U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

15.4.6 INADVERTENT DECREASE IN BORON CONCENTRATION IN THE REACTOR COOLANT SYSTEM (PWR)

REVIEW RESPONSIBILITIES

Primary - Organization responsible for review of transient and accident analyses for PWRs/BWRs

Secondary - None

I. AREAS OF REVIEW

Unborated water can be added to the reactor coolant system (RCS), via the chemical volume and control system (CVCS), to increase core reactivity. This may be inadvertent due to operator error or CVCS malfunction, and cause an unwanted increase in reactivity and a decrease in shutdown margin. A specific plant design may include other inadvert additions of unborated water to the RCS, like instrument flushing systems. During refueling, the RCS is an open system. An inadvertent addition of unborated water to the RCS is possible due to operator error or malfunction of systems not connected to the RCS. The operator must stop this unplanned dilution before the shutdown margin is eliminated. As sequences of events that may occur depend on plant conditions at the time of the unplanned moderator dilution, the review includes conditions like refueling, startup, power operation (automatic control and manual modes), hot standby, hot shutdown, and cold shutdown.

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The specific areas of review are as follow:

1. The review of postulated moderator dilution events considers causes, initiating events, the sequence of events, the analytical model, the values of parameters in the analytical model, and predicted consequences of the event.

2. The sequence of events described in the applicant's safety analysis report (SAR) is reviewed. The reviewer concentrates on the need for the reactor protection system and required operator action to secure and maintain the reactor in a safe condition.

3. The analytical methods are reviewed for whether the mathematical modeling and computer codes have been accepted by the staff. If a referenced analytical method has not been previously reviewed, the reviewer initiates a generic evaluation of the new analytical model.

4. The predicted results of moderator dilution events are reviewed to assure that the consequences meet the acceptance criteria of subsection II of this Standard Review Plan (SRP) section. The results of the transients are also reviewed to ascertain that the values of pertinent system parameters are within expected ranges for the type and class of reactor under review.

5. COL Action Items and Certification Requirements and Restrictions. For a DC application, the review will also address COL action items and requirements and restrictions (e.g., interface requirements and site parameters).

   For a COL application referencing a DC, a COL applicant must address COL action items (referred to as COL license information in certain DCs) included in the referenced DC. Additionally, a COL applicant must address requirements and restrictions (e.g., interface requirements and site parameters) included in the referenced DC.

Review Interfaces

Other SRP sections interface with this section as follows:

1. General information on transient and accident analyses is provided in SRP Section 15.0.

2. Design basis radiological consequence analyses associated with design basis accidents are reviewed under SRP Section 15.0.3.

3. Values of the parameters in the analytical models of the reactor core are reviewed for compliance with plant design and specified operating conditions, acceptance criteria for fuel cladding damage limits are determined, and the core physics, fuel design, and core thermal-hydraulics data in the SAR analysis are reviewed under SRP Sections 4.2, 4.3, and 4.4.

4. Systems for emergency injection of borated cooling water are reviewed under SRP Section 6.3.

5. Aspects of the sequence described in the SAR are reviewed to confirm that reactor and plant protection, engineered safety features (EFS) controls, interlocks, and other instrumentation and control systems important to safety will function as assumed in the safety analyses under SRP Sections 7.2 through 7.7.

6. Functional and operational characteristics and potential failure modes of the CVCS are reviewed under SRP Section 9.3.4. This includes the functional and operational characteristics and potential failure modes of other systems identified as having the potential for an inadvertent addition of unborated water into the RCS due to operator error or system malfunction. The reviewer of this section makes use of this review to evaluate initiating causes and the expected sequence of events.

The specific acceptance criteria and review procedures are contained in the referenced SRP sections.

II. ACCEPTANCE CRITERIA

Requirements

Acceptance criteria are based on meeting the relevant requirements of the following Commission regulations:

1. General Design Criterion (GDC) 10, as it relates to the reactor core and its coolant, control, and protection systems with appropriate design margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences.

2. GDC 13 as to the availability of instrumentation to monitor variables and systems over their anticipated ranges to assure adequate safety, and of appropriate controls to maintain these variables and systems within prescribed operating ranges.

3. GDC 15, as it relates to the RCS and its auxiliary, control, and protection systems with sufficient design margin to assure that the design conditions of the reactor coolant pressure boundary (RCPB) are not exceeded during any condition of normal operation, including anticipated operational occurrences.

4. GDC 26, as it relates to the capability of control rods to reliably control reactivity changes to assure that under conditions of normal operation, including anticipated operational occurrences (AOOs), and with appropriate margin for malfunctions like stuck rods, specified acceptable fuel design limits are not exceeded.

5. The general objective of the review of moderator dilution events is to confirm either of the following conditions is met:

    A. The consequences of these events are less severe than those of another transient that results in an uncontrolled increase in reactivity and has the same anticipated frequency classification.

B. The plant responds to events such that the criteria regarding fuel damage and system pressure are met and the dilution transient is terminated before the shutdown margin is eliminated.

SRP Acceptance Criteria

Specific SRP acceptance criteria acceptable to meet the relevant requirements of the NRC's regulations identified above are as follows for the review described in this SRP section. The SRP is not a substitute for the NRC's regulations, and compliance with it is not required. However, an applicant is required to identify differences between the design features, analytical techniques, and procedural measures proposed for its facility and the SRP acceptance criteria and evaluate how the proposed alternatives to the SRP acceptance criteria provide acceptable methods of compliance with the NRC regulations.

1. Pressure in the reactor coolant and main steam systems should be maintained below 110 percent of the design values.

2. Fuel cladding integrity must be maintained so the minimum departure from nucleate boiling ratio (DNBR) remains above the 95/95 DNBR limit for pressurized-water reactors (PWRs) based on acceptable correlations with SRP Section 4.4.

3. An incident of moderate frequency should not generate a more serious than moderate plant condition without other faults occurring independently.

4. If operator action is required to terminate the transient, the following minimum time intervals must be available between the time an alarm announces an unplanned moderator dilution and the time shutdown margin is lost:

   A. During refueling: 30 minutes.

   B. During startup, cold shutdown, hot shutdown, hot standby, and power operation: 15 minutes.

5. The applicant's analysis of moderator dilution events should use an acceptable analytical model. Staff must evaluate any proposed unreviewed analytical methods. The reviewer initiates an evaluation of new generic methods. The following plant initial conditions should be considered in the analysis: refueling, startup, power operation (automatic control and manual modes), hot standby, hot shutdown and cold shutdown. Parameters and assumptions in the analytical model should be suitably conservative. The following values and assumptions are acceptable:

   A. For analyses during power operation, the initial power level is rated output (licensed core thermal power) plus an allowance of 2 percent to account for power-measurement uncertainty. The analysis may use a smaller power-measurement uncertainty if justified adequately.

   B. The boron dilution is assumed to occur at the maximum possible rate.

C. Core burnup and corresponding boron concentration must yield the most limiting combination of moderator temperature coefficient, void coefficient, Doppler coefficient, axial power profile, and radial power distribution. The core burnup must be justified by either analysis or evaluation.

D. All fuel assemblies are installed in the core.

E. A conservatively low value is assumed for the reactor coolant volume.

F. For analyses during refueling, all control rods are withdrawn from the core. An alternate assumption requires adequate justification and delineation of necessary controls so the alternate assumption remains valid.

G. For analyses during power operation, the minimum shutdown margin allowed by the technical specifications (usually 1 percent) is assumed prior to boron dilution.

H. A conservatively high reactivity addition rate is assumed for each analyzed event to take into account the effect of increasing boron worth with dilution.

I. Conservative scram characteristics are assumed (*i.e.*, maximum time delay with the most reactive rod out of the core).

Technical Rationale

The technical rationale for application of these acceptance criteria to the areas of review addressed by this SRP section is discussed in the following paragraphs:

1. GDC 10 requires design of the reactor core and its coolant, control, and protection systems with appropriate margin so acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of AOOs. Fuel design limits are established to assure the integrity of fuel cladding as a FP barrier.

   In PWRs, boron is added to the reactor coolant in sufficient concentrations for reactivity control. PWR conditions of normal operation include startup, power operation, hot standby, shutdown (hot and cold), and refueling modes. Because of the frequency of boron dilution events (one or more times during the life of the nuclear power unit) without other concurrent failures or incidents, regulatory requirements for AOOs apply to their analyses or evaluations. Uncertainties of quantification or measurement of relevant boron dilution event parameters are verified by analyses including appropriate design margins.

   Thus, GDC 10 assures that analyses demonstrate, under all operating, shutdown, and refueling modes, whether the reactor core and its coolant, control, and protection systems are designed with sufficient margins for postulated boron dilution events to maintain fuel cladding integrity.

2. GDC 13 requires the provision of instrumentation that is capable of monitoring variables and systems over their anticipated ranges to assure adequate safety, and of controls that can maintain these variables and systems within prescribed operating ranges.

GDC 13 applies to this section because the reviewer evaluates the sequence of events, incuding automatic actuations of protection systems, and manual actions, and determines whether the sequence of events is justified, based upon the expected values of the relevant monitored parameters and instrumental indicators.

3. GDC 15 requires design of the RCS and its auxiliary, control, and protection systems with sufficient margin so RCPB design conditions are not exceeded during any normal operation, including AOOs. Design conditions (*e.g.,* pressure limits for transients) of the RCPB are established to assure its integrity. The RCPB provides a FP barrier, confined volume for the inventory of reactor coolant, and flow paths for core cooling.

   In PWRs, boron is added to the reactor coolant in sufficient concentrations for reactivity control. PWR conditions of normal operation include startup, power operation, hot standby, shutdown (hot and cold), and refueling modes. Because of the frequency of boron dilution events (one or more times during the life of the nuclear power unit) without other concurrent failures or incidents, regulatory requirements for AOOs apply to their analyses or evaluations.

   RCS pressure transients of power increases caused by postulated boron dilution events are analyzed for whether pressure limiting design features, including conservatively assumed responses of control and protection systems, maintain pressures below the RCPB design pressure limits for transients. Uncertainties of quantification or measurement of relevant boron dilution event parameters are verified by analyses including appropriate design margins.

   Thus, GDC 15 assures that analyses demonstrate, under conditions of normal operation, including the effects of postulated boron dilution events, design of the RCS and its auxiliary, control, and protection systems with sufficient margin to maintain RCPB integrity.

4. GDC 26 requires control rods to control reactivity changes to assure that acceptable fuel design limits are not exceeded under normal operation, including AOOs, and with appropriate margin for malfunctions such as stuck rods. Fuel design limits are established to assure the integrity of fuel cladding as a FP barrier.

   In PWRs, a control rod system is provided for reactivity control. Boron is also added to the reactor coolant in sufficient concentrations for reactivity control. PWR conditions of normal operation include startup, power operation, hot standby, shutdown (hot and cold), and refueling modes; however, the control rods may reduce reactivity only when withdrawn and operable (*i.e.* during startup and power operation). Because of the frequency of boron dilution events (one or more times during the life of the nuclear power unit) without other concurrent failures or incidents, regulatory requirements for AOOs apply to their analyses or evaluations. Uncertainties of quantification or measurement of relevant boron dilution event parameters are verified by analyses including appropriate design margins. To address single failures not attributable to a common cause/mode, the control rod system is designed for a specified minimum shutdown margin without credit for the functioning of the highest worth control rod.

Thus, GDC 26 assures that analyses demonstrate whether the control rods reliably control reactivity changes with appropriate margin for malfunctions like stuck rods under applicable conditions of normal operation (startup and power operation), including the effects of postulated boron dilution events, to maintain fuel cladding integrity.

III. REVIEW PROCEDURES

The reviewer will select material from the procedures described below, as may be appropriate for a particular case.

These review procedures are based on the identified SRP acceptance criteria. For deviations from these acceptance criteria, the staff should review the applicant's evaluation of how the proposed alternatives provide an acceptable method of complying with the relevant NRC requirements identified in Subsection II.

The procedures below are for both the construction permit (CP) and operating license (OL) reviews. During the CP review, the values of system parameters and setpoints in the analysis are preliminary in nature and subject to change. At the OL review, final values should be used in the analysis, and the reviewer should compare these to the limiting safety system settings in the proposed technical specifications.

1. The SAR describes moderator dilution transients reviewed by the staff for the occurrences leading to the initiating events. The sequence of events, from initiation to a stabilized condition, is reviewed for:

   A. The extent that normally operating plant instrumentation and controls are assumed to function. Alarms that alert operators to the unplanned boron dilution are of particular importance.

   B. The extent that the plant and reactor protection systems are required to function.

   C. The credit taken for normally operating plant systems.

   D. The operation of required engineered safety systems.

   E. The extent of required operator actions.

   F. The appropriate margin for malfunctions (*e.g.,* stuck rods) is accounted for.

2. The reviewer confirms that analyses are included for a boron dilution incident during each of the following plant initial conditions: refueling, startup, power operation (automatic control and manual modes), hot standby, hot shutdown, and cold shutdown. Refueling condition analyses should consider when the reactor vessel head is removed and the coolant is drained to the elevation of the hot leg piping. For each reviewed incident, the applicant must consider all causes and justify the cause selected for analysis as allowing the operator the least time to take corrective action.

3. The staff reviews the timing of initiation of protection, engineered safety, and other systems needed to limit the consequences of each boron dilution incident to acceptable

levels. The reviewer compares the predicted variations of system parameters to various trip and system initiation setpoints. The reviewer also evaluates automatic initiation, actuation delays, possible bypass modes, interlocks, and the feasibility of manual operation where the SAR states that operator action is needed or expected.

4. When necessary, the reviewer evaluates the effects of single active failures of systems and components that may affect the course of the transient. This phase of the review uses SRP system review procedures for SAR Chapters 5, 6, 7, 8, and 9. In particular, redundant alarms that alert the operator to the unplanned dilution are confirmed.

5. The mathematical models used by the applicant to evaluate core performance and reactivity status are reviewed to determine whether these models have been accepted by staff. If not, a generic review of the model proposed by the applicant is initiated.

6. The staff reviews system parameter values and initial core and system conditions used as input to the model. The reactivity coefficients and control rod worths used by the applicant are of particular importance. The reviewer evaluates the justification provided by the applicant to show that the selected core burnup condition, boron concentration, and rod worths yield the minimum margins. The staff reviews the reactivity parameter values in the applicant's analysis under SRP Section 4.2. The value of core reactivity as a function of time following each analyzed incident is confirmed by comparison to an acceptable analysis for another plant, by comparison to staff calculations for typical plants, or by independent calculations of the reviewer.

7. The assumed dilution flow rates are reviewed, taking into consideration the system parameters acting to limit the flow. The reviewer examines the flow limiting equipment characteristics provided by the applicant to justify flow rate assumptions (*e.g.*, if the flow is limited by the charging pump capacity, the assumed flow is compared to that for all charging pumps acting at full capacity). If a lesser flow value is assumed (*e.g.,* not all pumps operating or flow limited by a valve), justification is necessary. The secondary reviewer is consulted concerning any interlocks for which credit is taken.

8. The results of the analyses are reviewed and compared to the acceptance criteria of subsection II of this SRP section regarding the time available for the operator to take corrective action. Variations with time during the transient of important parameters are compared to those predicted for other similar plants for compliance with the expected range. Parameters of particular importance are core reactivity, boron concentration, rate of addition of unborated water, power level, core pressure, and minimum DNBR.

9. For review of a DC application, the reviewer should follow the above procedures to verify that the design, including requirements and restrictions (e.g., interface requirements and site parameters), set forth in the final safety analysis report (FSAR) meets the acceptance criteria. DCs have referred to the FSAR as the design control document (DCD). The reviewer should also consider the appropriateness of identified COL action items. The reviewer may identify additional COL action items; however, to ensure these COL action items are addressed during a COL application, they should be added to the DC FSAR.

For review of a COL application, the scope of the review is dependent on whether the COL applicant references a DC, an early site permit (ESP) or other NRC approvals (e.g., manufacturing license, site suitability report or topical report).

IV. EVALUATION FINDINGS

The reviewer verifies that the applicant has provided sufficient information and that the review and calculations (if applicable) support conclusions of the following type to be included in the staff's safety evaluation report. The reviewer also states the bases for those conclusions.

Various operator errors and system malfunctions that could lead to an inadvertent boron dilution incident have been reviewed. Operator errors and system malfunctions that allow the operator the shortest time for corrective action have been analyzed from plant conditions of startup, power operation (automatic and manual), hot standby, hot shutdown, cold shutdown, and refueling. The applicant evaluated these events using a mathematical model previously reviewed and found suitably conservative. Results of the analyses showed that the operator has __ minutes to take corrective action if a boron dilution incident occurs during refueling and __ minutes if at-power operation (automatic and manual), startup, hot standby, hot shutdown, and cold shutdown. In the latter case, the most severe transient results in a minimum DNBR of __ and reactor coolant and main steam system pressures of less than 110 percent of design.

The staff concludes that analysis for the decrease in the reactor coolant boron concentration event is acceptable and meets GDCs 10, 13, 15, and 26 requirements. This conclusion is based on the following findings:

1. The applicant meets GDC 10 requirements by demonstrating that the specified acceptable fuel design limits are not exceeded for this event. This requirement is met as the results of the analysis show that the thermal margin limits (minimum DNBR for PWRs) are satisfied as indicated by SER Section 4.4.

2. The applicant meets GDC 13 requirements by demonstrating that all credited instrumentation was available, and that actuations of protection systems, automatic and manual, occurred at values of monitored parameters that were within the instruments' prescribed operating ranges.

3. The applicant meets GDC 15 requirements by demonstrating whether the RCPB limits are not exceeded for this event. This requirement is met as the analysis show that the maximum pressure in the reactor coolant and main steam systems did not exceed 110 percent of the design pressure.

4. The applicant meets GDC 26 requirements by demonstrating that the control rod system can overcome the effects of boron dilution events during reactor operation. The applicant fulfills these requirements by showing under the postulated operational occurrence conditions, and with appropriate margins for stuck rods, that the specified acceptable fuel design limits are not exceeded.

For DC and COL reviews, the findings will also summarize the staff's evaluation of requirements and restrictions (e.g., interface requirements and site parameters) and COL action items relevant to this SRP section.

V. IMPLEMENTATION

The staff will use this SRP section in performing safety evaluations of DC applications and license applications submitted by applicants pursuant to 10 CFR Part 50 or 10 CFR Part 52. Except when the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the staff will use the method described herein to evaluate conformance with Commission regulations.

The provisions of this SRP section apply to reviews of applications submitted six months or more after the date of issuance of this SRP section, unless superseded by a later revision.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, GDC 10, "Reactor Design."

2. 10 CFR Part 50, Appendix A, GDC 13, "Instrumentation and Control."

3. 10 CFR Part 50, Appendix A, GDC 15, "Reactor Coolant System Design."

4. 10 CFR Part 50, Appendix A, GDC 26, "Reactivity Control System Redundancy and Capability."

5. American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," Article NB-7000, "Overpressure Protection 60," ASME.