Appendix F
U.S. EPR Anti-Dilution Mitigation

The purpose of this appendix is to describe the trip function and associated methodology. Compliance with GDCs (Reference 1) is demonstrated in the FSAR. The plant instrumentation, protection functions, and equipment are sufficient to preclude fuel or cladding damage. The core remains adequately cooled throughout this event. Fuel integrity is not challenged for any mode of operation.

F.1 Boron Dilution Event

Unborated water can be added to the RCS, via the reactivity control system (the 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 inadvertent additions of unborated water to the RCS (e.g., instrument flushing systems). During refueling, the RCS is an open system. The operator must stop this inadvertent dilution before the shutdown margin is eliminated. Sequences of events that may occur depend on plant conditions at the time of the inadvertent moderator dilution, the review includes conditions such as refueling, startup, power operation (automatic control and manual modes), hot standby, hot shutdown, and cold shutdown (Reference 2).

The form of the trip algorithm is defined for each of three conditions. The first condition is at power operation (Modes 1 and 2). The second condition is hot/cold shutdown operation with at least one RCP running (~~Modes 3, and a portion of Modes 4 and 5~~). The final condition is shutdown operation with no RCPs in operation (Mode 6 and a portion of ~~Modes 5 and 4~~). This report takes the best information available to date and derives an actual uncertainty for the various anti-dilution trips.

Mode 3, Mode 4, and a portion of Mode 5

Mode 5

F.2 Scenarios of an uncontrolled Boron Dilution Event

The main scenarios leading to a potential uncontrolled boron dilution are:

- Third trip: “Anti-Dilution trip while Shutdown and with No RCPs Operating” (~~Modes 6 and a portion of Modes 5 and 4~~). This trip is also designed to prevent a boron dilution event proceeding to the point at which the core goes critical, and accounts for the fact that water mixing in the core is significantly reduced with no RCPs in operation. The Anti-Dilution trip while Shutdown and with No RCPs Operating calculation is a conventional boron dilution analysis based on time from initiation of the dilution event.

Mode 6 and a portion of Mode 5

F.5 Operation at Power (Modes 1 and 2)

In this mode of operation, the reactor control rods are latched; at least one rod is partially withdrawn. An inadvertent boron dilution event is initiated either through operator error or through a malfunction in the RBWMS. The typical result of this action is that water with a reduced boron concentration (relative to the RCS) or no boron is injected into the RCS. This injection causes the RCS boron concentration to drop slowly, which leads to a positive reactivity insertion similar to that seen during a rod or bank withdrawal event. Since RCPs are in operation, it can be assumed that the dilution flow is mixed instantaneously with the contents of the RCS.

When the plant is in MRC mode, the reactivity insertion leads to a relatively slow increase in core power and temperature. If no action is taken to discontinue the boron dilution event, dilution continues until a PS setpoint is reached. The actual setpoint reached is a function of core conditions and the rate of positive reactivity addition.

The available trips and actions that can potentially intervene in this event are:

- DNB LCO alarm.
- DNBR RT.
- High core power level RT.
- LPD LCO alarm.
- HLPD RT.

F.8 Operation at Shutdown with RCPs Operating (Modes 3, 4, and 5)

In "operation at shutdown with RCPs operating" modes, the reactor is subcritical with the rods inserted. RCS boron concentrations are maintained high enough to provide sufficient shutdown margin. The initiation of boron dilution causes positive reactivity insertion leading to a continuous reduction in shutdown margin. Because RCPs are in operation, it can be assumed that the dilution flow is mixed instantaneously with the contents of the RCS. If no action is taken to discontinue the boron dilution event, dilution continues until the setpoint for the anti-dilution in standard shutdown conditions limitation trip is reached. Actuation of this limitation initiates a signal to stop dilution. Eventually a signal is issued to start boration but, no credit is taken in the analysis because it is not a safety-grade signal. Subsequently, the anti-dilution in standard shutdown conditions PS trip is reached. This trip is based on a real-time derivation of the homogeneous RCS boron concentration and is designed to actuate prior to a loss of shutdown margin. This trip automatically isolates the CVCS, which terminates the boron dilution event. Additional indications of a dilution event would be generated by the source range audible speaker and control room displays. Also prior to receiving an anti-dilution trip the source range high neutron flux setpoint would be reached which generates an alarm in the control room.

F.8.1 Anti-Dilution Setpoints at Shutdown with RCPs Operating (Modes 3, 4 and 5)

F.6

The anti-dilution trip for "Shutdown Conditions (with at least one RCP operating)" relies on the same algorithm described in Section ~~A.5~~ to reconstruct the transient RCS boron concentration. The main difference is in the calculation of the M_p^N term in Equation F-2. The analysis used the conservative RCS volume (less the pressurizer, surge line, and upper head) given and multiplies by the density values as determined for the given pressure and T_{cold} (Wide Range) temperatures to determine the mass values. The temperature difference used to calculate the mass uncertainty is now based on the T_{cold} (WR) uncertainty rather than the T_{avg} uncertainty. An example value for this parameter is given below.

T_{cold} Measurement Uncertainty = ± 7.62 ^{o}F

The fit contains a bias of 3.0 ppm so that it bounds all calculated trip points. This equation remains valid for all follow on cycles or core designs that retain or are bounded by the same parameter values (i.e., RCS volume, nominal T_{avg} and T_{avg} uncertainty, demineralizer pump characteristics, nominal system pressure, CVCS flowmeter uncertainty, trip system delay times, Technical Specification value for negative MTC, and minimum design boron worth) Figure F-2 shows the example calculated data points and general curve.

Modes 5 and 6

F.9 Anti-Dilution Setpoints at Shutdown with RCPs Not Operating (~~Modes 4 to 6~~)

In “shutdown with RCPs not operating” mode, the reactor is subcritical with no operating RCPs. Heat removal is provided by the RHR system. The reactor vessel might be open or closed, and fuel may or may not be present. The RCS boron concentration is maintained at a refueling concentration level designed to provide adequate shutdown margin regardless of the core configuration. The initiation of boron dilution causes positive reactivity insertion, which leads to a continuous reduction in shutdown margin. If no action is taken to discontinue the boron dilution event, dilution continues until the setpoint for the anti-dilution in shutdown conditions with RCPs secured trip is reached. This trip is based on the measured boron concentration being injected into the core. This trip automatically isolates the CVCS, which terminates the boron dilution event. Additional indications of a dilution event would be generated by the source range audible speaker and control room displays. Also prior to receiving an anti-dilution trip the source range high neutron flux setpoint would be reached which generates an alarm in the control room.

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F.9.1 Results of Anti-Dilution Setpoints analysis at Shutdown with RCPs Not Operating (~~Modes 4 to 6~~) Modes 5 and 6

Example value for the "Shutdown with RCPs Not Operating" anti-dilution trip setpoint was calculated to be [ ] ppm, based on a minimum IRWST boron concentration of [ ] ppm (using boron enriched to 37 atom percent boron-10), minus the general boronometer uncertainty value example of 246 ppm.

Measured boron concentrations below [ ] ppm level indicate that some source of water other than the IRWST is being used and a boron dilution event is likely in progress. The setpoint [ ] ppm is sufficiently high to maintain the RCS boron concentration higher than the maximum refueling mode critical boron concentration.

In the example calculation, the margin from the trip setpoint to the critical boron concentration is [ ] ppm ([ ] ppm – [ ] ppm).

F.10 Conclusion

The Anti-Dilution, safety-related protection channels provide effective protection by automatically eliminating the dilution source prior to the loss of shutdown margin for all modes of operation. Automatic actions, terminating the source(s) of dilution, are initiated whenever the calculated boron concentration decreases below the Anti-Dilution trip setpoint. These automatic actions include closure of redundant valves to isolate the main CVCS dilution sources and injection of borated water from the IRWST.