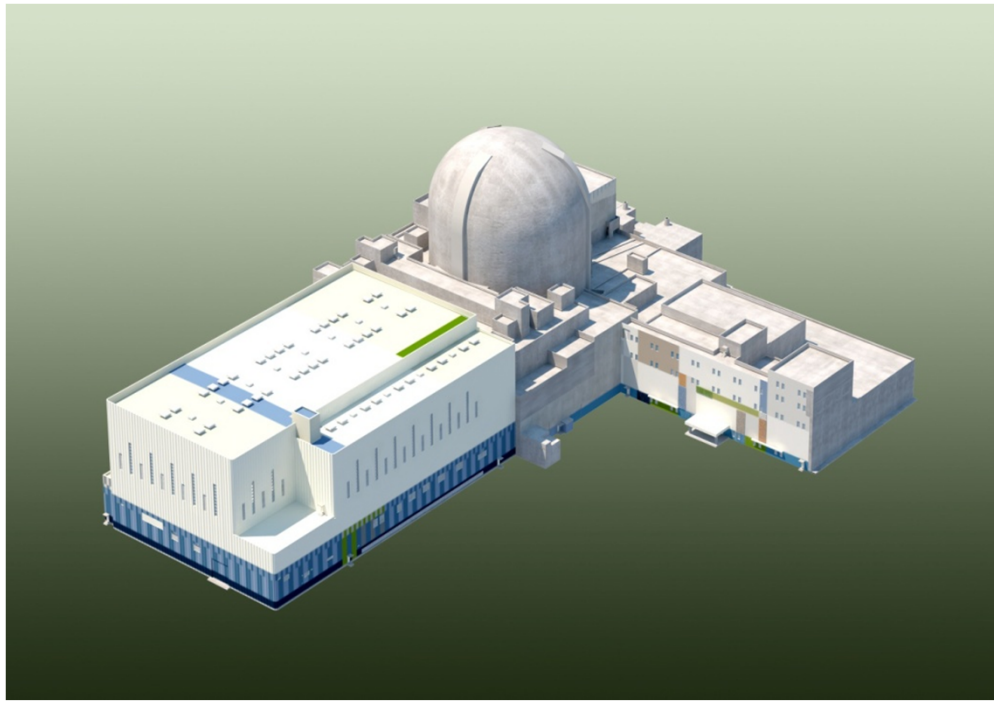
NON-PROPRIETARY

Boron Dilution Analysis for APR1400



KEPCO/KHNP

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Public Meeting

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Introduction

Introduction

- **Background and Relevant RAI**

In early 1990's, ABB-CE addressed post-SBLOCA boron dilution issues for System 80+ as described below:

- Unborated Water Delivery Due to RCP Start
  - ✓ ABB-CE performed a FULENT analysis to demonstrate that dumping un-borated water collected in loop seals after a SBLOCA due to a start of an RCP does not cause recriticality in the core.
- Unborated Water Delivery Due to Start of Natural Circulation
  - ✓ For the issue of injecting un-borated water into the vessel due to the start of natural circulation in the loop, ABB-CE assumed that the un-borated water flows to the core without any mixing in the unlimited quantity.
  - ✓ Under this condition, ABB-CE demonstrated that a hypothetical core recriticality due to the non-realistic conditions is a short-lived and it does not cause a danger to the core.
- US NRC accepted the ABB-CE results for the System 80+.
- The initial KHNP approach was to follow the ABB CE approaches.

Introduction

- **Background and Relevant RAI**
  - NRC RAI 8455 requires that the core should not reach a recriticality when the boron dilution accident occurs for the APR1400 plants and NRC requested a natural circulation calculation for APR1400 using the ABB-CE methodology with relaxed assumptions.
  - Since the ABB CE methodology assumes the core reaches a criticality, this methodology is not consistent with the no recriticality requirement.
  - Therefore, instead of using the ABB CE methodology, KHNP will show why a start of natural circulation will not cause core recriticality by a simple mixing calculation and a scoping CFD calculation.

Introduction

- **GSI-185**
  - An NRR request for reconsideration of the safety priority ranking(DROP) of GSI-22, "Inadvertent Boron Dilution Events," based on new information on high burn-up fuel and new calculations provided by the B&W Owners' Group (B&WOG).
  - MEMORANDUM: Generic Issue No. 185, "Control of recriticality following Small-break LOCAs in PWRs, NRR, July 7, 2000.
  - Resolution of Generic Safety Issues: Issue 185: Control of Recriticality Small-Break LOCAs in PWRs (NUREG-0933, Main Report with Supplements 1-33)
  - MEMORANDUM: Closure of Generic Safety Issue 185, "Control of Recriticality following Small-Break LOCAs in PWRS", NRR, Sep 23, 2005.

Introduction

- **One of the Closure Document of Generic Safety Issue 185**

Boron Dilution With Restart of Natural Circulation

Westinghouse, Combustion Engineering, and Framatome B&W Reactors: Westinghouse or Combustion Engineering reactors will remain subcritical in any boron dilution scenario with restart of natural circulation. Under the most bounding assumption for the size of a diluted slug, and with realistically conservative treatment of mixing, calculations for a Framatome B&W reactor indicated a return to criticality with no fuel damage. Therefore, boron dilution with restart of natural circulation is not a significant event at all Westinghouse, Combustion Engineering, and Framatome B&W reactors.

Boron Dilution With Restart of an RCP

Westinghouse and Combustion Engineering Reactors: Calculations for Westinghouse and Combustion Engineering reactors showed that they will remain subcritical for boron dilution with restart of an RCP. These reactor designs have relatively small loop seal volumes that might accumulate unborated water, and the piping geometry in the loops is similar among plants designed by both vendors. Larger plants, such as the Combustion Engineering System 80+, have larger volumes throughout the systems, as well as larger cores. Hence, the loop seal volumes we considered should be typical. The calculations also show significant margin before recriticality is predicted to occur. Therefore, boron dilution with restart of an RCP is not a significant event at Westinghouse and Combustion Engineering reactors.

Introduction

- **One of the Closure Document of Generic Safety Issue 185**

The staff presented its technical findings to the NRC's Advisory Committee on Reactor Safeguards (ACRS), Subcommittee on Thermal-Hydraulic Phenomena, on June 26 and September 9, 2002, and September 23, 2004. The staff then presented its draft technical assessment to the ACRS on October 7, 2004, and received ACRS agreement on the proposed completion of GSI-185 on October 22, 2004. As such, the staff has completed all work on GSI-185, and the issue will be closed with no changes to existing regulations or guidance. For additional information on this issue, please contact David E. Bessette at (301) 415-6763 or deb@nrc.gov.

Introduction

- **Findings from tests and calculations**
  - PKL
    - Research activities are being performed in Germany with the aim to improve and validate the methods for predicting boron dilution events. Integral experiments in the PKL test facility investigate the thermal-hydraulic system behavior in a wide range of conditions.
    - PKL reveals that simultaneous onset of natural circulation in several loops do not occur
    - Minimum concentration of boron in the de-borated water accumulating in the RCP suction piping is approximately 50 ppm

Introduction

- **Findings from tests and calculations**
  - ISP 43
    - In 1997, OECD/CSNI approved testing the mixing associated with inadvertent injection of a boron-dilute slug in a PWR primary system as International Standard Problem No. 43. The tests were performed in the UM 2x4 Loop, a reduced-height, reduced-pressure scale model of the TMI 2 reactor system. The experimental program consisted of four test series, which increased in realism from separate effect to integral facility.
    - Goal of ISP 43 was to examine CFD codes' capability to properly predict mixing of fluids under the natural circulation condition.
    - Good agreement between experiments and many of the computational predictions shows that computational fluid dynamics methods have reached the maturity necessary to obtain realistic predictions.

Introduction

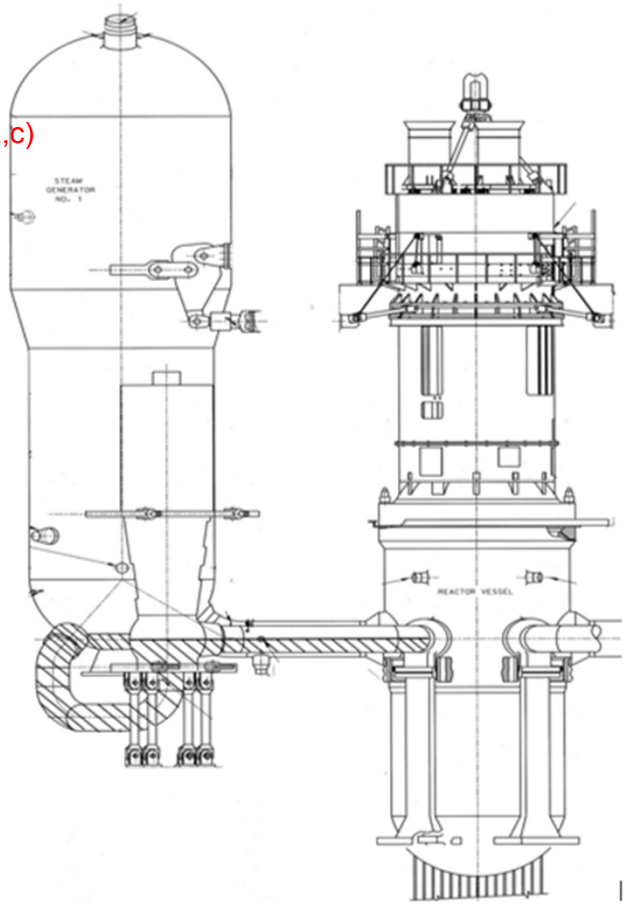
- **Findings from tests and calculations**
  - BNL
    - Brookhaven National Laboratory (BNL) has been tasked with the responsibility to do the analysis with the PARCS/RELAP5 code package. PARCS provides the three-dimensional time-dependent neutronics calculation. It is coupled to RELAP5 which provides the thermal hydraulics analysis.
    - For the case with the restart of natural circulation it was shown that no fuel damage was expected.
    - For the case with the restart of an RCP it was shown that fuel damage was possible under the conditions assumed for the B&W lowered loop design but not for the WH or C-E designs. These consequences have to be put into the context of a very low frequency of occurrence.

Natural Circulation

Natural Circulation

- **Comparison of RCS geometry**
  - ✓ Assumed unborated water volume
    - System 80+ (262 ft^3) > APR1400 (246 ft^3).
  - ✓ Sum of borated coolant volume is same.

No	Component	System80+, ft^3	APR1400, ft^3	Difference, %
1	S/G outlet nozzle and lower part	TS,(a,c)	17.5	TS,(a,c)
2	Suction Leg		123.5	
3	Pump		115.0/2	
4	Cold Leg		94.9/2	
	Assumed unborated slug volume		**245.95**	
5	Downcomer (upper region)		319.4	
6	Dowoncomer (Nozzle)		123.8	
7	Downcomer (lower region)		730.4	
8	Lower Head		439.2	
9	Lower Support Structure		225.0	
	Sum of borated coolant		**1837.8**	



Natural Circulation

- **Mixing Calculation**
  - If the assumed unborated slug volume in the one or two loop seal enter into reactor vessel and also if there is no mixing in the downcomer region, the unborated slug water will mix with borated coolant in the lower plenum region.
  - Here, it may be assumed that unborated water will be mixed completely with borated water in the lower plenum region instead of no mixing assumption in the cold leg region, downcomer region, and flow skirt region.
  - Full mixing phenomena in the lower plenum was verified in ISP-43 test (with no flow skirt) evaluation.
  - Actually, the unborated water will mix actively in the cold leg region, downcomer region, and flow skirt.
  - The boron concentration inside CSB at RCS refill time is above 20,000 ppm.
    - ✓ Reference: CESSAR-DC Chapter 6.3, Appendix 6C, Table 6C-1

Natural Circulation

- **Mixing Calculation**
  - Mixed boron concentration entering into core can be simply calculated as follow.
  - Considering four loop unborated slug volume (984 ft^3) with 0 ppm instead of 50 ppm and the lower plenum volume (664.2 ft^3) with 4,000 ppm instead of 20,000 ppm, the calculation result is [ ]TS

TS

[ ]

Natural Circulation

- **3D CFD Results**
  - As further investigations, KHNP performed a scoping study of the boron dilution using the FLUENT code. (See the Table below)
  - The resulting boron concentrations at the bottom of core are shown in the following Table.
  - It is noted that the boron concentrations are much higher than the critical boron concentration.

[ppm] TS

[ ]

RCP Restart Case

RCP Restart

- **Background and Relevant RAI (repeated)**
  - Restart of one RCP would cause the slug of unborated water stagnated inside loop seal to move into the reactor vessel.
  - NRC requested to satisfy N-1 criteria with modified BC for RCP restarting BDA in same methodology for System 80+ on previous Ch.15 public meeting.
  - For the RCP restarting boron dilution analysis, 2D CFD methodology was used for System 80+.

- **Criteria**
  - The critical boron concentration determined [ ]^{TS} considering ARI condition
  - The critical boron concentration determined [ ]^{TS} considering N-1 condition

RCP Restart

- **Assumptions**
  - Considered amount of unborated water: [ ]TS case
  - The [ ]TS of mass flow and [ ]TS of mass flow condition were analyzed for comparison.
  - .
  - Re-calculation
    - ✓ The volume of [ ]TS unborated water is injected and [ ]TS of [ ]TS water is delivering as follow.
    - ✓ The later following [ ]TS unborated water must be sucked with the water existing in hot leg region simultaneously.
    - ✓ The existing water in hot leg was discharged from core and mixed with injected highly borated safety water.
    - ✓ Therefore the later following water is assumed to be [ ]TS of boric acid water.

TS

[ ]

Mass flow distribution for one RCP starting

RCP Restart

- **Result of Re-calculation**
  - The pre-limit case results [ ]TS for [ ]TS unborated water case.
  - The Re-calculation case [ ]TS unborated water results [ ]TS.
  - The re-calculation result satisfies the minimum boron concentration criteria of [ ]TS.

TS

[

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Conclusion

Conclusion

- **Findings**
  - APR1400 design has basically the same geometry as the geometry of System80+.
  - Therefore, the NRC conclusion made in an System80+ “Memorandum” is applicable to the APR1400 design.
- **Natural Circulation**
  - APR1400 plant is the same as System80+ when it comes to the boron dilution.
  - recriticality does not occur after initiating the natural circulation for the APR1400 plants.
- **RCP Restart**
  - The re-calculation was performed with modified Boundary Condition.
  - The methodology, assumptions, and Initial Condition of previous licensed analysis were applied to the re-calculation.
  - The re-calculation result shows that the core remains subcritical even considering the N-1 criteria.