provide the limiting results for both the peak cladding temperature and maximum local oxidation figures of merit. In many cases, [ ]. The results of the demonstration cases included in ANP-10332P appear to support this view. [ ], which the NRC staff finds acceptable. [ ]. Consequently, the NRC staff considers the implementation of this approach to be beyond the scope of the present review. In accordance with Limitation and Condition 22, [ ].

3.3.4.2.2 Countercurrent Flow Limitation

ANP-10332P ranks the countercurrent flow limitation as [ ].[34] However, as noted in response to RAI 100, Framatome stated [ ]

The response to RAI 100 further describes the countercurrent flow limitation correlation parameters [ ]. In particular, the NRC staff found the correlation parameters Framatome used [ ] The parameters used in the [ ]. While the NRC staff [ ], the NRC staff agreed with Framatome's position [ ]

Framatome proposed in ANP-10332P [ ] Beyond this, more generally, [ ]. As a result, the NRC staff concluded [ ]

[34] Note that the PIRT in ANP-10332P [ ].

3.3.4.2.3 Bypass Leakage Flowpaths

Engineered bypass leakage flowpaths (i.e., particularly those between the fuel bundles, core bypass region, lower plenum, and guide tubes) have a significant impact on the distribution of liquid within the reactor vessel during a BWR LOCA event, **[**

], which prompted the NRC staff to issue RAI 33.

Framatome's response to RAI 33 describes and diagrams the bypass leakage flowpaths modeled in the AURORA-B LOCA evaluation model. Framatome further characterized the general significance of these leakage paths in its response. The NRC staff found the vendor's characterization consistent with the demonstration case input decks provided for audit purposes. Framatome's response **[**

]. Framatome's response further briefly discussed the modeling of hot wall effects **[**

]

The NRC staff's review of Framatome's response to RAI 33 found the response generally acceptable, as it provided the requested information and appeared to include modeling of all significant leakage paths. **[**

] The NRC staff's audit of the S-RELAP5 code theory manual (Reference 11) and draft modeling guidelines for the AURORA-B LOCA evaluation model (Reference 26) could not locate the relevant information. Therefore, the NRC staff designated Limitation and Condition 23 in Section 5.0 of this SE **[**

]

3.3.4.2.4 Noncondensable Gas Intrusion

As discussed in Framatome's response to RAI 34, the AURORA-B evaluation model
[

] However, Framatome's response to RAI 34 stated **[**

]

While the calculations performed by Framatome **[**

] The NRC staff **[**

]

3.3.4.2.5 Safety/Relief Valves

In its review of the BWR/6 small-break demonstration analysis presented in Section 7.7.6 of ANP-10332P, the NRC staff questioned why perturbations associated with the actuation of safety/relief valves were not apparent on the calculated trace of upper plenum pressure. A nearly constant pressure trace (after reaching the presumed safety/relief valve lift setpoint) was likewise observed in the corresponding BWR/4 small-break demonstration case. The NRC staff addressed these observations to Framatome in RAI 89. Framatome responded **[**

]

3.3.4.3 Nodalization

Computerized evaluation models require a nodalized representation of the reactor system (i.e., division of the spatial domain into discrete computational volumes and junctions) to permit numerical simulation of a given condition or event. In accordance with applicable regulatory guidance (e.g., Chapter 15.0.2 of the SRP, RG 1.203), the nodalization used for plant-specific safety analyses should be

- consistent with the nodalization used for the assessment and validation of the evaluation model, as well as the demonstration analyses,

- consistent with requirements imposed in the code theory manual and user's manual to maintain code stability and proper numerical performance,

- sufficient to determine all phenomena of interest at an appropriate resolution, and

- assessed using appropriate sensitivity studies.

The nodalization Framatome proposed for the AURORA-B LOCA evaluation model is described in Section 6.3.7 of ANP-10332P.[35] The AURORA-B LOCA evaluation model **[** **]**

According to ANP-10332P, the nodalization used for the **[** **]** for the AURORA-B LOCA evaluation model.

Excepting isolated instances specifically identified in this SE, the NRC staff generally found that Framatome's proposed nodalization scheme conforms to applicable regulatory guidance concerning nodalization. The nodalization scheme appears sufficiently detailed and relies on modeling practices **[** **]** Several aspects of the nodalization of particular interest to the present review are discussed in succeeding sections of this SE, including the nodalization used for modeling breaks, connected systems, and the reactor core.

Consistency of the proposed nodalization scheme with the assessment and validation will be discussed further below in Section 3.4. Framatome's nodalization sensitivity studies will be discussed further below in Section 3.5.

3.3.4.3.1 Nodalization for Recirculation Line Breaks

Framatome provided various nodalization diagrams for the reactor vessel and recirculation system in Section 6.3.7 of ANP-10332P. Specific locations of **[** **]**. The NRC staff found these break locations reasonable and noted **[** **]**. Section 3.5.6 of this SE discusses sensitivity studies associated with nodalization near the break location.

[35] See in particular Figures 6-3 through 6-9 and Tables 6-5 and 6-6.

3.3.4.3.2 Nodalization for Connected Systems

The nodal structure for connected systems (e.g., ECCS, main steam, feedwater), was [ ]. In response to RAI 35, Framatome stated [ ] Framatome further identified that [ ].

The NRC staff considered the overall modeling approach for connected systems proposed by Framatome to be reasonable. [ ] In particular, Framatome intends [ ] Therefore, the NRC staff concluded [ ] For example, nodalization [ ]. This position is documented in Limitation and Condition 24 in Section 5.0 of this SE.

As expected, [ ] in the AURORA-B LOCA evaluation model [ ].

3.3.4.3.3 Nodalization for Modeling Parallel Channel Flow

In contrast [ ] used in Framatome's current evaluation model for analyzing the BWR LOCA event (EXEM BWR-2000 (Reference 16)), the proposed AURORA-B LOCA evaluation model described in ANP-10332P simulates the reactor core using [ ]. This nodalization allows the LOCA analysis to reflect realistic differences in channel flow regime. Multi-channel phenomena occur throughout the spectrum of LOCA events, [ ]. As observed experimentally in the SSTF, [ ]. In particular, depending

upon channel power, location, and other factors, the fuel channels in a BWR core have the potential to enter one of three possible parallel flow regimes:

- co-current upflow of vapor and liquid, which tended to be exhibited by high-power channels,
- countercurrent flow, which tended to be exhibited by average channels, or
- liquid downflow, which tended to be exhibited by non-limiting, low-power peripheral channels.

The testing further revealed that fuel channels may transition from one flow regime to another, depending upon the **[** **]**.

Accurate or conservative prediction of the parallel channel **[** **]**. While the basic phenomena governing parallel channel flow behavior during a BWR LOCA event are known, **[** **]**[36]

While the **[** **]** in the AURORA-B LOCA evaluation model offers the potential for improved analytical realism, the NRC staff **[** **]**. The impact of this observation, coupled with NRC staff **[** **]**

3.3.5 Application Framework

In ANP-10332P, Framatome concentrated on describing the AURORA-B code system and providing justification for its physical models and correlations according to the EMDAP paradigm. Although the S-RELAP5 code represents the foundation of the AURORA-B LOCA evaluation model, as noted above, it is the entire evaluation model that is under review in this SE, which further involves the framework of inputs, assumptions, code modeling options, boundary conditions, nodalizations, analysis procedures, and so forth.

In particular, the following sections of this SE describe steps of practical importance in performing plant-specific safety analyses using the AURORA-B LOCA evaluation model. Because these aspects of the evaluation model, referred to herein as the application framework,

[36] For example, if the **[** **]**

[ ]. Important points from these interactions are summarized below.

3.3.5.1 Plant Safety Analysis Process

In response to RAI 116, Framatome outlined the process for performing plant-specific analysis using the AURORA-B LOCA evaluation model, as summarized below in Table 4.

Table 4: Plant-Specific Safety Analysis Process for the AURORA-B LOCA Evaluation Model

[ ]

3.3.5.2 Steady-State Initialization

The NRC staff requested in RAI 43 that Framatome explain how steady-state calculations are performed in both S-RELAP5 and RODEX4 to establish the initial conditions for the transient LOCA simulation with the AURORA-B LOCA evaluation model. In response to RAI 43, Framatome discussed how steady-state calculations are performed [ ] The response further notes that steady-state calculations [

] The NRC staff considered the initialization practices described in response to RAI 43 to be reasonable and appropriate.

3.3.5.3 Break Selection

The NRC staff requested in RAI 29.a that Framatome specify which break locations will be considered within the scope of a plant-specific analysis. Framatome responded that plant-specific analyses will address breaks in both recirculation and non-recirculation systems, including ECCS, feedwater, and main steam piping. Framatome stated **[**

] However, the NRC staff noted **[**

] As a result, the NRC staff imposed Limitation and Condition 25 **[**

].

The NRC staff requested in RAI 29.b that Framatome specify the break spectrum span and resolution for use in plant-specific analysis. Considering the results from the demonstration cases in Section 7.7 of ANP-10332P, the NRC staff **[**

]. Framatome's response to RAI 29.b provides an overview of the proposed break spectrum for plant-specific analysis, which incorporates changes in response to the NRC staff's concerns. Framatome's response is summarized below in Table 5, **[**

], it is documented below in Section 5.0 as Limitation and Condition 26.

Table 5: Break Spectrum for the AURORA-B LOCA Evaluation Model

[

	[37]

]

Framatome's response to RAI 29.b provided the requested information and generally addressed the concerns raised by the NRC staff by proposing improvements to the break spectrum analysis procedure in ANP-10332P; consequently, the NRC staff found the response acceptable with the slight modification imposed in Limitation and Condition 26. In particular, **[**

]

Using a size increment **[**

]. Furthermore, a finer resolution **[**

]

The NRC staff requested in RAIs 29.c and 29.d that Framatome discuss **[**

]. Framatome responded that **[**

[37] For reference, note that the single-sided pipe areas considered in the demonstration cases were approximately **[** **]**.

][38]

In light of the simplified modeling and general lack of available data for validation, the NRC staff considered it appropriate that the AURORA-B LOCA evaluation model **[** **]**. The NRC staff **[** **]**

3.3.5.4 Selection of Limiting Scenario

The NRC staff requested in RAI 29.e that Framatome identify whether a single simulation can achieve limiting conditions for peak cladding temperature, maximum local oxidation, and core-wide oxidation, or whether the analysis of separate cases, potentially with different limiting single failure combinations, is necessary. The NRC staff further requested that Framatome address how the limiting oxidation results **[** **]**. Framatome responded **[** **]**. Framatome further stated that, **[** **]**. The NRC staff found this approach **[** **]**, acceptable.

In RAI 29.f, the NRC staff requested that Framatome clarify how the limiting single failure for each scenario is determined. Framatome responded **[** **]**. Framatome further indicated **[** **]**. The NRC staff considers this approach acceptable and agrees **[** **]**.

In RAI 29.g, the NRC staff requested that Framatome discuss the key initial conditions **[** **]**. Framatome responded **[** **]** Framatome stated that the following conservative initial conditions are assumed **[** **]**:

[38] This conservatism mainly applies **[** **]**

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

The NRC staff found Framatome's proposed modeling practices to be appropriate [ ]. However, while ANP-10332P recognizes that [ ] Plant-specific applications of the ANP-10332P methodology [ ], which the NRC staff has designated as Limitation and Condition 27 in Section 5.0 of this SE.

In RAI 29.h, the NRC staff requested that Framatome explain whether it is necessary to model explicitly cases with and without offsite power availability, [ ]. Framatome responded that [ ]. Framatome stated that the AURORA-B LOCA evaluation model [ ] The NRC staff's review found Framatome's response acceptable [ ], the NRC staff designated Limitation and Condition 28 for [ ].

In RAI 29.I, the NRC staff requested that Framatome discuss the modeling of the linear heat generation rate, decay heat, and stored energy, and [ ]. Framatome responded that [ ]. Conservative assumptions [ ]. The NRC staff found Framatome's modeling approach acceptable because it conforms to Appendix K.

3.3.5.5 Component Modeling

The NRC staff requested in RAI 29.i that Framatome clarify **[** **]**. Framatome's response **[** **]**. The NRC staff finds this approach conservative and acceptable.

In RAI 29.j, the NRC staff requested that Framatome clarify **[** **]**. Framatome responded **[** **]**. The NRC staff considers **[** **]** Limitation and Condition 28.

Section 6.2.3 of ANP-10332P notes that Framatome **[** **]**. The NRC staff requested in RAI 45 **[** **]**. Alternately, the NRC staff requested **[** **]**. Framatome responded by **[** **]** is acceptable.

In RAI 113, the NRC staff requested that Framatome **[** **]**. Framatome responded by **[** **]** While generally considering Framatome's response appropriate, **[** **]** Furthermore, **[**

] This position is specified as Limitation and Condition 29 in Section 5.0 of this SE.

3.3.5.6 Exposure Dependence

Framatome mentions in ANP-10332P the **[ ]** Therefore, the NRC staff issued RAIs 46 and 117 to request that Framatome **[ ]**. In response, Framatome **[ ]**

Framatome further stated **[ ]**, in accordance with Limitation and Condition 13.

Framatome stated **[ ]**

The NRC staff found the proposed approach **[ ]** appropriate **[ ]**.

3.3.5.7 Analysis Termination Criteria

Framatome stated in ANP-10332P that AURORA-B LOCA simulations may be terminated **[ ]** In RAIs 30 and 31, the NRC staff **[ ]**

- if defined [ ],
- considering the potential [ ], and
- [ ].

Framatome responded to RAI 30 [ ]

- [ ],
- [ ],
- [ ], and
- [ ][39]

To further support assessment [ ].

The NRC staff's review [ ]

In response to RAI 31, Framatome [

[39] Note that in the [ ]. Similar tendencies were observed [ ].

] As evidence, Framatome [ ] The NRC staff noted in particular that the demonstration cases [ ].

The NRC staff concludes [ ] Therefore, the [ ], the NRC staff has incorporated Limitation and Condition 30 into Section 5.0 of this SE [ ]

During the NRC staff’s review of the AURORA-B LOCA evaluation model, [ ]

As a result, Framatome [ ]

While the NRC staff observed **[** **]**, which issue is discussed further in Section 3.5. The NRC staff designated this position as Limitation and Condition 31.

3.4 Assessment and Validation of Evaluation Model

According to Chapter 15.0.2 of the SRP, assessment and validation of code models and correlations should encompass the following areas and general features:

- Assessments should cover all code models, commensurate with their importance and required fidelity.

- Models should be assessed over the entire range of conditions encountered in the transient or accident scenario.

- Assessments and validation should be performed with a single, frozen version of the evaluation model that applies the same code modeling options as would be used for plant-specific calculations.

- Comparisons of evaluation model calculations should be performed against separate-effects (i.e., local) testing as well as integral-effects (i.e., global or system-wide) testing.

- An analysis should be performed to identify and evaluate scaling distortions that may affect the assessment and validation process.

Framatome has presented information summarizing the assessment and validation of the AURORA-B LOCA evaluation model in Sections 5.4 and 7 of ANP-10332P. **[** **]**. In particular,

- Framatome elected to change the S-RELAP5 code version used by the AURORA-B LOCA evaluation model from USEP12 (on which ANP-10332P was based) to UMAR16 during the NRC staff's review. By contrast, a fundamental tenet of the code assessment and validation process is that calculations submitted in support of the NRC staff's review of the evaluation model (e.g., for assessment, validation, demonstration) should all derive from the same frozen code version. While Framatome undertook a significant effort to assess and validate the UMAR16 version of S-RELAP5, as documented in its

responses to a number of RAIs, including 15, 28, 51, and 126, **[ ]**. Furthermore, **[ ]** analyses in ANP-10332P. Thus, the majority of the NRC staff's review documented in Section 3.4 of this SE pertains to assessments of the USEP12 version of S-RELAP5. Consideration of the UMAR16 version of S-RELAP5 is discussed specifically in Section 3.4.5.

- Framatome performed a significant portion of the assessment and validation of the AURORA-B LOCA evaluation model **[ ]**

The term **[ ]**. In response to RAI 27, Framatome clarified **[ ]**. Framatome stated **[ ]**. Framatome also noted in response to RAI 90 **[ ]**, which provide an illustration of their impacts.

The NRC staff's review of Framatome's response to RAI 27 **[ ]**. However, the NRC staff reasoned that a sufficient body of evidence is available to support the assessment of the Appendix K-based AURORA-B LOCA evaluation model, as constituted by

- the **[ ]** assessment comparisons included in ANP-10332P,

- two integral assessments presented in Section 7.9 of ANP-10332P that incorporate a subset of the required evaluation model conservatisms,

- the demonstration analyses and timestep / nodalization sensitivity cases **[ ]**, and

- the response to RAI 58, **[ ]**.

Ideally, validation of an evaluation model **[**

]

Regulatory guidance recognizes the inescapable truth that all testing relied upon for evaluation model assessment and validation involves scaling compromises and scoping limitations. To mitigate to the greatest extent possible the consequences of such distortions, assessment and validation should include testing at different scales and in different facilities for the phenomena of greatest importance.

The assessment and validation effort documented in ANP-10332P follows this general principle. In Section 5.4 of ANP-10332P, Framatome stated that it relies upon four types of comparisons that consider relevant phenomena across a range of scales and test facilities, including

- foundation methodology assessments, which terminology characterizes models that may be considered to have undergone an external validation process (e.g., models required by or found acceptable in Appendix K to 10 CFR 50, supporting methodologies from TRs previously approved by the NRC staff),

- component effects tests, which are specific to the performance of specialized components such as centrifugal pumps, jet pumps, and steam separators,

- separate effects tests, which are specific to individual phenomena of importance to the event under consideration, and

- integral effects tests, which consider the overall response of the entire system (or a significant portion thereof) to a multitude of phenomena associated with the event under consideration.

Succeeding sections of this SE discuss assessments performed by Framatome in each of these categories. In assessing agreement between evaluation model predictions and test data, Framatome used the four-tiered schema described in RG 1.203. Likewise, the present SE applies these criteria, which are paraphrased below in Table 6.

Table 6: Assessment and Validation Evaluation Criteria

Level of Agreement	Definition
Excellent	Evaluation model exhibits no deficiencies in modeling a given behavior. Major and minor phenomena and trends are correctly predicted. The calculated results agree closely with data.
Reasonable	Evaluation model exhibits minor deficiencies but overall provides an acceptable prediction. All major trends and phenomena are predicted correctly. Differences between calculated values and data are greater than are deemed necessary for excellent agreement.
Minimal	Evaluation model exhibits significant deficiencies and overall provides a prediction that is not acceptable. Some major trends or phenomena are not predicted correctly, and some calculated values lie considerably outside the specified or inferred uncertainty bands of the data.
Insufficient	Evaluation model exhibits major deficiencies and provides an unacceptable prediction of the test data because major trends are not predicted correctly. Most calculated values lie outside the specified or inferred uncertainty bands of the data.

To demonstrate the adequacy of the AURORA-B LOCA evaluation model for the prediction of highly ranked PIRT phenomena, Framatome stated **[ ]**. In general, the NRC staff considers this an appropriate standard for assessing the capability of an evaluation model.

A recurring issue in the NRC staff's review of the assessment and validation of the AURORA-B LOCA evaluation model is that Framatome **[ ]**.

While this SE notes such instances of **[ ]**. Since the AURORA-B LOCA evaluation model **[ ]**. Framatome's ultimate satisfaction of this objective will be assessed below in Section 3.4.6.5.

The NRC staff was assisted in its review of the AURORA-B LOCA evaluation model by consultants from Brookhaven National Laboratory, who particularly focused upon the area of assessment and validation. Further details supporting the NRC staff's review of Framatome's assessment and validation effort may be found in the technical evaluation report prepared by Brookhaven National Laboratory (Reference 35) (withheld for proprietary reasons).

3.4.1 Foundation Methodology Assessments

In Sections 5.4 and 7.3 of ANP-10332P, Framatome invokes three sources of foundation methodology assessments, namely: Appendix K required and acceptable features,

Framatome's approved core simulator methodology, and Framatome's approved fuel thermal-mechanical performance methodology, each of which is discussed below by the NRC staff.

3.4.1.1 Appendix K Required and Acceptable Features

Models and correlations defined within Appendix K to 10 CFR 50 as being required or acceptable evaluation model features have been previously reviewed by the NRC staff and do not require an additional demonstration of their acceptability for use in an Appendix K-based LOCA evaluation model. **[**

].[40] The situation is clarified below in Table 7.

Table 7: Evaluation of Appendix K Foundation Methodology Assessment

[

]

In considering Table 7, the **[**

]. Furthermore, the **[**

].

The AURORA-B LOCA evaluation model's approach for modeling each of the phenomena in Table 7 has been described in the preceding discussion. Of these approaches, **[**

]. While requiring consideration of the remaining phenomena on the right-hand side of Table 7, **[**

[40] Note that a similar list in **[**

].

]. As observed in the technical evaluation report from Brookhaven National Laboratory (Reference 35), however, the phenomena on the right-hand side have generally been included in one or more assessment comparisons described in ANP-10332P. **[**

].

3.4.1.2 Lattice Physics/Core Simulator Methodology

The use of an approved lattice physics/core simulator methodology in support of the AURORA-B LOCA evaluation model is **[**

] As discussed above in Section 1.1, the NRC staff has designated Limitation and Condition 1 for Framatome to use approved core simulator and lattice physics methods in support of the AURORA-B LOCA evaluation model.

ANP-10332P associates **[**

]. From the NRC staff's perspective, **[**

]. As noted in the previous section, the **[**

]

3.4.1.3 Fuel Thermal-Mechanical Methodology

The use of an approved fuel thermal-mechanical methodology in support of the AURORA-B LOCA evaluation model **[**

] As noted above in Section 1.1 and captured in Limitation and Condition 2, **[**

], the NRC staff considers it appropriate that the AURORA-B LOCA evaluation model **[** **]** RODEX4 code.

The NRC staff agreed that the approved RODEX4 methodology (Reference 27) **[**

] In fact, the methods for determining these LOCA phenomena are associated with neither the RODEX4 steady-state code nor the kernel of transient RODEX4 routines incorporated into S-RELAP5. As described above, the S-RELAP5 code **[**

].

Table 8: Evaluation of Fuel Thermal-Mechanical Foundation Methodology Assessment

[ ]

3.4.2 Component Effects Tests

In Sections 5.4 and 7.6 of ANP-10332P, Framatome cites five sources of component effects test data for assessment and validation:

- Rod Bundle Pressure Drop Tests
- Jet Pump Performance Tests
- Steam Separator Tests
- Critical Power Tests
- Countercurrent Flow Limitation Mini-Loop Tests

This SE reviews each source of assessment data successively below. The NRC staff found the tests **[** **]** to the assessment of the AURORA-B LOCA evaluation model. Reduced emphasis is placed on other areas where a similar or identical assessment has been recently reviewed that the NRC staff finds applicable to the AURORA-B LOCA evaluation model.

3.4.2.1 Rod Bundle Pressure Drop Tests

As described in Section 7.6.1 of ANP-10332P, the S-RELAP5 code was assessed against a large database of rod bundle pressure drop measurements taken at the ATLAS and KATHY test facilities to validate the **[** **]**. Framatome indicated that the experimental database includes measurements taken across a wide range of **[** **]**.

Framatome's database of differential pressure measurements **[**

], there was excellent agreement between S-RELAP5's prediction and the test measurements. The NRC staff concludes that [ ] to the capability of S-RELAP5 to determine the initial rod bundle pressure drop prior to the LOCA event in support of the [ ] for the AURORA-B LOCA evaluation model.

3.4.2.2 Jet Pump Performance Tests

As described in Section 7.6.2 of ANP-10332P, predictions of the S-RELAP5 code were compared to single-phase and two-phase test measurements using 18 different reduced-scale and prototypical jet pump assemblies to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**

The single-phase tests compared calculated and measured flow- and pressure-drop-ratios across reduced-scale and prototypical jet pump assemblies.

The two-phase tests simulated blowdown behavior for 1/6th-scale jet pump assemblies at conditions applicable to both the intact (i.e., all flows in normal, forward direction) and broken (i.e., suction flow in forward direction, drive and discharge flows in reverse) recirculation loops. Comparisons to pressure measurements using both the homogeneous equilibrium and Moody critical flow models are included in ANP-10332P.

The majority of the jet pump performance testing **[** **]** Therefore, the present review focused primarily on these issues, **[** **]** These component effects tests for BWR jet pumps supplement the more general separate effects assessment of the Marviken critical flow testing (discussed subsequently in Section 3.4.3.13).

3.4.2.3 Steam Separator Tests

As described in Section 7.6.3 of ANP-10332P, predictions of the S-RELAP5 code were compared to steam carryover, steam carryunder, and pressure drop measurements for two- and three-stage steam separators[41] to assess **[** **]**. Framatome concluded in ANP-10332P that the agreement of the S-RELAP5 predictions to the measured data for each of the three phenomena ranges from reasonable to excellent.

[41] A two-stage separator is used in BWR/2-5 designs, and a three-stage separator is used in the BWR/6 design.

The NRC staff [ ] The NRC staff ultimately agreed that the S-RELAP5 predictions provide reasonable to excellent agreement with the measured data for all three phenomena (carryover, carryunder, and pressure drop). [ ].

3.4.2.4 Critical Power Tests

Section 7.6.4 of ANP-10332P cites Section 6.5.4 of ANP-10300P (Reference 7) as providing the assessment basis for the capability of the S-RELAP5 code to address [ ]. Framatome concluded that the previous assessment performed for ANP-10300P remains valid for the LOCA event. Framatome added that the calculation of critical power using an approved fuel-specific correlation is performed during the steady-state initialization of the AURORA-B LOCA evaluation model [ ] the Groeneveld CHF lookup table.

From the NRC staff's perspective, [ ] Thus, there is [ ]. Nevertheless, the NRC staff considers Framatome's approach reasonable and appropriate, [ ].

3.4.2.5 Countercurrent Flow Limitation Mini-Loop Tests

As described in Section 7.6.5 of ANP-10332P, predictions of the S-RELAP5 code were compared to tests performed in the Countercurrent Flow Limitation Mini-Loop Test Facility to assess prediction of the [ ].

Framatome described the Mini-Loop test facility [ ]

Framatome stated that the experimental data [

]

The NRC staff considered the S-RELAP5 prediction of the Mini-Loop test data to be in reasonable to excellent agreement with the measured data. However, in RAIs 22 and 100, the NRC staff asked several questions to confirm the applicability of the test scaling to actual plant conditions. In response, Framatome **[**

], the NRC staff found the results of this assessment adequately supportive of the AURORA-B LOCA evaluation model.

3.4.3 Separate Effects Tests

Sections 5.4 and 7.3 of ANP-10332P cite 14 sources of separate effects test data **[**

]. The NRC staff considers validation of significant phenomena using separate effects testing to be appropriate, since it is intended to isolate the performance of individual code models against relevant test data. **[**

]. The NRC staff's review of this issue is provided below in Section 3.4.4.

The first four separate effects test comparisons consider experiments dealing with void distribution and level swell absent post-dryout heat transfer. These assessments have been recently evaluated by the NRC staff in similar or identical form during the review of ANP-10300P (Reference 8), and will not be emphasized in the present review. The remaining ten comparisons involve LOCA phenomena including post-dryout heat transfer, critical flow, and the countercurrent flow limitation. These comparisons have not been previously reviewed and are the focus of the present evaluation.

3.4.3.1 Rod Bundle Void Tests

As discussed in Section 7.3.4 of ANP-10332P, Framatome assessed S-RELAP5 against void fraction measurements in rod bundles taken at several different test facilities under a variety of conditions. The test facilities in the assessment include FRIGG2, FRIGG3, and KATHY. The FRIGG testing was performed in the late 1960s using simulated Marviken fuel elements of unique design, whereas the KATHY testing simulated a modern ATRIUM 10A fuel bundle. Framatome stated **[**

].

Framatome's assessment of this test data was previously evaluated by the NRC staff in Section 3.3.1.2 of its SE on ANP-10300P (Reference 8). In response to RAIs from the NRC staff during the review of ANP-10300P, Framatome **[**

], the NRC staff ultimately found AURORA-B capable of providing reasonable predictions of the void distribution in rod arrays.

With respect to the present review of ANP-10332P, the NRC staff finds that the conclusions regarding the rod bundle void test assessments originally performed for ANP-10300P generally remain valid, insofar as they are applicable for the AURORA-B LOCA evaluation model. However, the NRC staff notes **[**

]

Therefore, **[**

] the LOCA transient calculation.

3.4.3.2 Christensen Void Tests

As discussed in Section 7.3.5 of ANP-10332P, Framatome assessed S-RELAP5 against void fraction measurements in 7 tests performed in 1961 at Argonne National Laboratory. Framatome stated that, while the primary purpose of the testing was to study void oscillations and stability, the experiments provide data on steady-state axial void distributions, particularly for the subcooled boiling regime. The test facility used a simplified geometry involving a heated rectangular tube constructed of stainless steel. The rectangular tube measured 1.11 × 4.44 centimeters in cross section and was 127 centimeters in height.

Framatome stated that these tests are used to assess the following PIRT items:

- **[** **]**
- **[** **]**
- **[** **]**

The assessment of 7 Christensen void tests (a total of 112 test points) was originally performed in support of ANP-10300P. The NRC staff finds the conclusions of that review generally remain valid, insofar as they are applicable to ANP-10332P. **[**

[42]

]

[42] Note that inconsistent pressure ranges are specified in ANP-10332P; Framatome's response to RAI 103 clarifies that **[** **]** is the correct range.

3.4.3.3 Allis-Chalmers Large-Diameter Void Tests

As discussed in Section 7.3.6 of ANP-10332P, Framatome assessed S-RELAP5 against 162 void fraction datapoints from tests performed by Allis-Chalmers in the mid-1960s using circular pipes of 2.9, 18, and 36 inches in diameter. ANP-10332P presents a series of plots comparing S-RELAP5 predictions against void fractions reported for these tests. The pressures examined in the tests ranged from 615 to 2015 psia, with a maximum measured void fraction of 0.69.

Framatome stated that these tests are used to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**

Framatome's assessment of the Allis-Chalmers testing was originally performed in support of ANP-10300P. As noted in Section 3.3.1.3 of the NRC staff's SE on ANP-10300P (Reference 8), while some direct measurements were made in the 2.9-inch test setup, the 18- and 36-inch tests inferred the void fraction using a homogeneous two-phase flow model and measured pressure drops. The NRC staff finds that the conclusions from its SE on ANP-10300P generally remain valid, insofar as they are applicable to the present review of ANP-10332P. **[**

]

3.4.3.4 GE Level Swell Test 1004-3

As discussed in Section 7.3.7 of ANP-10332P, Framatome assessed S-RELAP5 against void fraction measurements taken during GE Level Swell Test 1004-3. The test involved the blowdown of a pressurized vessel containing saturated water at a pressure of 1011 psia. This experiment was performed in the smaller of two test vessels, which was 14 feet in height and 1 foot in diameter.

Framatome stated that this test is used to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**[43]

Framatome stated that the assessment of GE Level Swell Test 1004-3 was originally performed for the AURORA-B AOO evaluation model (Reference 7) and remains applicable for the

[43] Note that there is an inconsistency in ANP-10332P; **[ ]** items are included in Section 5.4.12 but not Section 7.3.7.

AURORA-B LOCA evaluation model. While the NRC staff generally agreed with this statement for the portion of the LOCA event covered by the test data, the NRC staff observed that ANP-10332P presents comparisons to data only through 100 seconds. At this time, the test was not complete, and the NRC staff estimated that the vessel pressure had only depressurized to **[ ]**. In RAI 103, the NRC staff requested that Framatome extend its assessment of this test to validate more fully the range of pressures experienced during postulated LOCA events.

In response, Framatome stated that **[ ]**; however, Framatome included additional plots of the void fraction distribution at 140 and 180 seconds, **[ ]**. The level of agreement in the void fraction comparisons in the RAI response (at 140 and 180 seconds) was slightly reduced but overall comparable to that seen in similar plots (at 40 and 100 seconds) presented ANP-10332P. In particular, **[ ]**; therefore, the NRC staff categorized the S-RELAP5 predictions as being in reasonable agreement to the data.

The additional data in response to RAI 103 **[ ]**. Although the expanded pressure range also does not fully cover the possible range of pressures during the LOCA event, in the NRC staff's judgment, it does substantially characterize the regime where level swell in both the reactor core and lower plenum are most significant. Evidence supporting this statement can be seen from examining plots of the demonstration cases included in Section 7.7 of ANP-10332P. In particular, **[ ]**

The NRC staff further **[ ]**

3.4.3.5 THTF Mixture Level Tests

As discussed in Section 7.3.8 of ANP-10332P, Framatome assessed S-RELAP5 against void fraction and temperature measurements taken from six tests performed at the Thermal-Hydraulic Test Facility (THTF). The tests considered in the assessment included the 3.09 Series 10 Tests I, J, K, M, N, and DD. **[ ]**. The pressures considered in the testing ranged from 581 to 1173 psia. Framatome stated that the test series investigates conditions where a two-phase mixture covers about 70-80 percent of the test bundle. Framatome's assessment of these tests compared measured and predicted values of void fraction and heater rod temperature.

Framatome stated that these tests are used to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

Framatome concluded that predictions of void fraction are in excellent agreement with the data, with the exception of Test K, which Framatome suggested may be affected by a measurement inconsistency. Framatome concluded that the predicted temperatures generally follow the trend of the data, showing overall conservatism.

The NRC staff found the results of most comparisons to be in the reasonable-to-excellent range. **[ ]** Furthermore, the NRC staff made several general observations on these tests:

- **[ ]**
- **[ ]**
- **[ ]**

Framatome briefly addressed the first two observations in response to RAIs 66 and 67. However, **[ ]**

While Framatome **[**

]. Therefore, as discussed further below in Section 3.6.2.1, the NRC staff imposed Limitation and Condition 35 [

]

3.4.3.6 TLTA Boiloff Tests

The TLTA was originally designed for simulating phenomena occurring during the blowdown phase of a large-break LOCA. However, the facility was subsequently modified on numerous occasions to address additional phenomena, including those associated with (1) the refill and reflood phases of a large-break LOCA and (2) small-break LOCA scenarios. TLTA represented a 1:624 scaled-down model of a BWR/6 reactor using a single, electrically heated fuel bundle.

As discussed in Section 7.3.9 of ANP-10332P, Framatome simulated two boiloff tests, Tests 6441-6 and 6441-7. These tests were performed at pressures of 400 and 800 psia, respectively. Comparisons were made for void fraction at various locations in the test facility (e.g., fuel bundle, bypass region, downcomer) and heater rod temperature.

Framatome stated that these tests are used to assess the following PIRT items:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

As discussed in RAI 70 and its response, [

] The response to RAI 70 addressed this issue, showing improved agreement after [

] The NRC staff found this approach reasonable, [
].

From the information provided in ANP-10332P, only the [ ] could be directly compared to measured data on an individual basis. [

] That being said, the NRC staff generally found the S-RELAP5 predictions of void fraction and heater rod temperature for the assessed TLTA boiloff tests to be in reasonable overall agreement with measured data over the range of comparison, [
].

3.4.3.7 Bennett Tube Tests

As discussed in Section 7.3.10 of ANP-10332P, the Bennett tube tests involved a series of experiments designed to investigate both critical heat flux and post-dryout heat transfer. The tests involved injection of subcooled water into a heated tube pressurized to approximately 1000 psia. The vertically oriented tube was approximately 0.5 inch in diameter and had a total length of 19 feet (i.e., 228 inches). The heated length could be varied; **[ ]** The tests Framatome evaluated considered “low-flow” and “high-flow” conditions. **[ ]**

Framatome stated that these tests are used to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

Of these PIRT items, the NRC staff could **[ ]** on an individual basis against the data that was presented in ANP-10332P. Furthermore, **[ ]** That being said, the NRC staff found the predictions of S-RELAP5 to be in reasonable to excellent agreement with the test data. In particular, the high-flow test prediction was somewhat conservative, but still in reasonable agreement with the data.

3.4.3.8 THTF Steady-State Film Boiling Tests

As discussed in Section 7.3.11 of ANP-10332P, Framatome used **[ ]**. In fact, the vendor used these tests **[ ]** Additional data from the remaining tests was used in the validation; **[ ]**. Framatome also stated **[ ]**

Framatome stated that these tests are used to assess the following PIRT items:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

From the NRC staff's perspective, Section 7.3.11 of ANP-10332P [ ].

The NRC staff requested additional information [ ] In RAI 119, the NRC staff requested that Framatome provide Reference 84 to ANP-10332P, which describes additional steady-state film boiling data from the Combustion Engineering/Columbia [ ].

In response to RAI 105, Framatome confirmed [ ]

While the above information generally appeared reasonable, the NRC staff's review of Figure R105-1 in Framatome's response to RAI 105 identified additional considerations that had not been addressed. [ ]

While the NRC staff could not locate measured [ ] As a result, the NRC staff imposed Limitation and Condition 32 [

]

3.4.3.9 FCTF Spray and Steam Cooling Tests

As discussed in Section 7.3.12 of ANP-10332P, Framatome assessed S-RELAP5 against tests of heat transfer using a prototypical ATRIUM 10 rod bundle geometry at nearly atmospheric pressure. The tests were conducted in Framatome's FCTF. Multiple conditions were simulated, including adiabatic heatup, downdraft, updraft, and bypass entrainment. All tests except the adiabatic heatup tests included simulated core spray. Heater rod temperature comparisons at several axial elevations were provided for five FCTF tests.

Framatome stated that these tests are used to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

Based upon the comparisons presented in ANP-10332P, the NRC staff generally found the temperatures predicted by S-RELAP5 to be in reasonable, and in some cases excellent, agreement with the measured data. That being said, **[**

].

The NRC staff observed that Framatome provided an example plot showing the predicted heat transfer mode as a function of time for one FCTF test in response to RAI 72. **[**

]:

- Regarding the **[**

  ]

- Regarding the **[**

  ]. The NRC staff found **[**

]

In RAI 111, the NRC staff questioned [ ] The NRC staff found this approach acceptable.

Framatome stated that [ ] However, [ ] (Limitation and Condition 10) and the need [ ] (Limitation and Condition 39), the NRC staff considered the issue adequately addressed.

In response to RAI 47, Framatome concluded that FCTF Test 79 could be used to validate an additional phenomenon, [ ]

Finally, the NRC staff notes several additional important observations [ ]:

- [ ]

- [ ]

- [ ]

- [ ]

Consideration of these issues contributed to the NRC staff's decision to impose Limitations and Conditions 10 [ ] and 21 [ ] in Section 5.0 of this SE.

3.4.3.10 THTF Reflood Tests

As discussed in Section 7.3.13 of ANP-10332P, Framatome assessed S-RELAP5 against data from 11 THTF reflood tests. Framatome stated that these experiments simulated the reflooding of a test bundle with an initial water level at about 25-30 percent of the bundle height. Key parameters for each of these tests, including pressure, reflood rate, and linear heat generation rate, are summarized in Table 7-9 of ANP-10332P.

Framatome stated that these tests are used to assess the following PIRT items:

- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]
- [ ]

Framatome provided a series of plots comparing S-RELAP5 predictions of the temperature at the highest measurement elevation in the bundle against test data. Framatome concluded that the predicted heater rod temperatures are generally consistent with or greater than the measured data.

Of the PIRT items Framatome associated with the THTF reflood tests, the NRC staff found [ ]. Regarding the data that was presented, while the influence of individual heat transfer regimes generally was not apparent, the NRC staff found that S-RELAP5 tended to predict peak heater rod temperatures in the THTF reflood tests with reasonable to excellent accuracy. However, the time to quench was generally overpredicted.

The THTF reflood tests were performed at [

[44] **]**

In response to RAIs 104 and 125, **[ ]**

3.4.3.11 FLECHT Reflood and Steam Cooling Tests

As discussed in Section 7.3.14 of ANP-10332P, Framatome assessed S-RELAP5 against data from 10 tests in the FLECHT and FLECHT-SEASET series. The FLECHT and FLECHT-SEASET tests simulated the reflood phase of a PWR LOCA event. As such, they modeled bottom-up reflood and quenching on simulated Westinghouse-type fuel bundles of 15×15 and 17×17 design. Framatome selected tests from these series that included both cosine-shaped and upskewed axial profiles.

Framatome stated that these tests are used to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

Framatome presented a series of plots comparing S-RELAP5 predictions of heater rod temperatures against measured data.

The NRC staff found **[ ]**

From the NRC staff's perspective, **[**

[44] In particular, limiting small-break LOCA scenarios for operating BWRs typically involve failure of the high-pressure **[ ]** systems, necessitating activation of the automatic depressurization system.

], and this topic became the subject of RAI 74.

In response to RAI 74, Framatome **[**

]

In assessing the response to RAI 74, the NRC staff **[**

]

Figure 3 reveals that, **[**

]

In conclusion, the NRC staff found that Framatome **[**

], the NRC staff ultimately found these assessments satisfactory for an Appendix K-based LOCA evaluation model.

[ ]

Figure 3: Illustration of the Impact of **[**
] Realistic Large Break LOCA Methodology for PWRs

3.4.3.12 CCTF Reflood Tests

As discussed in Section 7.3.15 of ANP-10332P, Framatome assessed S-RELAP5 against four experiments performed in the CCTF. The CCTF was a 1:21 scaled model of a four-loop PWR used to simulate the reflood phase of a large-break LOCA. Framatome performed its assessment against Tests 54, 62, 67, and 68, presenting a series of plots comparing S-RELAP5 predictions of heater rod temperatures against measured data.

Framatome stated that the above tests are used to assess the following PIRT items:

- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**
- **[ ]**

From the NRC staff's perspective, **[**

]

While keeping the above points in mind, the NRC staff observed that S-RELAP5 generally made reasonable predictions of the overall test behavior. [

]

However, a nonconservative aspect of the CCTF comparison [

] As discussed above in Section 3.3.1.2.2, the NRC staff imposed Limitation and Condition 8 [

]

3.4.3.13 Marviken Critical Flow Tests

As discussed in Section 7.3.16 of ANP-10332P, Framatome assessed S-RELAP5 against measurements of choked flow taken at the Marviken test facility. The Marviken facility was originally constructed to operate as a prototype heavy-water BWR; however, prior to reaching operation, the plant was converted to a facility for performing reactor-scale choked flow tests. In essence, the reactor vessel served as reservoir of heated, pressurized fluid that was permitted to blow down in a series of tests involving nozzles of various size and geometry.

Framatome made comparisons against measured data from a selection of nine Marviken tests using both the homogeneous equilibrium and Moody critical flow models within S-RELAP5. Framatome concluded that the homogeneous equilibrium model agrees well with the measured data, while the Moody model makes conservative predictions.

Framatome stated that these tests are used to assess the following PIRT items:

- [ ]
- [ ]
- [ ]

The AURORA-B LOCA evaluation model uses [

]
Nevertheless, because [

]

Regarding the Moody model, the NRC staff observed [

]

In response to RAI 47, Framatome stated that the Marviken assessment can be considered to validate [

]

3.4.3.14 UPTF Countercurrent Flow and Entrainment Tests

As discussed in Section 7.3.17 of ANP-10332P, Framatome assessed S-RELAP5 against data from two tests performed at the Upper Plenum Test Facility (UPTF). Although the UPTF was designed to simulate a German four-loop PWR, Framatome concluded that several specific tests from this facility are applicable to the BWR LOCA event, including those that assess the capability of predicting countercurrent flow and liquid entrainment.

In particular, Framatome stated that these tests are used to assess the following PIRT items:

- [ ]
- [ ]

The NRC staff [

]

3.4.4 Integral Effects Tests

Validation of an evaluation model against integral effects test data is intended to assure that the evaluation model is capable of representing the full set of phenomena associated with a given event, with particular emphasis on the complex, multifarious interactions between them during the scenario of interest. As discussed in Section 7.7 of ANP-10332P, Framatome performed integral effects test comparisons against data from three facilities, namely

- the TLTA
- the Full Integral Simulation Test (FIST) facility
- the SSTF

Comparisons of S-RELAP5 code predictions to testing from each of these facilities will be discussed in succeeding sections of this SE.

Framatome listed **[**

].[45] As such, this SE generally will **[**

]

However, an exception where further discussion **[**

[46]

] As a result, the NRC staff issued RAI 47 to request that Framatome **[**

].

Framatome responded to RAI 47 by briefly summarizing **[**

] While, in some cases, the NRC staff was able to conclude **[**

]. Details concerning the NRC staff's evaluation of RAI 47 may be found in the technical evaluation report from Brookhaven National Laboratory (Reference 35). The impact of this issue will be discussed further below in the summary of Framatome's assessment and validation effort in Section 3.4.6.

3.4.4.1 TLTA Integral Tests

The TLTA was originally designed for simulating phenomena occurring during the blowdown phase of a large-break LOCA. However, the facility was subsequently modified on numerous

[45] Moreover, as discussed in Section 3.4.3, from the information presented in ANP-10332P, **[** **]**.

[46] Note that this is **[** **]**.

occasions to expand its capabilities for modeling additional phenomena, including those associated with (1) the refill and reflood phases of the LOCA event and (2) small-break LOCA scenarios. TLTA represented a 1:624 scaled-down model of a BWR/6 reactor using a single, electrically heated fuel bundle.

Framatome selected two integral tests from the TLTA series for the assessment and validation of the S-RELAP5 code, namely

- Test 6425-2 (Large-Break LOCA)
- Test 6432-1 (Small-Break LOCA)

The latter case (Test 6432-1) resulted in no heatup in both the test and the **[** [47] **]** The NRC staff's evaluation of these comparisons is provided below.

3.4.4.1.1 TLTA Large-Break Test 6425-2

Test 6425-2 modeled the double-ended rupture of a recirculation line with two low-pressure coolant injection pumps inoperative. Thus, available ECCS equipment included high-pressure core spray, low-pressure core spray, and one low-pressure coolant injection pump.

Framatome presented the results of its S-RELAP5 simulation of Test 6425-2 in Section 7.7.2.1 of ANP-10332P. While S-RELAP5 calculated some measured parameters acceptably, **[** **]** For example,

- whereas complete heater rod quenching was observed **[** **]**, and
- the measured peak cladding temperature of approximately 700 °F was **[** **]**.

A **[** **]** is not provided in ANP-10332P. However, from included comparison plots, it is apparent that the S-RELAP5 analysis **[** **]** The NRC staff issued RAIs 80 and 106 to request that Framatome **[** **]**.

[47] As noted previously, S-RELAP5 **[** **]** for performing assessment and validation analyses.

In its response, Framatome **[**

]. Framatome stated **[**

]. Framatome noted **[**

][48]

While Framatome's responses to RAIs 80 and 106 added some clarity, the NRC staff found **[**

] For example,

- Framatome reasonably concluded **[**

  ]

- While Framatome observed **[**

  ]

The NRC staff further observed that

- The test condition simulated by TLTA Test 6425-2 is very similar to that of FIST Test 6DBA1-B, which, as discussed below, was a "tie-back" test intended to benchmark the two facilities. Measured peak cladding temperatures for both tests were approximately 700 °F. **[**

  ]

- Past assessments of TLTA Test 6425-2 **[**
  ][49]

[48] Note that section 7.7.2.1 of ANP-10332P states S-RELAP5 **[**
].

[49] Note that this observation contrasts with subsequent discussion in Sections 3.4.4.2.2 and 3.4.4.2.3 regarding FIST Test 6SB2C, for which many codes and analysts have underpredicted the measured data.

- As described above in Section 3.3.4.2.2, the [ ]

In light of the discussion above, the NRC staff concluded that the S-RELAP5 simulation of TLTA Test 6425-2 [ ] Therefore, the NRC staff designated Limitation and Condition 33 [ ]

3.4.4.1.2 TLTA Small-Break LOCA Test 6432-1 ("Best-Estimate" Modeling)

Test 6432-1 modeled a small break (i.e., simulated size of 0.05 ft^2) on the recirculation line with the high-pressure core spray system inoperative. Thus, available ECCS equipment included low-pressure core spray and three low-pressure coolant injection pumps.

Framatome presented the results of its S-RELAP5 simulation of Test 6432-1 in Section 7.7.2.2 of ANP-10332P. Overall, the NRC staff considered the agreement of the S-RELAP5 predictions to the measured test data to be reasonable. However, it should be immediately pointed out that TLTA Test 6432-1 resulted in essentially no measured heatup of the test bundle. [[50]]

Several anomalies were present in the measured ECCS flow rates shown in ANP-10332P [ ] The NRC staff's review of RAI 81 found the explanation concerning [ ] acceptable. However, the NRC staff considered Framatome's [ ].

[50] For example, see discussion in Section 7.7.2.2 of ANP-10332P and Framatome's response to RAI 81 regarding TLTA Test 6432-1.

3.4.4.1.3 TLTA Small-Break LOCA Test 6432-1 (Conservative Modeling)

In Section 7.9.2.1, Framatome described an additional simulation of TLTA Test 6432-1 that incorporated three generally conservative modeling practices from the AURORA-B LOCA evaluation model (the first two of which derive from Appendix K), namely,

- decay heat increased by 20 percent,
- Moody critical flow, and
- **[ ]**

As noted above, there was essentially no measured heatup in TLTA Test 6432-1; neither was a heatup predicted in the S-RELAP5 "best-estimate" simulation. However, with the three above conservatisms applied, S-RELAP5 predicted heatup to a peak cladding temperature of approximately **[ ]**. In addition to various plots of cladding temperature, Framatome included plots of coolant mass in the test bundle and upper plenum. Reduced bundle mass and increased upper plenum mass were predicted in the conservative modeling prediction of Test 6432-1. Such behavior is expected **[ ]** test facility.

While Framatome's comparison with Test 6432-1 using conservative modeling can be considered a demonstration of the conservativism of the AURORA-B LOCA evaluation model, **[ ]** These issues will be revisited in greater detail below in Section 3.4.4.2.3, which concerns an equivalent small-break test conducted in a different facility (i.e., FIST Test 6SB2C).

3.4.4.2 FIST Integral Tests

The FIST facility was used to perform thermal-hydraulic testing for LOCA and non-LOCA transients for BWRs. The FIST facility can be considered an upgraded version of the TLTA facility; while many of the same components were used, a number of scaling improvements were made, such as increasing the height of the jet pumps to full scale. While generally employing full-height components, FIST also used a single, electrically heated fuel bundle. This led to an overall scaling ratio of 1:624, equivalent to that of TLTA.

As discussed in Sections 7.7.3 and 7.9.2.2 of ANP-10332P, Framatome validated the S-RELAP5 code using the following tests performed at the FIST facility:

- BWR/6 Large-Break Test 6DBA1-B
- BWR/6 Small-Break Test 6SB2C
- BWR/6 Low-Pressure Coolant Injection Line Break Test 6LB1
- BWR/4 Large-Break Test 4DBA1

In general, these tests were simulated using the S-RELAP5 code **[ ]**. However, the S-RELAP5 simulation for Test 6SB2C (BWR/6 small-break) **[ ]**. Framatome subsequently performed additional

calculations for this test [ ] from the AURORA-B LOCA evaluation model. Successive sections of this SE assess the comparisons of S-RELAP5 predictions against measured data from these FIST tests.

3.4.4.2.1 BWR/6 Large-Break Test 6DBA1-B

Test 6DBA1-B modeled the double-ended rupture of a recirculation suction line with two low-pressure coolant injection pumps inoperative. Thus, available ECCS equipment included high-pressure core spray, low-pressure core spray, and one low-pressure coolant injection pump. Note that FIST Test 6DBA1-B is considered a “tie-back” test to the TLTA large-break Test 6425-2 that was discussed above, in that both tests were intended to model the same scenario. The measured peak cladding temperature for FIST Test 6DBA1-B was 703 °F.

Framatome presented the results of its S-RELAP5 simulation of Test 6DBA1-B in Section 7.7.3.1 of ANP-10332P. Overall, the NRC staff considered the S-RELAP5 predictions to be in reasonable agreement with the measured test data. In particular, cladding temperatures were predicted accurately or conservatively. [

]

3.4.4.2.2 BWR/6 Small-Break Test 6SB2C (“Best-Estimate” Modeling)

Test 6SB2C modeled a small-break rupture of a recirculation suction line with the high-pressure core spray system inoperative. Thus, available ECCS equipment included low-pressure core spray and three low-pressure coolant injection pumps. Note that FIST Test 6SB2C is considered a “tie-back” test to the TLTA small-break Test 6432-1 that was discussed above. However, while TLTA Test 6432-1 did not result in significant heatup, FIST Test 6SB2C experienced a mild heatup to 925 °F.

Framatome presented the results of its S-RELAP5 simulation of Test 6SB2C in Section 7.7.3.2 of ANP-10332P. Despite having predicted trends for many parameters similarly to measured data, S-RELAP nevertheless underpredicted the measured peak cladding temperature by [

]

As shown in ANP-10332P, the heatup of the peak node was measured as occurring [

]

The NRC staff [

] The NRC staff issued RAI 53 to address these concerns to Framatome.

Framatome's response to RAI 53 [[51]]

Beyond the [ ] In RAI 84, the NRC staff requested that Framatome provide the results of the S-RELAP5 simulation [ ]

3.4.4.2.3 BWR/6 Small-Break Test 6SB2C (Conservative Modeling)

[ ], as described in Section 7.9.2.2 of ANP-10332P, Framatome performed another simulation of the same test that incorporated three conservatisms from the AURORA-B LOCA evaluation model (the first two of which derive from Appendix K), namely

- decay heat increased by 20 percent,
- Moody critical flow, and
- [ ]

[51] The TRACE assessment (Reference 58) references the prediction of excessive drainage of liquid from the upper plenum into the test bundle as a potential cause for the underprediction. This phenomenon may be at work in the S-RELAP5 prediction as well, as suggested by Figure 7-342 of ANP-10332P.

With these conservatisms imposed, S-RELAP5 was observed to conservatively overpredict the measured peak cladding temperature **[**

]

While ANP-10332P presents a more limited set of results for this conservative simulation of Test 6SB2C **[** **]**, the NRC staff found the overall level of agreement reasonable, if somewhat conservative. However, the NRC staff observed that the FIST facility contains a single channel. **[**

]. Furthermore, as explained in the response to RAI 94, Framatome **[**

] Framatome replied to this concern in response to RAI 53, **[**

]

The NRC staff's review of the third simulation of FIST Test 6SB2C made the following observations:

- The underprediction of peak cladding temperature was of a similar magnitude to those of other analysts and codes.

- The conservatism in the full AURORA--B LOCA evaluation model for the prediction of BWR small-break LOCA scenarios would be increased considerably because no credit was taken in the simulation of FIST Test 6SB2C for a number of additional conservatisms. For example:

    - **[**

      ]

    - No credit was allowed for Appendix K heat transfer lockouts, the impact of which is discussed further below in Section 3.6.2.3.

    - No credit was taken for evaluation model conservatisms associated with fuel rod stored energy due to the comparison against a test facility using heater rods.

    - Due to the use of heater rods and the mild peak cladding temperature in FIST 6SB2C **[**

]

In light of the considerable conservatisms associated with the evaluation model, the full effect of which, in a number of cases, cannot be reasonably assessed via comparisons to existing integral effects tests, the NRC staff's remaining concerns with Framatome's modeling of FIST Test 6SB2C were addressed.

3.4.4.2.4 BWR/6 Low-Pressure Coolant Injection Line Break Test 6LB1

Test 6LB1 modeled complete severance of a low-pressure coolant injection line for a BWR/6 with the high-pressure core spray system inoperative. Thus, available ECCS equipment included low-pressure core spray and two low-pressure coolant injection pumps. While a break on the low-pressure coolant injection line results in an additional reduction in the available ECCS flow rate (i.e., beyond that associated with a postulated single failure), the higher elevation of the break (i.e., relative to a break of similar size on a recirculation line) confers the salutary effects of an earlier transition of the break flow to vapor and full core refloodability. Test 6LB1 experienced only a slight heatup that terminated at a peak cladding temperature of 635 °F.

Framatome presented the results of its S-RELAP5 simulation of Test 6LB1 in Section 7.7.3.3 of ANP-10332P. The S-RELAP5 results reported for Test 6LB1 generally provide accurate predictions of key test parameters. **[**

]

During the review, **[**

]

3.4.4.2.5 BWR/4 Large-Break Test 4DBA1

According to NUREG/CR-4128 (Reference 43), FIST Test 4DBA1 modeled a double-ended guillotine rupture of a recirculation line for a BWR/4 with one low-pressure coolant injection pump inoperative. The available ECCS equipment included high-pressure coolant injection, one low-pressure core spray, and two low-pressure coolant injection pumps (Reference 43). The measured peak cladding temperature for FIST Test 4DBA1 was 960 °F.

Framatome presented the results of its S-RELAP5 simulation of Test 4DBA1 in Section 7.7.3.4 of ANP-10332P. The NRC staff found the cladding temperature comparisons in ANP-10332P to be reasonable to conservative. **[**

]

In Framatome's assessment of FIST Test 4DBA1, and to some degree in other assessments as well (e.g., TLTA Test 6425-2), the NRC staff **[** **]** In response to RAI 57, Framatome confirmed this **[** **]**

The **[** **]** void fraction comparisons for FIST Test 4DBA1 in at least two locations:

- The fuel bundle, where the NRC staff observed **[** **]**

- The lower plenum, where the NRC staff made similar observations **[** **]**. In response to RAI 86, Framatome attributed **[** **]**

As noted above, these **[** **]** the conservativism of the predicted figures of merit for FIST Test 4DBA1.

3.4.4.3 SSTF Integral Tests

The SSTF was used to model phenomena associated with 3D liquid and vapor flows during the refill and reflood phases of a BWR LOCA event. The SSTF simulated, at nearly full-scale, a 30-degree section of a reactor core containing 58 rod bundles. The SSTF core was unheated; it merely served as a prototypical geometric obstruction for the representative steam and liquid flows injected into the test facility. Due to test facility design limitations, SSTF tests typically began at reduced pressure (e.g., 150 psia).

Testing in the SSTF was intended to complement the single-channel TLTA and FIST facilities discussed above. In particular, the scaling of both the TLTA and FIST facilities led to tall,

narrow test-facility components which had the effect of constraining certain inherently 3D phenomena into a single dimension.

Two SSTF tests were modeled in S-RELAP5 for the purpose of assessment and validation, namely,

- SSTF System Test EA3.1, Run 111 (BWR/4 reference case)
- SSTF System Test SRT-3, Run 26 (BWR/6 reference case)

As described in further detail in NUREG/CR-2568, each of these tests simulated a large-break LOCA with a design-specific ECCS configuration and appropriate single-failure.

For each of these tests, the S-RELAP5 model **[**

]

For both of these tests, Framatome compared S-RELAP5 **[** **]** The NRC staff found a number of the comparisons for these two SSTF tests to be reasonable; in particular, most fuel bundle differential pressure comparisons appeared reasonable. In addition the NRC staff found the lower plenum subcooling predictions discussed in response to RAI 50 in reasonable-to-excellent agreement with measured data. **[**

] While a plot provided in response to RAI 47 showed better agreement **[**

] in Limitation and Condition 37, in Section 5.0 of this SE. Also, **[**

], as noted in RAI 79, **[**

]

From the NRC staff's perspective, prediction of the 3D phenomena occurring in the SSTF is challenging, even for detailed mechanistic models. **[**

] in Limitation and Condition 10 **[**

].

3.4.5 Impact of UMAR16 Code Version

The NRC staff's evaluation of the assessment and validation for the S-RELAP5 code has focused upon the material included in ANP-10332P. **[** **]**

[**]**, across several RAIs (primarily 15 and 126) the NRC staff requested that Framatome **[** **]**

As described in response to RAI 15, Framatome **[** **]**

Framatome's **[** **]**

The **[** **]** to this general statement, including the following:

- As noted in RAI 51, the NRC staff observed a conservative **[**

] to the NRC staff's decision to impose Limitation and Condition 37.

- The [ ], generally resulted in improved agreement with measured data.

- Improved agreement [ ]

Based upon its review, the NRC staff found the [ ] In particular, as addressed in RAI 126, the NRC staff [ ].

Framatome provided the requested results in response to RAI 126; [ ] for these integral tests is summarized below in Table 9.

Table 9: Impact of UMAR16 Code Version on Integral Effects Test Comparisons

[ ]

Overall, the NRC staff considered the results shown in Table 9 reasonably consistent [ ]

3.4.6 Summary of Assessment and Validation

The foregoing discussion of the assessment and validation effort for the AURORA-B LOCA evaluation model considered these comparisons at an individual level. However, the assessment of an evaluation model must ultimately be done on a holistic basis. In particular, for an Appendix-K-based evaluation model, the assessments must provide confidence of conservative prediction of the figures of merit. This section of the NRC staff's SE summarizes each set of assessment comparisons and concludes with an overall evaluation of adequacy.

3.4.6.1 Foundation Methodology Assessments Summary

The foundation methodology assessments for the AURORA-B LOCA evaluation model cover models and modeling practices associated with Appendix K to 10 CFR 50, core simulator and lattice physics methods, and fuel thermal-mechanical methods. In a number of cases cited above, the NRC staff determined **[** **]**, and Limitations and Conditions specified in Section 5.0 of this SE. As a result, the NRC staff concluded that the foundation methodology assessments adequately support the AURORA-B LOCA evaluation model.

3.4.6.2 Component Effects Tests Summary

Component effects tests were used for the assessment of specialized component models in S-RELAP5, namely, rod bundle pressure drop tests, jet pump performance tests, steam separator tests, critical power tests, and countercurrent flow limitation tests. Of these, the NRC staff found **[** **]**. As documented in the discussion above, the NRC staff generally found these tests in reasonable agreement with data and concluded the component effects tests adequately support the AURORA-B LOCA evaluation model.

3.4.6.3 Separate Effects Tests Summary

The separate effects test comparisons Framatome performed for the AURORA-B LOCA evaluation model **[** **]**

Regarding the topic of test scaling and distortion, the NRC staff observed that a significant proportion of the separate effects assessments for the AURORA-B LOCA evaluation model **[** **]** In RAI 48, the NRC staff requested that Framatome **[** **]**.

Framatome's response to RAI 48 **[** **]**

As discussed above, the NRC staff **[** **]**, the NRC staff found Framatome's response to RAI 48 acceptable. In particular, the NRC staff agreed **[** **]** to provide confidence that the Appendix K-based AURORA-B LOCA evaluation model will predict conservative results for BWR LOCA scenarios.

An issue that recurs in the NRC staff's evaluations of individual separate effects test series above is **[** **]** However, the NRC staff found that many key phenomena were included in multiple test series, such that the selected assessment suite provided reasonable coverage of the BWR LOCA event domain; furthermore, the assessments generally showed reasonable agreement with test data. In a handful of cases where minimal agreement was observed **[** **]**, the results tended to be conservative and did reflect overall correct trends. Also, Limitation and Condition 32 **[** **]**.

In conclusion, **[** **]** Nevertheless, as explained further below in Section 3.4.6.5, the NRC staff ultimately found Framatome's assessment sufficient for a conservative, Appendix K-based evaluation model.

3.4.6.4 Integral Effects Tests Summary

The integral effects test comparisons Framatome performed for the AURORA-B LOCA evaluation model incorporated data from eight integral tests conducted at three different

facilities. Framatome's selection of integral tests considered both the BWR/4 and BWR/6 plant designs. As noted above in Section 1.2, while these designs are similar, there are relevant differences that Framatome has explicitly taken into account in its validation. **[** **]**, overall, the NRC staff found the quantity and variety of tests selected for comparison appropriate, particularly for an Appendix K-based evaluation model.

A **[** **]** pertaining to integral effects test assessments that deserves mention is discussed in RAI 52. In particular, over the course of reviewing the validation of the AURORA-B LOCA evaluation model against integral-effects test data, the NRC staff **[** **]**. The NRC staff also found **[** **]**. In response to the NRC staff's concern, Framatome stated **[** **]**. While ultimately agreeing that the practices used by Framatome **[** **]** in the validation comparisons correspond reasonably well with those for performing plant-specific safety analyses, the NRC staff concluded that, in general, **[** **]** assessment of the predictive accuracy of the code being validated.

Reasonable agreement was observed in most of the integral effects tests presented in ANP-10332P. **[** **]**, the NRC staff deemed Limitation and Condition 33 necessary, **[** **]**, the NRC staff ultimately found the prediction acceptable. Furthermore, **[** **]** (as extended by Limitation and Condition 10), the NRC staff considered the AURORA-B LOCA evaluation model capable of making conservative predictions of relevant phenomena.

In conclusion, the NRC staff found that, subject to limitations and conditions specified in this SE, Framatome has presented sufficient evidence of the assessment of S-RELAP5 against integral effects test data. However, **[** **]**
Nevertheless, as explained below in Section 3.4.6.5, the NRC staff ultimately found Framatome's assessment appropriate for a conservative, Appendix K-based evaluation model.

3.4.6.5 Assessment and Validation Conclusion

Prior to concluding discussion of Framatome's assessment and validation of the AURORA-B LOCA evaluation model, several overarching summary observations should be made:

- A sufficiently wide range of separate and integral effects tests was assessed.

- **[ ]** the selection of specific tests for assessment, as opposed to others of equal or occasionally greater apparent applicability.

- **[ ]**. A significant number of relevant phenomena was assessed **[ ]**.

- Given the reliance in ANP-10332P **[ ]**, which influenced the NRC staff's determination to impose Limitation and Condition 10. **[ ]**.

- **[ ]**. However, staff-imposed limitations and conditions **[ ]**.

- While the full set of assessments **[ ]** is capable of calculating conservative results when used in the Appendix K-based AURORA-B LOCA evaluation model was generally provided (noting, however, Limitations and Conditions 33 and 34).

- While evidence of consistency was observed between the nodalization used in many assessment and validation cases and that intended for plant safety analysis (e.g., nodalization for core and reactor vessel), test facility scaling differences make a direct comparison difficult. Framatome in some cases **[ ]**.

The NRC staff has made a point in this SE of emphasizing that Framatome's assessment and validation applies **[ ]**. That being stated, it is reasonable to expect that **[ ]** will in general tend to result in more conservative predictions. A demonstration of the impact of applying a selection of important conservatisms is provided in

Framatome's response to RAI 58, which as discussed further below in Section 3.6.1, shows a peak cladding temperature **[ ]**. Based upon this evidence, and further evidence of reasonably expected predictions for the demonstration cases, the NRC staff ultimately considers the validation Framatome performed on the S-RELAP5 code as providing sufficient indication that the full AURORA-B LOCA evaluation model will reliably produce conservative figures of merit, as intended by Appendix K to 10 CFR 50.

The NRC staff concluded that the assessment and validation performed for the AURORA-B LOCA evaluation model **[ ]** that satisfy the requirements of Appendix K to 10 CFR 50.[52] In particular, the assessment and validation effort described in ANP-10332P provides adequate confidence that, subject to the limitations and conditions in Section 5.0 of this SE, the AURORA-B LOCA evaluation model will predict conservative figures of merit for the BWR LOCA event. Therefore, the NRC staff found the validation and assessment presented in ANP-10332P for the AURORA-B LOCA evaluation model acceptable.

3.5 Sensitivity Studies

Inasmuch as the AURORA-B LOCA evaluation model is submitted as an Appendix K evaluation model, formal statistical quantification of uncertainties is not necessary to support the demonstration of compliance with 10 CFR 50.46. Nevertheless, Section II.2 of Appendix K requires the performance of sensitivity studies to provide assurance that arbitrary modeling practices do not adversely affect predicted figures of merit.

Sensitivity studies supporting the AURORA-B LOCA evaluation model are presented in Section 7.9 of ANP-10332P and consider the following perturbations:

- requested maximum timestep length
- hot channel axial nodalization
- core axial power shape
- core radial power shape
- fuel channel grouping and its impact on predicting parallel channel flow
- break and ECCS injection nodalization (see response to RAI 41)

Framatome found the results of all sensitivity studies presented in ANP-10332P acceptable, including several that exhibited **[ ]**, and issued RAIs 112 and 126 to request that Framatome address **[ ]**.

[52] Interestingly, all integral effects tests assessed in ANP-10332P post-date the promulgation of 10 CFR 50.46 and Appendix K, as do many of the separate effects tests. Such tests were performed primarily to support an improved understanding of physical phenomena to support the development of more realistic analysis methods.

In response to RAIs 112 and 126, Framatome reperformed a number of the sensitivity cases in ANP-10332P. The results reported in these responses showed significant improvement relative to the original analyses in ANP-10332P. **[** **]**. Details of these sensitivity studies are discussed in succeeding sections of this SE.

As it turns out, while not mentioned in ANP-10332P, many of the original sensitivity analyses for the BWR/4 case were **[** **]** The evidence provided in response to RAIs 112 and 126 provides confidence that the AURORA-B LOCA evaluation model is not unduly sensitive to changes in timestep and nodalization **[** **]** Therefore, as part of Limitation and Condition 31, **[** **]**.

3.5.1 Timestep Length

Sensitivity studies for the requested maximum timestep length are described in Section 7.9.3 of ANP-10332P. The sensitivity analyses used a BWR/4 input deck and considered four permutations of large and small breaks on the recirculation system pump discharge and suction lines. Three sensitivity timesteps (ranging from 0.001 to 0.01 seconds) were considered in addition to the nominal value of 0.005 seconds. The sensitivity results in ANP-10332P **[** **]**. Thus, in RAI 112.a, the NRC staff requested that Framatome **[** **]**

Framatome responded to the NRC staff's questions **[** **]**. As documented in response to RAI 126.d, the updated sensitivity studies show significantly increased robustness against perturbation. Framatome's response states that the results support use of timesteps 0.005 seconds and smaller. The NRC staff found that these sensitivity studies addressed the issues identified in RAIs 112.a and 126.d and considered the results consistent with expectations. In particular, for timesteps within the qualified range **[** **]**, the largest peak cladding temperature variation observed in the revised sensitivity analysis was **[** **]**.

3.5.2 Hot Channel Axial Nodalization

A sensitivity study of the axial nodalization for the hot channel is described in Section 7.9.4 of ANP-10332P. In particular, Framatome's study varied the number of hydraulic nodes **[**

]. The NRC staff found **[** **]** and, in RAI 112.b, requested that Framatome **[** **]**.

Framatome responded by providing a revised sensitivity study of hot channel axial nodalization that **[** **]**. The revised comparison showed a sensitivity **[** **]**, which the NRC staff found reasonable.

Framatome's sensitivity study only considered the hydraulic nodalization of the hot channel. Framatome stated that **[** **]**. According to the draft modeling guidelines and demonstration cases audited by the NRC staff, Framatome specifies **[** **]**. In light of the fairly detailed heat structure nodalization scheme employed, Framatome assumed the nodalization to be "converged."

While agreeing that the **[** **]** used by Framatome appears reasonable, the NRC staff did not agree with the logic expressed in ANP-10332P **[** **]**. However, the NRC staff ultimately found Framatome's focus on the **[** **]** reasonable based upon the level of detail employed and evidence observed during an audit of the demonstration analysis cases, wherein **[** **]**.

Furthermore, the hot channel nodalization sensitivity studies performed by Framatome **[** **]**. This issue is discussed above in Section 3.3.4.1.2, as well as in Limitation and Condition 16.

3.5.3 Core Axial Power Shape

Section 7.9.5 of ANP-10332P provides the results of Framatome's sensitivity study of core axial power shape, which considered two cases:

- varying only the hot channel between mid- and top-peaked axial power shapes
- varying the remainder of the core between mid- and top-peaked axial power shapes

3.5.3.1 Hot Channel Axial Power Shape

Varying the axial power shape for the hot channel was observed to **[** **]** On this basis, Framatome concluded **[** **]**.

While it appears reasonable [ ]

However, Framatome clarified the situation in response to RAI 111.c, stating [ ]

From the NRC staff's perspective, [ ], according to Limitation and Condition 10 in Section 5.0, [ ]:

- The BWR/6 SF-LPCS scenario discussed in Framatome's response to RAI 15 [ ]
- ANP-10332P and Framatome's responses to RAIs 15 and 111 confirm [ ]

Therefore, the NRC staff found the results of [ ], as specified in Section 6.2.1 of ANP-10332P.

3.5.3.2 Average Channel Axial Power Shape

Section 7.9.5 of ANP-10332P describes a second sensitivity study, wherein the hot channel was set to a top-peaked axial power shape, and the remainder of the core was varied between the mid- and top-peaked profiles. Both small- and large-break LOCA scenarios were considered. [ ]

3.5.4 Core Radial Power Shape

As described in Section 7.9.6.1 of ANP-10332P, Framatome performed analysis for both a large- and a small-break scenario to illustrate the sensitivity of the core to radial power shape. In the reference case, [

] The NRC staff [ ] and requested further explanation in RAI 112.c.

Framatome's response to RAI 112.c provided revised results that demonstrated [ ].

The NRC staff found the results of the revised sensitivity study reasonable [ ]

3.5.5 Fuel Channel Grouping / Parallel Channel Flow

As described in Section 7.9.6.2 of ANP-10332P, Framatome performed a [ ].[53] Framatome's sensitivity study built off of one of the SSTF cases used as an integral effects assessment of the AURORA-B LOCA evaluation model [ ].

Framatome performed four sensitivity cases, in addition to the base case. [ ]

Unlike the SSTF assessment case described in Section 3.4.4.3, [ ]

Framatome characterized the flow regime [ ], Framatome recognized this method as an approximation capable of providing an overall sense of channel flow regime. Based upon the results presented in ANP-10332P, Framatome observed [

[53] Parallel channel flow and its influence on the LOCA event are described above in Section 3.3.4.3.3.

].

The NRC staff performed its own assessment of the results presented in ANP-10332P and [

] The situation is illustrated below in Figure 4.

The results shown in Figure 4 [

]

[ ]

Figure 4: Average Fraction of Time [ ] in ANP-10332P

The NRC staff's review further observed [

]

Table 10: Fuel Channel Grouping Resolution for AURORA-B LOCA Evaluation Model

[ ]

Beyond this, the NRC staff noted that a number of additional factors play a role in the [ ]:

- [ ]
- [ ]
- [ ]
    - [ ]
    - [ ][54]
    - [ ]
    - [ ]

The NRC staff questioned the degree of accuracy in the modeling [ ] led the NRC staff to issue multi-part RAI 32, which addressed concerns with the capability of the AURORA-B LOCA evaluation model to predict parallel channel flow behavior. Recognizing the challenge with addressing this set of complex issues, the NRC staff further indicated in RAI 32 that [ ].

In response to RAI 32, Framatome [ ]:

- [ ]
- [

[54] Note that the AURORA-B LOCA evaluation model [ ].

]

- **[**

  ]

The NRC staff found the results of Framatome's sensitivity studies relevant and informative. The studies generally increased the NRC staff's assurance **[** **]** in S-RELAP5 is conservative. However, the NRC staff ultimately concluded **[**

]

As a result, despite the somewhat compelling evidence shown in **[**

] contributed to the NRC staff's decision to impose Limitations and Conditions 10 and 20, **[**

].

3.5.6 Break and ECCS Injection Nodalization

In RAI 41, the NRC staff observed that ANP-10332P does not appear to provide a basis for the satisfaction of Section I.C.1.d of Appendix K to 10 CFR 50, which states that the nodalization in the vicinity of and including the broken or split sections of piping and the points of ECCS injection shall be chosen to permit a reliable analysis of the thermodynamic history during blowdown. In response, Framatome performed a nodalization sensitivity study to illustrate the consistency of its predictions. As shown in Table R41-1 of its response, Framatome **[**

] Based upon this relatively mild variation, the NRC staff found the response to RAI 41 acceptable for the conservative AURORA-B LOCA evaluation model.

3.6 Demonstration Analyses

Section 7.7 of ANP-10332P and various RAI responses describe the demonstration analyses Framatome completed to illustrate application of the full AURORA-B LOCA evaluation model to two sample plants (i.e., a BWR/4 and a BWR/6).

The NRC staff paid particular attention to the demonstration analyses in ANP-10332P, auditing input and output files for four demonstration cases. The NRC staff has previously related [ ]. Consequently, the NRC staff found the demonstration cases valuable as both reference material for interpreting and understanding the evaluation model and as a source of insight into code stability and predictability with all Appendix K models and other required features activated.

The NRC staff's review of the demonstration analyses from ANP-10332P, including the results of its audit of demonstration case input decks, is presented below. Since the majority of the NRC staff's review [ ], discussion primarily focuses on that material. However, in RAI 15, the NRC staff requested that Framatome [ ] on the demonstration analysis cases. This information will be discussed specifically in Section 3.6.3.

It should be emphasized that the NRC staff's audit [ ] Rather, [ ] must be selected conservatively on an individual basis for each analysis, and will be subject to review, as appropriate, by the NRC staff in connection with license amendment requests or other regulatory processes. The NRC staff has designated this position as Limitation and Condition 34 in Section 5.0 of this SE.

3.6.1 BWR/4 and BWR/6 Demonstration Cases

Sections 7.7.4, 7.7.5, and 7.7.6 of ANP-10332P contain analyses demonstrating application of the AURORA-B LOCA evaluation model to two sample plants (i.e., a BWR/4 and a BWR/6). These demonstration analyses, as supplemented by responses to RAIs 15 and 56, among others, focus primarily on the break spectrum analysis step in the plant safety analysis process described in Section 3.3.5.1 of this SE. In particular, for each sample plant, the demonstration analyses considered the spectrum of postulated recirculation line breaks (both suction and

discharge), two axial power profiles (mid- and top-peaked), and a sampling of potentially limiting single-failure scenarios.[55]

Description is provided in ANP-10332P for each analyzed scenario concerning the assumed plant parameters, initial conditions, failure scenarios, event sequences, and calculated figures of merit. Plots of key calculated parameters as a function of time are included. For the demonstration analyses presented in ANP-10332P **[ ]**, Framatome reported limiting conditions and results for each analyzed failure scenario[56] as tabulated below. Note in particular that the calculated results in Table 13 are **[ ]**

Table 11: Limiting Results for BWR/4 Demonstration Case (USEP12 Code Version)

[ ]

Table 12: Limiting Results for BWR/6 Demonstration Case (USEP12 Code Version)

[ ]

[55] It should, however, be emphasized that the break spectrum analysis for an actual plant safety analysis **[ ]**.

[56] Note that, while a specific description of each single failure scenario is not relevant to this safety evaluation (reference instead Tables 7-36 and 7-52 of ANP-10332P), it is worth noting that the scenarios considered in Table 11 and Table 12 involve postulated single failures; whereas, Table 13 involves a beyond-design-basis scenario with multiple failures that leaves available only a single train of the low-pressure core spray system.

Table 13: Limiting Results for BWR/4 Reduced ECCS Case (USEP12 Code Version)

[

			[57]		[58]

]

The NRC staff's review of the demonstration analyses in ANP-10332P resulted in a number of questions, which will be summarized briefly below. Issues relating particularly to the NRC staff's audit of the input and output files for four demonstration case input decks will be presented below in Section 3.6.2.

In RAI 27, the NRC staff requested that Framatome **[** **]**. Framatome's response affirmed that the ANP-10332P demonstration analyses **[** **]**. The NRC staff found Framatome's response consistent with the intent of the EMDAP paradigm.

In RAI 56, the NRC staff requested that Framatome complete additional simulations for the BWR/6 case **[** **]**. The NRC staff considered these simulations of interest due to the differences in the ECCS configuration between the BWR/4 and BWR/6 designs and **[** **]**. Framatome's response provided the requested results, which, as may be inferred from Table 12, **[** **]** presented in ANP-10332P.

In RAI 54, the NRC staff requested that Framatome explain **[** **]**. In Section 7.7 of ANP-10332P, Framatome presented peak cladding temperature results for the BWR/4 and BWR/6 demonstration cases in **[** **]**

[57] Note that Section 7.7.5 of ANP-10332P cites **[** **]**

[58] ANP-10332P notes that the **[** **]**, which conservatively satisfies the 1 percent criterion in 10 CFR 50.46.

[ ]

Figure 5: Break Spectra for BWR/6 Demonstration Case, Recirculation Line Break, Low-Pressure Core Spray Single-Failure[59]

In response to RAI 54, Framatome explained]. In particular, Framatome's **[** **]** The NRC staff agreed with Framatome's response to RAI 54, finding it physically well-reasoned and supported by sufficient evidence.

In RAI 58, the NRC staff requested that Framatome illustrate the margin associated with the conservative positions specified in Appendix K by **[**

[59] Note that in the figure legend, **[** **]**

]

- [ ], and

- [ ]

As a result, the NRC staff could not make an informed assessment of the conservatism of the AURORA-B LOCA evaluation model.

Framatome responded to RAI 58 [ ] with the following changes:

- [ ][60]
- [ ]
- [ ]
- [ ]

For both the [ ] case scenarios included in the sensitivity study, a significant conservative margin of [ ] sensitized conservatisms.

3.6.2 NRC Staff Audit of Demonstration Case Files

As noted above, to better understand and assess the AURORA-B LOCA evaluation model and its application, the NRC staff requested that Framatome provide files containing input decks, output decks, and graphics files for four demonstration cases included in ANP-10332P:

- BWR/4, mid-peaked axial profile, double-ended guillotine break on the recirculation pump suction line, with an opposite-unit-false-LOCA-signal single failure,

- BWR/6, mid-peaked axial profile, double-ended guillotine break on the recirculation pump suction line, with a low-pressure core spray single failure,

- BWR/4, top-peaked axial profile, 0.1-ft^2 split break on the recirculation pump suction line, with a battery single failure, and

- BWR/4, top-peaked axial profile, 0.4-ft^2 split break on the recirculation pump discharge line, with multiple failures (i.e., crediting only a single train of low-pressure core spray).

Regarding the fourth case, the NRC staff specifically requested an audit of this case in RAI 115 to illustrate the behavior of S-RELAP5 at conditions near regulatory limits, with particular focus

[60] Note in particular that the [ ], is not explicitly required by Appendix K to 10 CFR 50.

on the prediction of cladding swelling and rupture. Note that the highest peak cladding temperature in the three demonstration cases initially audited by the NRC staff [ ] neither in rupture nor significant swelling.

As described further below, the NRC staff's audit of these input decks resulted in a number of valuable observations. In particular, [ ] that required additional effort from Framatome to address and influenced several limitations and conditions in Section 5.0 of this SE.

3.6.2.1 Impact of Spacer Grids

In auditing certain demonstration cases provided by Framatome, the NRC staff [ ] Therefore, the NRC staff requested in RAI 60 that Framatome [ ] in Figure 6.

In response to RAI 60, Framatome explained that the temperature decrease in the two affected heat structure nodes was associated with the enhancement of interphase friction due to the presence of a spacer grid at the exit junction of the upstream hydrodynamic volume. Framatome stated that [ ] similar behavior to that shown in Figure 6.

[ ]

Figure 6: **[** **]** Temperature **[** **]** Observed by NRC Staff During Audit

The NRC staff's review of Framatome's response to RAI 60 noted **[** [61] **]**

[61] Note that this value is consistent with the NRC staff's earlier estimate, based upon audit review of demonstration case results, **[** **]** (e.g., see Figure 6).

Furthermore, the response to RAI 60 **[**

]

Based upon the evaluation above, the NRC staff imposed Limitation and Condition 35 **[**

]

3.6.2.2 Hot-Channel **[** **]**

The NRC staff audited Framatome's implementation **[** **]** for several of the demonstration cases. The NRC staff confirmed that, in all audited cases, **[** **]**. In fact, similar behavior was observed between the BWR/4 and BWR/6 large-break demonstration cases.

However, the NRC staff's audit found that Framatome's stated **[** **]** During the review, Framatome clarified that, **[** **]** While a mild reduction in calculated cladding oxidation could have resulted, this possibility does not detract from the purpose of the demonstration analyses.

In response to RAI 111, Framatome concluded that the **[** **]** should provide a conservative impact for limiting small- and large-break LOCAs. The NRC staff's audit of the demonstration cases indicated that, **[**

] Evidence supporting this viewpoint was observed in the audit of both the BWR/4 and BWR/6 large-break demonstration cases, **[** **]**.

Framatome’s response to RAI 111 **[** **]**

On the other hand, the available evidence indicates **[** **]**

3.6.2.3 Heat Transfer Modes and Appendix K Lockouts

The NRC staff examined the output of Framatome’s demonstration cases to assess the heat transfer modes reported by S-RELAP5, particularly for the hot node of the hot rod.

During the period of core heatup, the NRC staff confirmed that the heat transfer mode for the hot node of the audited small- and large-break LOCA cases **[** **]**

While the S-RELAP5 and TRACE results are not directly comparable, due in part to modeling differences, the NRC staff noted that, for the AURORA-B LOCA evaluation model, Framatome **[**

] A sample plot of the heat transfer mode for the peak node of the hot rod from the S-RELAP5 prediction of the BWR/4 large-break LOCA case is provided below as Figure 7.

[ ]

Figure 7: S-RELAP5-Predicted Heat Transfer Mode at Peak Node for BWR/4 Large-Break Demonstration Case

Ultimately, however, the NRC staff found no evidence that **[**

] resulted in a nonconservative impact on the assessment and validation results or demonstration cases. In particular, for the demonstration cases, **[**

], considering the evidence from the NRC staff's audit of the demonstration cases, as well as the generally conservative assessment comparisons

discussed in Section 3.4, the NRC staff ultimately found the current approach acceptable for the conservative AURORA-B LOCA evaluation model.

In addition, the NRC staff considered it worthwhile to assess the impacts of the Appendix K heat transfer lockouts in the demonstration cases. The times of imposition and release of both required heat transfer lockouts are shown below in Table 14.

Table 14: Appendix K Heat Transfer Lockout Imposition in Demonstration Cases

[ ]

It is apparent that, as the break size is reduced, imposition of the Appendix K heat transfer lockouts **[ ]** Limited evidence available from the demonstration cases suggests that the lockouts have **[ ]** Framatome's response to RAI 17 further suggests that, **[ ]**[62]

For all audited scenarios, the cladding temperature rise was observed to be turned around and effectively mitigated **[ ]**. Around the time of cladding temperature turnaround, the flow regime was observed **[ ]**.

3.6.2.4 Swelling and Rupture

The NRC staff's audit of Framatome's demonstration input decks discovered that swelling and rupture modeling **[ ]**, which resulted in the issuance of RAI 108.

Framatome's response to RAI 108 justified its approach by noting that the modeling of swelling and rupture **[ ]** As discussed further below in Section 3.6.2.7, the NRC staff found Framatome's approach **[**

[62] Positing an average heatup rate **[ ]**.

] to be conservative and appropriate. However, the NRC staff **[** **]**

3.6.2.5 Calculation of Oxidation

As noted above, **[** **]** one of the demonstration cases in ANP-10332P (see Table 13, above). **[** **]**, the NRC staff further requested in RAIs 115 and 126 that Framatome provide **[** **]**. As noted above, this case considered a bounding, beyond-design-basis scenario with reduced ECCS availability. Because the three other demonstration cases initially audited by the NRC staff **[** **]**.

Framatome's responses to RAIs 115 and 126 provided updated demonstration case results; **[** **]**.

In light of **[** **]**, the NRC staff performed an independent confirmatory calculation using the TRACE code with a simplified single-channel model. **[** **]**, the NRC staff generated representative curves that approximately envelop Framatome's calculated temperature profile, as shown below in Figure 8.

[ ]

Figure 8: Cladding Temperature Profiles Used in
NRC Staff Confirmatory Calculation for Cladding Oxidation

Table 15 shows the results of the confirmatory calculation, **[** **]**, such a demonstration of expected behavior increases the NRC staff's confidence that the calculation of oxidation in S-RELAP5 is being performed appropriately.

Table 15: Results of TRACE Confirmatory Calculation of Cladding Oxidation

[ ]

Comparing these results to those presented earlier in Table 13 shows that **[** **]** In particular, when cladding **[**

] on the calculation of maximum local oxidation.

3.6.2.6 BWR/4 Reduced ECCS Case

The NRC staff's audit of the BWR/4 reduced ECCS demonstration case, discussed in response to RAI 115, [ ]. As shown below in Table 16, while the peak cladding temperature [ ].

Table 16: Figures of Merit for BWR/4 Reduced ECCS Case[63]

[ ]

Figure 9, below, plots S-RELAP5-predicted cladding temperatures [ ]

In investigating the cause of the [ ] [64]

[63] The analysis described in response to RAI 115 [ ] Therefore, the magnitude of the calculated figures of merit differs from the values shown above in Table 13.

[64] In its review of this issue, the NRC staff noticed an inconsistency between the nodalization Framatome used in the demonstration cases and the nodalization diagram shown in Figure 6-6 of ANP-10332P. In particular, [ ].

[ ]

Figure 9: S-RELAP5-Predicted Peak Cladding Temperature at Limiting Nodes for BWR/4 Reduced ECCS Case

[ ]

Figure 10: S-RELAP5-Predicted Lower Plenum **[ ]** for BWR/4 Reduced ECCS Case

The NRC staff is not aware of **[ ]**

While code comparisons are not definitive, as a source of insight into the S-RELAP5 predictions, the NRC staff performed a set of confirmatory calculations using the TRACE code. The NRC staff's calculations corroborated **[ ]**

Considering the evidence discussed above, the NRC staff determined the following:

- **[ ]** were observed only in the BWR/4 reduced ECCS case, which involves challenging, beyond-design-basis conditions. In particular, with the low-pressure coolant injection system assumed inoperative, coolant injected by the single available train of low-pressure core spray essentially saturates prior to draining into the lower plenum. **[ ]**.

- Provided that **[ ]** result in a more conservative overall prediction of figures of merit.

The NRC staff recommends that **[ ]** in accordance with Limitation and Condition 20.

3.6.2.7 Figure-of-Merit Determination

In auditing the demonstration case output decks provided by Framatome, the NRC staff **[ ]**. In particular, the NRC staff observed that

- the **[ ]** in one audited demonstration case had a peak cladding temperature **[ ]**,

- an **[ ]** for one audited demonstration case **[ ]**, and

- for **[ ]** in the cases audited by the NRC staff, the cladding temperature and local oxidation **[ ]**.

[**]**. The NRC staff addressed these observations in RAIs 61 and 107, requesting that Framatome explain and justify the criteria used for determining figures of merit for reporting purposes.

Framatome responded to RAIs 61 and 107 **[** **]**.

With regard to the NRC staff's first point, above, Framatome stated **[** **]**. As noted above in the discussion regarding Limitation and Condition 20, the NRC staff **[** **]**

While the **[** **]**, a set of confirmatory analyses performed by the NRC staff using the TRACE code **[** **]**

Ultimately, while the AURORA-B LOCA evaluation model has substantial conservative margin, **[** **]**. Hence, the NRC staff designated Limitation and Condition 20 **[** **]**.

With regard to the NRC staff's **[** **]**, Framatome stated that the difference is attributable **[**

[65]], the NRC staff considered it reasonable to infer [ ], including the following:

- [ ] due to an expanded rod surface area,
- [ ] due to an increase in the fuel-to-cladding gap radius, and
- [ ] due to an expanded rod surface area.

At high cladding temperatures approaching regulatory limits, the effect of increased heat generation from the metal-water reaction becomes quite significant. However, at lower temperatures [ ]. In particular, the evidence provided by Framatome indicates [ ] will in general lead to conservative predictions [ ]. Therefore, the NRC staff considers Framatome’s [ ] to be conservative and acceptable. Furthermore, since the evaluation model [ ]

With regard to the NRC staff’s third point, above, regarding [ ], Framatome stated that, in the four audited demonstration cases, [ ] Framatome attributed the tendency [ ]. To illustrate the effect, Framatome performed a sensitivity analysis that was described in its response to RAI 107. The scenario used for the sensitivity case was the BWR/4 reduced ECCS case audited by the NRC staff, [ ]

The NRC staff’s review of Framatome’s response and related information found that [ ]. Therefore, the NRC staff concluded that, in general, [

[65] Note that [ ].

] Therefore, the NRC staff [

] Therefore, the NRC staff concluded that [ ]. This position is captured as Limitation and Condition 36 in Section 5.0 below.

Framatome further added [ ]. The NRC staff considered [ ]

3.6.3 Impact of UMAR16 Code Version [ ]

The NRC staff's review of the demonstration analysis results described above generally focuses upon the results provided in ANP-10332P [ ]. However, in RAI 15, the NRC staff requested that Framatome address any impacts on the demonstration analyses resulting from its decision to update the [ ]. In response, Framatome provided tables of peak cladding temperature results for several demonstration analysis scenarios [ ]. The limiting peak cladding temperature for each single-failure scenario, as reported by Framatome, is summarized in the following tables, along with the difference in the peak cladding temperature [ ].

Table 17: Limiting Results for BWR/4 Demonstration Case (UMAR16 Code Version)

[ ]

Table 18: Limiting Results for BWR/6 Demonstration Case (UMAR16 Code Version)

[ ]

Table 19: Limiting Results for BWR/4 Reduced ECCS Case (UMAR16 Code Version)[66]

[ ]

The above results are largely comparable to the **[** **]**.[67] However, the **[** **]**. Note that this **[** **]** of the integral effects comparison results in Table 9. Framatome stated that **[** **]**. However, **[** **]**, the NRC staff imposed Limitation and Condition 37 **[** **]**, specifically including the following items:

- **[** **]**
- **[** **]**
- **[** **]**
- **[** **]**

For the BWR/4 SF-LOCA scenario, the NRC staff observed that **[** **]**. As made clear in response to RAI 111, **[** **]**.

3.6.4 AURORA-B Comparison Cases Versus EXEM BWR-2000 Model

In addition to reviewing the demonstration cases provided in ANP-10332P, the NRC staff requested in RAI 3 that Framatome provide a comparison of the predictions of the AURORA-B LOCA evaluation model against Framatome's current LOCA evaluation model, EXEM BWR-2000. In response, Framatome provided comparative analyses for one small-break and one large-break case that were intended to model the same plant experiencing an identical LOCA scenario from equivalent initial conditions.

Plots of key parameters for the comparison cases for the AURORA-B LOCA and EXEM BWR-2000 evaluation models are included in response to RAI 3 and generally show reasonable agreement. In particular, the plots **[**

[66] Note that the **[** **]**.

[67] Note in particular that the calculated results in Table 13 are **[** **]**.

[68]

]

Table 20: Approximate Peak Cladding Temperature Difference [ ] in EXEM BWR-2000 Comparison Cases

[ ]

Framatome observed that perfect agreement between the AURORA-B LOCA and EXEM BWR-2000 evaluation models is not expected due to fundamental differences in code modeling capabilities. For example, the EXEM BWR-2000 model uses a three-equation, drift-flux homogenous-equilibrium formulation (as opposed to the two-fluid model employed in S-RELAP5). Framatome further stated that the RELAX model used in the EXEM BWR-2000 evaluation model contains [ ] volumes, as compared to the S-RELAP5 input deck for the AURORA-B LOCA evaluation model [ ] volumes.

Although some differences are apparent in the comparison plots, the NRC staff found the level of agreement reasonable overall and concluded that the information Framatome presented in response to RAI 3 increases confidence in the conservatism of the AURORA-B LOCA evaluation model. In particular, Framatome's response to RAI 3 [ ].

4.0 ADMINISTRATIVE REQUIREMENTS

4.1 Documentation

Acceptance criteria for the documentation of evaluation models for reactor safety analysis are provided in Chapter 15.0.2 of the SRP. The majority of the documentation necessary to support the AURORA-B LOCA evaluation model is contained in ANP-10332P itself. This includes an overview of the evaluation model, a description of the BWR LOCA event and relevant phenomena, the code assessment for S-RELAP5, justification that the requirements of Appendix K to 10 CFR 50 have been addressed, and description of a quality assurance plan. With the exception of the quality assurance plan (discussed in the following section), this information has been described and evaluated in the foregoing sections of this SE.

In addition, Chapter 15.0.2 of the SRP calls for theory and user's manuals for any codes supporting the evaluation model. As noted above, the AURORA-B LOCA evaluation model is based on the S-RELAP5 code, which incorporates a kernel of routines from RODEX4.

[68] While not included in this comparison, [ ] of the EXEM BWR-2000 evaluation model (e.g., Reference 60).

Therefore, in support of the present review of ANP-10332P, the NRC staff requested and Framatome supplied for information current versions of its S-RELAP5 code theory manual (Reference 11) and user's manual (Reference 12).

The NRC staff frequently referenced these manuals in support of its review of ANP-10332P, particularly during the audit of the demonstration analyses described above in Section 3.6.2. The NRC staff further sampled relevant sections of these manuals to assess whether they contain adequate descriptions of the S-RELAP5 code, with particular focus upon the recent changes made to support implementation of the AURORA-B LOCA evaluation model.

While the NRC staff concluded that these manuals generally provide the information necessary for analysts to apply the S-RELAP5 code to plant-specific analyses under the AURORA-B LOCA evaluation model, the NRC staff's **[** **]** with the code manuals:

- As detailed above in Section 1.2, Framatome **[** **]** could be helpful.

- The NRC staff noted that **[** **]**

- As discussed above in Section 3.3.1.1, the NRC staff **[** **]**.

- As discussed above in Section 3.3.1.2.4, the NRC staff **[** **]**

- Criteria for reporting the heat transfer modes **[** **]**.

- As noted above in Section 3.3.4.1.2, the theory manual **[**

  ].

While the NRC staff's audit of the S-RELAP5 code theory and user's manuals generally found them sufficient to support application of the AURORA-B LOCA evaluation model, the NRC staff **[**

]

At a further level of detail, Framatome is developing a modeling guidelines document (Reference 26) and procedures for performing plant-specific analysis with the AURORA-B LOCA evaluation model. The NRC staff audited a draft of the modeling guidelines document for the AURORA-B LOCA evaluation model and, in response to RAI 62, **[**

].

Particularly in light of the **[** **]** S-RELAP5 code theory manual, the NRC staff considered the modeling guidelines document essential for ensuring consistent implementation of the AURORA-B LOCA evaluation model. As such, the NRC staff **[**

] This expectation is formalized as Limitation and Condition 38.

Although it is possible that supporting documentation such as code manuals and modeling guidelines may be subject to audit reviews in the future, these documents are not formally a part of the approved evaluation model; hence, such documents are beyond the scope of the present review and are not explicitly approved. **[**

] and Limitation and Condition 40, **[**

].

4.2 Quality Assurance Plan

As noted by Framatome in Sections 3.1 and 10.0 of ANP-10332P, because analyses generated using the AURORA-B LOCA evaluation model are important to the safety of nuclear power plants, the evaluation model must be maintained under a quality assurance program that meets the criteria set forth in Appendix B to 10 CFR 50. According to Chapter 15.0.2 of the SRP, a vendor's quality assurance plan for accident and transient analysis methods should address, at a minimum, design control, document control, software configuration control and testing, and corrective actions.

Section 10.0 of ANP-10332P summarizes Framatome's quality assurance program, as applicable to the AURORA-B LOCA evaluation model. Framatome stated that its quality assurance program applies throughout all stages of the analysis process, including verification and validation. Framatome further stated that its quality assurance program covers procedures for design control, document control, software configuration control and testing, error

identification, and corrective actions. In addition the program covers training for personnel involved with performing analyses, code development, and code maintenance.

The NRC staff generally found the quality assurance program described in ANP-10332P to be appropriate and consistent with regulatory guidance in the SRP.

However, in RAI 64, the NRC staff **[** **]** Framatome responded that **[** **]** The NRC staff found Framatome's response to RAI 64 consistent with regulatory guidance and, hence, acceptable. The NRC staff further noted that, in accordance with Appendix B to 10 CFR 50, reviews performed by vendors and licensees would be responsible for assessing and, as necessary correcting, unexpected behaviors in calculations supporting plant safety analyses.

Chapter 15.0.2 of the SRP and RG 1.203 call for independent reviews of evaluation models at key steps in the development process. The NRC staff recognizes that **[** **]**. In the case of S-RELAP5, due to the similarity of many features with other code versions in the RELAP5 family that have been subject to extensive peer review over the years, this guidance position may be considered partially satisfied. However, **[** **]**. In this regard, past and present NRC staff reviews of evaluation models reliant upon the S-RELAP5 code may be considered as independent reviews of code development and assessment; as such, the NRC staff considers the intent of the guidance satisfied.

In RAI 27, the NRC staff requested that Framatome explain how **[** **]**. Framatome's response identified that, **[** **]** As a result, the NRC staff concludes there is confidence that **[** **]**.

As discussed above, the NRC staff's review found the quality assurance program Framatome proposed for the AURORA-B LOCA evaluation model to be adequate.

4.3 Update Process

Before discussing the update process proposed in Section 12.0 of ANP-10332P, it is worth reemphasizing the distinction maintained in this SE between the terms *evaluation model* and *code*.

In particular, 10 CFR 50.46(c)(2) defines an *evaluation model* for the LOCA event (e.g., the AURORA-B LOCA evaluation model) as follows:

> An evaluation model is the calculational framework for evaluating the behavior of the reactor system during a postulated loss-of-coolant accident (LOCA). It includes one or more computer programs and all other information necessary for application of the calculational framework to a specific LOCA, such as mathematical models used, assumptions included in the programs, procedure for treating the program input and output information, specification of those portions of analysis not included in computer programs, values of parameters, and all other information necessary to specify the calculational procedure.

The definition of an evaluation model was subsequently expanded in RG 1.203 and Chapter 15.0.2 of the SRP to encompass additional analytical methods used to simulate a broader set of transient and accident scenarios necessary for reactor safety analyses. Evaluation models are generally reviewed by the NRC staff either prior to licensing applications via the generic TR process (i.e., as in the present review) or on a plant-specific basis during licensing applications.

Whereas, a *code* (e.g., S-RELAP5) or *code system* (e.g., the AURORA-B code system) refers to one or more computer programs developed and maintained by a vendor, which may or may not be part of an NRC-approved evaluation model. If a code is not incorporated into any NRC-approved evaluation models, the vendor may generally modify the code at will. However, for codes that have been incorporated into one or more NRC-approved evaluation models, vendors are generally at liberty to make only changes that do not materially impact the approved evaluation model(s).

In Section 12.0 of ANP-10332P, Framatome proposed a process for making modifications to the AURORA-B LOCA evaluation model. However, as part of its acceptance of the methodology in ANP-10332P, the NRC staff does not specifically approve any new processes for implementing updates or changes that would impact the AURORA-B LOCA evaluation model, as documented in ANP-10332P, Framatome's RAI responses, or the basis for any conclusions made in the NRC staff's SE (e.g., changes to code models, required modeling options and assumptions, nodalization, required inputs, etc.).

The NRC staff does not object to code changes that do not substantially alter the approved AURORA-B LOCA evaluation model. For instance, as discussed previously in the NRC staff's SE for ANP-10300P (Reference 8), the NRC staff generally considers certain code changes as having low potential to impact the approved evaluation model, for example:

- enhancing source coding and its structure
- porting a code to a different computational platform

- parallelizing the existing numerical solution method across multiple processors
- updating the physical properties of water to current standards

In each of these examples, the effect of such code changes on an approved evaluation model is expected to be minimal, which would be confirmed by the vendor's continuity of assessment and quality assurance processes. Furthermore, since the above examples also reside at a level of detail that is typically below what the NRC staff reviews and approves, such changes appear unlikely to affect descriptions or information provided in ANP-10332P and associated RAI responses, or the basis for any conclusions made in the NRC staff's SE.

As a **[**

]

Application of the AURORA-B LOCA evaluation model to new types of fuel is addressed in Section 12.1 of ANP-10332P. While the NRC staff's review of the AURORA-B LOCA evaluation model is not explicitly tied to any particular fuel design(s), the NRC staff's evaluation of **[**

].
In light of this dependency, for new or modified fuel designs, the NRC staff finds necessary the demonstration of continued (1) compatibility of the AURORA-B LOCA evaluation model field equations and closure relations, and (2) applicability of the AURORA-B LOCA evaluation model assessment and validation effort. This expectation is captured in Limitation and Condition 39. Furthermore, implementation of new, previously approved critical power correlations in steady-state S-RELAP5 calculations as a means of validating (or recalibrating) **[**

] is acceptable to the NRC staff.

Regarding Framatome's proposal in Section 12.1 of ANP-10332P concerning evaluation model modifications to support the analysis of lead test assemblies (e.g., incorporation of unapproved models and correlations), the NRC staff considers this topic beyond the scope of the present safety evaluation. As noted by Framatome, licensees are responsible for assessing the need for NRC staff review prior to implementing methodology changes, including those they may deem necessary for the analysis of lead test assemblies. The acceptability of future changes implemented to address lead test assemblies cannot be judged at the present time and would instead be evaluated by the NRC staff, as necessary, in subsequent reviews.

In response to RAI 65, Framatome discussed **[**

] Framatome further stated, however,
[

]

In the NRC staff's view, the practical result of Framatome's response to RAI 65 is reasonable [

] Rather, proposed changes to a particular licensee's evaluation model must be assessed on a plant-specific basis [

]

Verification that code changes [

] including

- [ ],
- [ ],
- [ ],
- [ ], and
- [ ].

In response to RAI 63, Framatome stated [

]

Although Framatome's **[** **]** questions:

- **[** **]**.
  - **[** **]**.
  - **[** **]**.
- **[** **]**.
- **[** **]**.
- **[** **]**.
- **[** **]**.

[**]** associated with the change process that the NRC staff is not approving in this SE, the NRC staff **[** **]**.

Based on the discussion above, the NRC staff **[** **]**. This position is documented below as Limitation and Condition 40. However, consistent with existing practice, the NRC staff finds **[** **]**. Limitation and Condition 40 should not be construed as abridging in any way the authority of individual licensees to make plant-specific evaluation model changes under the process outlined in 10 CFR 50.59.

5.0 LIMITATIONS AND CONDITIONS

For reasons explained in the foregoing evaluation, the NRC staff finds the following limitations and conditions necessary, in general, to support application of the AURORA-B LOCA evaluation model for performing safety analysis for BWR/3-6 plants:

1. The AURORA-B LOCA evaluation model shall be supported by an approved nodal core simulator and lattice physics methodology. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model shall identify the nodal core simulator and lattice physics methods supporting the AURORA-B LOCA analysis and reference an NRC-approved TR that confirms compatibility of these methods with the AURORA-B LOCA evaluation model. (Section 1.1)

2. The full, stand-alone version of the RODEX4 code shall be used in accordance with an approved methodology to supply steady-state fuel thermal-mechanical inputs to the AURORA-B LOCA evaluation model. (Section 1.1)

3. The AURORA-B LOCA evaluation model may not be used to perform analyses that result in any of its constituent components or supporting codes (i.e., S-RELAP5, RODEX4 kernel, RODEX4, core simulator and lattice physics methods) being operated outside approved limits documented in their respective TRs, SEs, code manuals, and plant-specific licensing applications. (Section 1.2)

4. TR ANP-10332P **[**

   ] (Section 2.1)

5. The conclusions of this SE apply only to the use of the AURORA-B LOCA evaluation model for the purpose of demonstrating compliance against currently existing regulatory requirements discussed above in Section 2.1; **[**

   ]. (Section 2.1)

6. This SE does not constitute **[**

   ] of the evaluation model. (Section 3.2)

7. **[**

   ] (Section 3.3.1.2.2)

8. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model shall provide **[**

   ].

   (Section 3.3.1.2.2)

9. The AURORA-B LOCA evaluation model shall **[**

] in the response to RAI 114. (Section 3.3.1.2.4)

10. The AURORA-B LOCA evaluation model **[** **]** (Section 3.3.4.1.1)

11. Safety analyses performed with the AURORA-B LOCA evaluation model **[** **]** (Section 3.3.4.1.1)

12. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Section 3.3.4.1.1)

13. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]**. (Section 3.3.4.1.1)

14. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Section 3.3.4.1.1)

15. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]**. (Section 3.3.4.1.2)

16. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Section 3.3.4.1.2)

17. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]**. (Section 3.3.4.1.2)

18. The AURORA-B LOCA evaluation model **[** **]**. (Section 3.3.4.1.3)

19. The AURORA-B LOCA evaluation model **[** **]**. (Section 3.3.4.1.4)

20. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Sections 3.3.4.2.1, 3.5.4, and 3.6.2.6)

21. The AURORA-B LOCA evaluation model **[** **]**. (Section 3.3.4.2.1)

22. In lieu of the conservative approach of using **[** **]** (Section 3.3.4.2.1)

23. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Section 3.3.4.2.3)

24. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Section 3.3.4.3.2)

25. Safety analyses performed with the AURORA-B LOCA evaluation model [ ]. (Section 3.3.5.3)

26. Safety analyses performed with the AURORA-B LOCA evaluation model [ ]. (Section 3.3.5.3)

27. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model [ ] (Section 3.3.5.4)

28. To assure satisfaction of GDC 35 (or similar plant-specific requirement), [ ] (Sections 3.3.5.4 and 3.3.5.5)

29. Safety analyses for [ ] (Section 3.3.5.5)

30. Simulations supporting plant safety analyses [ ] (Sections 3.3.5.7 and 3.6.2.7)

31. As discussed in Section 3.3.5.7, Framatome used **[** **]** (Sections 3.3.5.7 and 3.5)

32. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Section 3.4.3.8)

33. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]** (Section 3.4.4.1.1)

34. The NRC staff has not specifically reviewed any plant parameters in ANP-10332P or deemed them acceptable for use in plant safety analyses. Therefore, **[** **]** (Section 3.6)

35. Safety analyses performed with the AURORA-B LOCA evaluation model **[** **]** (Sections 3.4.3.5 and 3.6.2.1)

36. The AURORA-B LOCA evaluation model **[** **]** (Section 3.6.2.7)

37. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** **]**:

- **[** **]**
- **[**
  ]
- **[** **]**
- **[** **]** (Section 3.6.3)

38. Plant-specific licensing applications referencing the AURORA-B LOCA evaluation model **[** [69] **]** (Section 4.1)

39. New or modified Framatome **[** **]** (Section 4.3)

40. Except as discussed in Section 4.3 of this SE, the NRC staff **[** **]** (Section 4.3)

6.0 COMPLIANCE SUMMARY

The foregoing evaluation has assessed the AURORA-B LOCA evaluation model, as described in ANP-10332P, that Framatome has proposed for evaluating the loss-of-coolant accident **[** **]**. Based upon the NRC staff's review of this TR (Reference 1), Framatome's RAI responses (Reference 5), and other supporting materials, the NRC staff proposed in Section 5.0 a series of limitations and conditions that are deemed necessary, in general, to ensure that safety analyses performed with the AURORA-B LOCA evaluation model will comply with applicable regulatory requirements. This section of the NRC staff's SE provides a summary assessment of the consistency of the AURORA-B LOCA evaluation model, as modified by limitations and conditions in Section 5.0, with applicable regulatory guidance and requirements.

[69] Note that the draft version of the modeling guidelines document audited by the NRC staff during this review is listed as Reference 26 to this SE.

6.1 Conformance with Relevant Regulatory Guidance

As noted previously in Section 2.2 of this SE, the primary sources of regulatory guidance applicable to the AURORA-B LOCA evaluation model include Chapter 15 of the SRP and RG 1.203.

With regard to Chapter 15 of the SRP, this SE has documented the basis for conformance in all major review areas including

- documentation (Section 4.1)
- evaluation model (Section 3.3)
- identification of accident sequence and phenomenon ranking (Section 3.2)
- assessment and validation (Section 3.4)
- addressing uncertainty via conformance to Appendix K to 10 CFR 50 (Section 6.2.1)
- quality assurance plan (Section 4.2)

With regard to RG 1.203, Framatome used the EMDAP structure to organize ANP-10332P, and further made a reasonable effort to show compliance against the EMDAP criteria. While the NRC staff found ANP-10332P generally responsive to the EMDAP criteria, **[**

]. However, as noted above, RG 1.203 allows for a reduction in the rigor of EMDAP implementation where justified by sufficient evaluation model conservatism. As noted above, the NRC staff found sufficient evidence of conservatism in the Appendix K-based AURORA-B LOCA evaluation model to justify such a reduction in rigor. Thus, RG 1.203 may be considered satisfied.

6.2 Compliance with Applicable Regulatory Requirements

As discussed above in Section 2.1, LOCA evaluation models may demonstrate compliance with 10 CFR 50.46 by either (1) realistically analyzing the LOCA event and explicitly accounting for uncertainty or (2) conservatively analyzing the LOCA event in accordance with the prescriptive requirements of Appendix K to 10 CFR 50. The AURORA-B LOCA evaluation model follows the second option.

6.2.1 Conformance to Appendix K to 10 CFR 50

As a practical convenience, the foregoing SE has presented its assessment of the AURORA-B LOCA evaluation model according to a format developed for best-estimate models that explicitly account for uncertainty. In particular, this organizational structure was selected for compatibility with ANP-10332P (the structure of which mirrors the EMDAP described in RG 1.203), as well as the review guidance in Chapter 15.0.2 of the SRP.

While the modern perspective of the EMDAP has contributed additional depth and rigor to the review process, ultimately, the NRC staff **[**

] of Appendix K have in fact been satisfied by the AURORA-B LOCA evaluation model. Appendix K to 10 CFR 50 specifies both (1) required and acceptable features for evaluation models used to analyze the LOCA event and (2) documentation requirements. The NRC staff's rationale for concluding that the AURORA-B LOCA evaluation model described in ANP-10332P, as modified by this SE, conforms to these Appendix K requirements is summarized below in Table 21.

Table 21: Conformance of AURORA-B LOCA Evaluation Model with Appendix K to 10 CFR 50

6.2.2 Compliance with Relevant Criteria from 10 CFR 50.46

The AURORA-B LOCA evaluation model is intended to provide a methodology [ ] licensees to perform safety analyses capable of demonstrating compliance with certain criteria specified in 10 CFR 50.46, namely

- the peak cladding temperature does not exceed 2200 °F,
- the calculated local cladding oxidation does not exceed 17 percent of the cladding thickness prior to oxidation,
- the total amount of hydrogen generated from the metal-water reaction is limited to 1 percent of the hypothesized theoretical maximum, and
- the reactor core is maintained in a coolable geometry.[70]

As an alternative to best-estimate models that explicitly account for uncertainty, 10 CFR 50.46 allows the development of LOCA evaluation models in conformance with the required and acceptable features of Appendix K to 10 CFR 50. The NRC staff has concluded that the AURORA-B LOCA evaluation model, as modified by this SE, conforms to the required and acceptable features of Appendix K. As discussed above in Section 3.3.5, the AURORA-B LOCA evaluation model would consider a sufficient number of postulated LOCA scenarios with break sizes, locations, and characteristics to ensure that the limiting condition is calculated. Therefore, it may be used to perform safety analyses [ ] licensees for the purpose of demonstrating compliance with 10 CFR 50.46.

6.2.3 Compliance with General Design Criterion 35

Inasmuch as 10 CFR 50.46 and Appendix K specify detailed requirements for demonstrating adequate ECCS performance for each “boiling or pressurized light-water reactor fueled with uranium oxide pellets within cylindrical zircaloy or ZIRLO cladding…,” the NRC staff’s conclusions above that analyses performed using the AURORA-B LOCA evaluation model would satisfy these requirements leads directly to an identical conclusion regarding GDC 35. However, [ ]. As noted above in Section 3.3.5.4, Limitation and Condition 28 [ ].

6.2.4 Proposed Rule 10 CFR 50.46c

Sections 2.5.1 and 4.4 of ANP-10332P discuss how the AURORA-B LOCA evaluation model [ ]. However, as documented above in Limitation

[70] Note that, although [ ] must also demonstrate that sufficient long-term core cooling is provided to maintain an acceptable core temperature, as discussed above in Section 2.1, this demonstration is beyond the scope of the AURORA-B LOCA evaluation model.

and Condition 5, the NRC staff [ ]

7.0 CONCLUSION

Based upon the foregoing evaluation, the NRC staff has concluded that, contingent upon the satisfaction of the limitations and conditions defined in Section 5.0 of this SE, the AURORA-B LOCA evaluation model described in ANP-10332P provides an acceptable methodology for performing safety analyses for [ ] for the purpose of demonstrating compliance with the criteria in 10 CFR 50.46 (b)(1)-(4) in accordance with the required and acceptable features prescribed in Appendix K to 10 CFR 50.

8.0 REFERENCES[71]

1. ANP-10332P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Loss of Coolant Accident Scenarios," AREVA Inc., February 2014 (ADAMS Package Accession No. ML14091A220).

2. Audit Report for the May 16 to May 18, 2017, Audit in Support of the Review of ANP-10332P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Loss of Coolant Accident Scenarios," NRC, December 5, 2017 (ADAMS Package Accession No. ML17262B138 (Non-Public)/ML17262B196 (Public)).

3. Request for Additional Information Regarding AREVA Inc., Topical Report ANP-10332P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Loss of Coolant Accident Scenarios," NRC, October 24, 2017 (ADAMS Package Accession No. ML17257A302 (Non-Public)/ML17257A309 (Public)).

4. Request for Additional Information Regarding AREVA Inc. Topical Report ANP-10332P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Loss of Coolant Accident Scenarios," NRC, January 29, 2018 (ADAMS Package Accession No. ML17360A202 (Non-Public)/ML17360A207 (Public)).

5. Response to Request for Additional Information Regarding Topical Report ANP-10332P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Loss of Coolant Accident Scenarios," Framatome Inc., April 30, 2018 (ADAMS Package Accession No. ML18122A227).

6. NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," NRC, June 1987 (ADAMS Package Accession No. ML052340514).

7. ANP-10300P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Transient and Accident Scenarios," AREVA Inc., December 2009 (ADAMS Package Accession No. ML100040163 (Non-Public)/ML100040157 and ML100040158 (Public)).

8. Final Safety Evaluation for AREVA Inc. Topical Report ANP-10300P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to

[71] Note that certain references may be proprietary and, hence, unavailable to the general public. These references may be denoted by a P in the suffix of the report number or otherwise labeled as proprietary in the list below; conversely, a report number suffix including NP is typically indicative of a redacted, non-proprietary version of a proprietary document. Where applicable, accession numbers for the NRC's Agencywide Document Access and Management System (ADAMS) are provided for the reader's convenience.

Transient and Accident Scenarios," NRC, January 5, 2018 (ADAMS Package Accession Nos. ML17346B039 (Non-Public)/ML18124A214 (Public)).

9. ANP-10333P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Control Rod Drop Accident (CRDA)," AREVA Inc., March 2014 (ADAMS Accession No. ML14098A332 (Public)/ML14098A333 (Non-Public))

10. Final Safety Evaluation for Topical Report ANP-10333P, Revision 0, "AURORA-B: An Evaluation Model for Boiling Water Reactors; Application to Control Rod Drop Accident (CRDA)," NRC, March 15, 2018 (ADAMS Accession No. ML18038B277 (Non-Public)/ML18128A002 (Public)).

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