High Burnup Alternative Licensing Strategy Update

LOCA induced Fuel Fragmentation, Relocation and Dispersal Topical Report

Fred Smith
Sr. Technical Executive

Pre-submittal Meeting
August 30, 2022

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ALS Objective

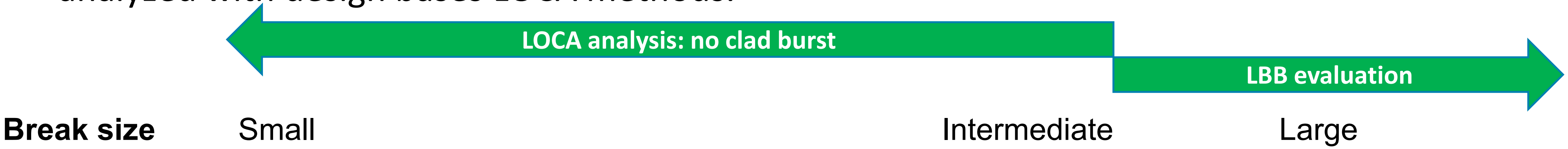
- Obtain NRC approval of generic method to address PWR LOCA induced FFRD in an expeditious manner
  - Initial scope focuses on Westinghouse NSSS designs
    - Framatome and Westinghouse fuel
    - ~90% plants that are likely to implement HBU, remaining are expected to delay implementation until successful demonstration of ALS
  - Avoid reliance on additional LOCA testing
  - Limit licensing complexity and risk
    - Use previously approved methods and licensing strategy to the extent possible
    - Update as needed to address high burnup phenomena
  - Minimize the plant specific implementation activities
    - Confirm applicability requirements apply to specific plant

Safety and Environmental Benefits of ALS

- Provide High Burnup Safety and Environmental Benefits on a more expeditious schedule
  - Reduce risk of transportation accidents across the entire fuel cycle due to reduced volume of special nuclear material
  - Reduced risk of fuel handling accidents within a plant due to smaller reload batch sizes
  - Reduced high level waste to store on site, load into dry cask containers and eventually transport and store in a repository
  - Improved economic performance for nuclear sites reduce the risk of early shutdown; thereby supporting US and international environmental goals of reduced greenhouse gases emissions
  - Improved core design efficiency reduces Uranium environmental and radiological impacts during mining and fuel shipping
  - Higher burnup core designs support longer fuel cycles and lower risk of outage related safety challenges
  - More effective use of limited NRC and Industry resources by avoiding modeling and analysis of fuel dispersal consequences

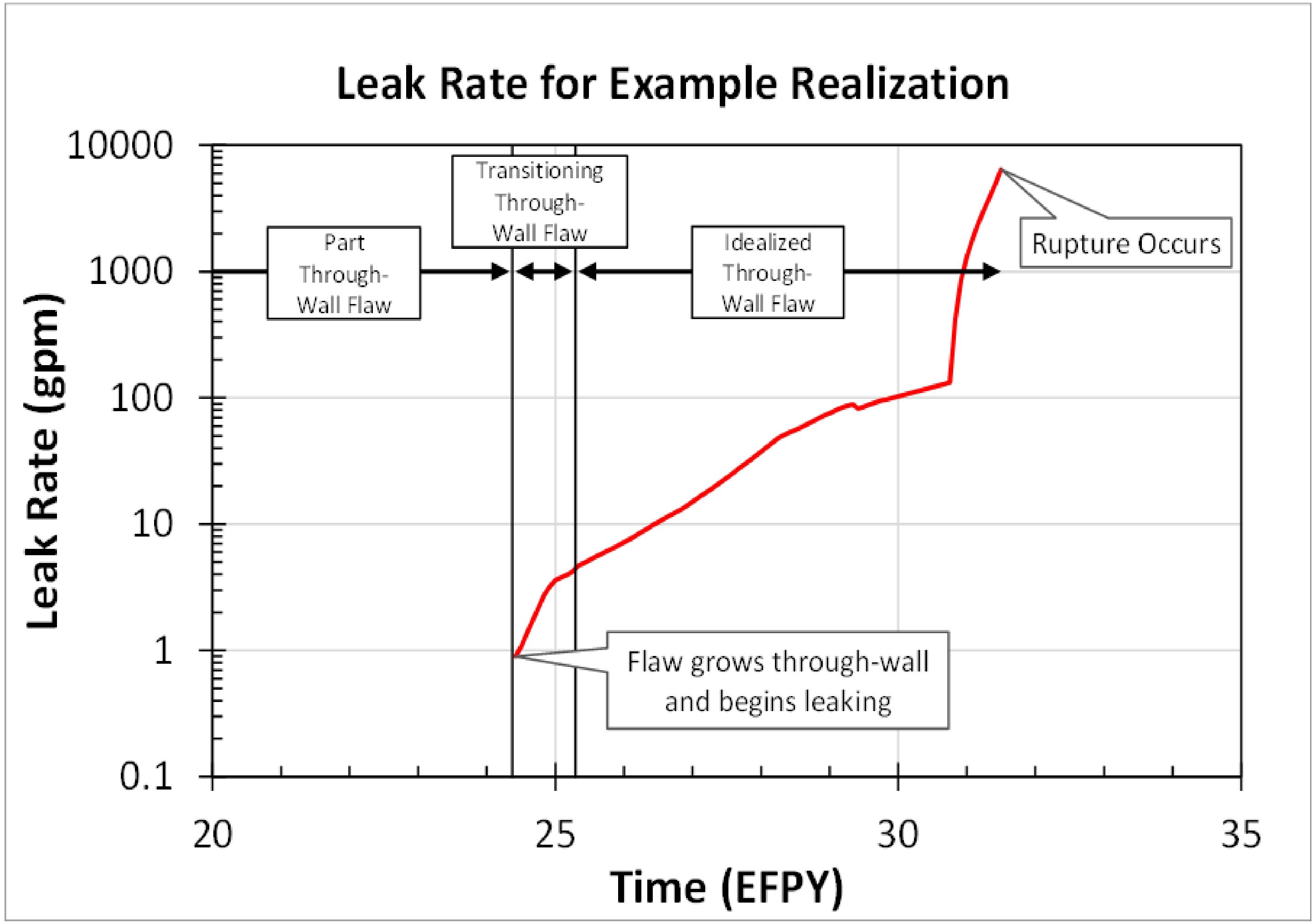
ALS Approach

- Approach to address FFRD in high burnup PWR fuel:
  - Perform small break and intermediate break LOCA analysis to demonstrate no clad rupture and acceptable fuel relocation
  - Realistic treatment of large break LOCAs based on xLPR calculated event propagation and T/S required plant shutdown requirements for LBB qualified piping
- Rationale: LBB has been used to exclude various local phenomena external to RPV (jet impingement, asymmetric vessel loading, failure of ECCS cross-connect valve) and internal to RPV (control rod scram, fuel mechanical loads). Similarly, LBB would be used to exclude FFRD caused by large break LOCA
- Implementation: EPRI will apply xLPR analysis to LBB piping for determining if time available to detect leakage and shut down is sufficient to justify excluding LOCA-induced FFRD. Non-LBB piping analyzed with design bases LOCA methods.



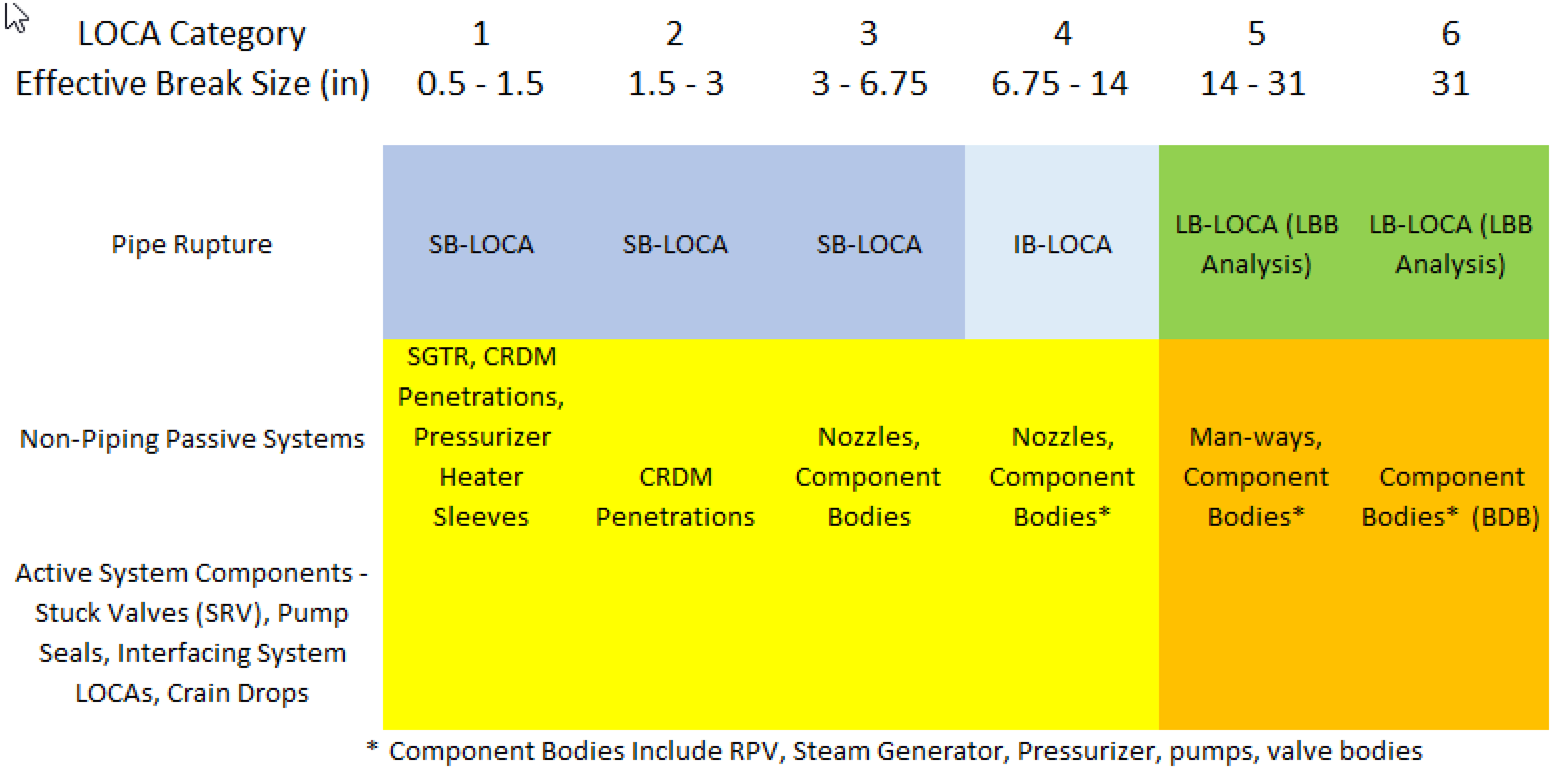
xLPR – Example of Crack Growth to Point of Rupture

- Reactor vessel outlet nozzle, flaw initiates at time 0
- In year 24, leak rate of 1 gpm is detectable and will require shut down
- Stored energy and decay heat drop rapidly after shutdown
- Even if pipe rupture occurs fuel clad rupture will not occur due to reduction in stored energy and decay heat.



Non-piping LOCA events*

- Evaluate failure mechanics/geometry of limiting components and interfacing piping, compare to LOCA analysis rupture size
- Previous evaluations of component failures



LOCA Category	1	2	3	4	5	6
Effective Break Size (in)	0.5 - 1.5	1.5 - 3	3 - 6.75	6.75 - 14	14 - 31	31
Pipe Rupture	SB-LOCA	SB-LOCA	SB-LOCA	IB-LOCA	LB-LOCA (LBB Analysis)	LB-LOCA (LBB Analysis)
Non-Piping Passive Systems	SGTR, CRDM Penetrations, Pressurizer Heater Sleeves	CRDM Penetrations	Nozzles, Component Bodies	Nozzles, Component Bodies*	Man-ways, Component Bodies*	Component Bodies* (BDB)
Active System Components - Stuck Valves (SRV), Pump Seals, Interfacing System LOCAs, Crain Drops						

* Component Bodies Include RPV, Steam Generator, Pressurizer, pumps, valve bodies

*Note: Existing LBB applications do not address non-piping LOCA events

ALS scope

- ALS is based on a realistic treatment of the potential for LB-LOCA generated FFRD
- ALS does not modify ECCS system design or analysis for non-FFRD LOCA evaluations
  - ECCS design bases heat removal and mass replacement capability are not modified
  - Other events (Fuel handling, RIA) are not addressed in the scope of ALS
- LBB credit is only applied to piping systems already qualified for LBB applications
  - Material performance and fracture mechanics analysis previously approved by NRC
  - Leak detection capability has been established
  - Supports conclusion that the specific piping system has an extremely low probability of rupture
- Clad rupture is expected to be precluded but should it occur the associated dispersal is a result of the dynamic effects (temperature and pressure) of the piping system rupture
- Clad rupture and dispersal is a local phenomena, similar to the LBB based evaluation of loads on individual fuel pins during blowdown

Recent Activities

- **xLPR NRC Public Meeting Briefing 6/14/22***
- Scope
  - Development of LOCA Frequencies – NUREG-1829
  - NRC Experience using xLPR
  - EPRI use of xLPR to support ALS
    - Phase 1 – xLPR Proof of Concept 2021
    - Use of LOCA Frequency Estimates in ALS
    - Phase 2 - Full Spectrum xLPR analysis 2022
- Result
  - NRC provided feedback/suggestion on specific areas of EPRI xLPR project plans
  - Follow up xLPR progress
    - Additional public meeting as results are near completion
  - NRC highlighted the need for similar deep dive into ALS project from fuel perspective

- June 14 Public Meeting with EPRI to discuss use of the xLPR code for LOCA estimates. All the meeting presentation slides are now available publicly via ADAMS (ML22166A345) and the link to the slide package is given below:
- https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML22166A345 [adamswebsearch2.nrc.gov]

Additional NRC engagements

- NRC High Burnup Workshop August 24, 2022
- Pre-submittal meeting: target date August 30, 2022
- Fee waiver request

ALS Scope/Schedule

- FFRD LOCA analysis to include Small and Intermediate Breaks
  - Consistent with LBB applications
    - Limiting branch lines are the Accumulator Line Break (Cold Leg) and Pressurizer Surge Line (Hot Leg)
- Address non-piping LOCA
  - Non-Piping Breaks – manways, component bodies, nozzles, heater sleeves
  - Active system Failures – Stuck open valves (SRV), pump seals
- Schedule
  - Submittal 4th quarter 2023

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Westinghouse Perspectives on Supporting the EPRI Alternate Licensing Strategy (ALS) for Fuel Fragmentation, Relocation, and Dispersal (FFRD)

Rachel Christian

August 2022

Significance of the Alternate Licensing Strategy

- Westinghouse views the EPRI alternate licensing strategy (ALS) as the most practical and efficient means of addressing phenomena related to fuel fragmentation, relocation, and dispersal (FFRD)
  - Accounts for the extremely low likelihood of occurrence for a postulated large-break LOCA (LBLOCA)
  - Alternative that does not require substantial amount of complex testing associated with fuel rod phenomena that occur post-rupture

Westinghouse Perspective on Interaction with 50.46

- EPRI ALS submittal would address FFRD for pipe rupture and non-pipe rupture LOCA events

- Supporting Westinghouse calculations intend to demonstrate that fuel dispersal will not occur for smaller break sizes via preclusion of cladding rupture

- EPRI ALS does not obviate the need for licensees to demonstrate compliance with the ECCS acceptance criteria
  - Licensing basis analyses would still be required to demonstrate compliance with 10 CFR 50.46

Method for Cladding Rupture Evaluation

- Current Methods
  - FULL SPECTRUM LOCA (FSLOCA) methodology
    - NRC-approved per WCAP-16996-P/NP-A, Revision 1
    - Limits on burnup and enrichment levels less than desired for high energy fuel designs under EPRI ALS
  - Incremental Burnup Extension
    - Currently under review per WCAP-18446-P/NP
    - Increased fuel rod average burnup limit but still less than desired
    - Developed a method for performing cladding rupture calculations

- The NRC-approved FSLOCA methodology and aspects of the incremental burnup extension will serve as the starting point for the method to predict cladding rupture supporting EPRI ALS

Modifications due to Higher Burnup / Enrichment

- Decay Heat and Kinetics Module
  - Update to cover full range of burnup and enrichment
- Transient Fission Gas Release
  - Refine modeling of fission gas release during a LOCA transient
- Pre-Burst Axial Fuel Relocation
  - Assess impact of pre-burst fuel relocation on LOCA transient response
- Cladding Rupture
  - Assess / update cladding rupture model as needed

Assessments and updates will be supported by experimental data

Westinghouse

Questions

Framatome overview of ALS support

Lisa Gerken

NRC Headquraters, 30 August 2022

Framatome Engagement with ALS

- EPRI goal to limit licensing complexity with minimal updates to previously approved methods for high burnup fuel and cladding rupture phenomena
- High burnup cladding rupture depends on:
  - Pre-transient conditions, e.g.,
    - core design,
    - possible operational space, etc.
  - Transient conditions, e.g.,
    - break,
    - plant design and response,
    - fuel and cladding response, etc.
- Existing Framatome methods capture all those features but not with the focus of the burnup extremes and ultimate criterion being rupture

Framatome Engagement with ALS

- Fundamental is the acceptability of the methodology and the assumptions in regulatory space
  - What are appropriate assumptions for state of HBU fuel?
  - What is acceptable modeling for the rupture determination?
  - Balance of necessary, appropriate, and acceptable conservatism
- Framatome presented their overall LOCA approach for increased BU recently in a proprietary meeting (May 2022)
  - Discussed approaches for licensing
  - EPRI goal of “no SBLOCA/IBLOCA cladding rupture” will be supported using portions of the discussed SBLOCA approach
- Framatome and EPRI are jointly developing plans to confirm the applicability of the ALS to Framatome supplied fuel

High Burnup Alternative Licensing Strategy

Leak-before-break Application and Analysis

Storm Kauffman, MPR
Fred Smith, EPRI
Cecile Dame, MPR

NRC Public Meeting
August 30, 2022

www.epri.com

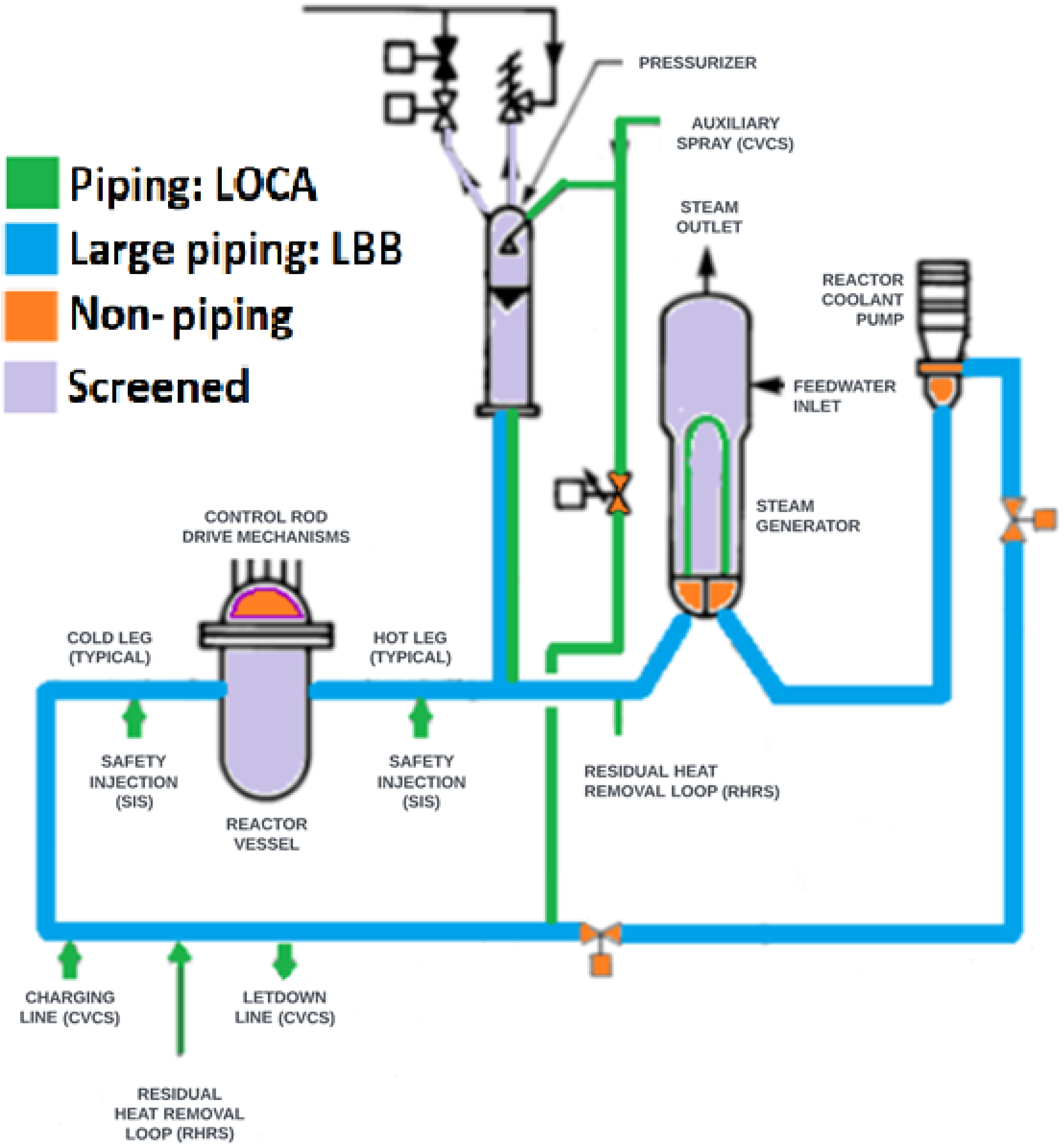
Purpose

- Review current status and plans for addressing potential loss of coolant accidents (LOCAs) that could cause high burnup fuel fragmentation, relocation, and dispersal (FFRD)
  - Realistic treatment of large piping breaks, considering
    - Leak-before-break (LBB) based on xLPR calculated flaw progression
    - Consideration of operating staff response to indicated leak in accordance with Technical Specification Limiting Conditions for Operation (LCO) plant shutdown requirements
  - Assessment of non-piping LOCAs

Realistic Treatment of LBLOCA

ALS Methodology Overview

- Piping:
  - Small/intermediate piping system: expect no fuel clad burst using conventional LOCA analysis
- Large piping systems: apply LBB
- Non-piping
  - Screened:
    - Beyond design basis (e.g., RPV failure)
    - Bounded by LOCA with larger flow rate
  - Bolted
    - Failure mechanisms
    - Evaluation of LBB-type behavior
    - Margin to failure
  - Component bodies
    - ASME allows higher stress in piping: should fail first
    - Intervening flow resistance prevents flow rate high enough to cause clad burst
    - Supports/restraints make large opening implausible
  - Active component failures



Realistic Scenario for Large Piping System

- Reactor coolant pressure boundary (RCPB) piping flaw develops
- Crack grows through-wall – RCS leakage begins
  - Based on material properties and degradation mechanisms, crack grows slowly
  - Probabilistic fracture mechanics (xLPR) predicts years of crack growth before rupture
- Leak rate through crack reaches point of detectability
  - Operations staff identify leakage
  - Technical Specifications 3.4.13(B) LCO for RCS leakage
  - If leak not detected, crack will not grow to rupture before next refueling outage
    - Plant walkdowns will detect signs of leakage (e.g., discoloration, boric acid deposits)

Leakage Technical Specifications

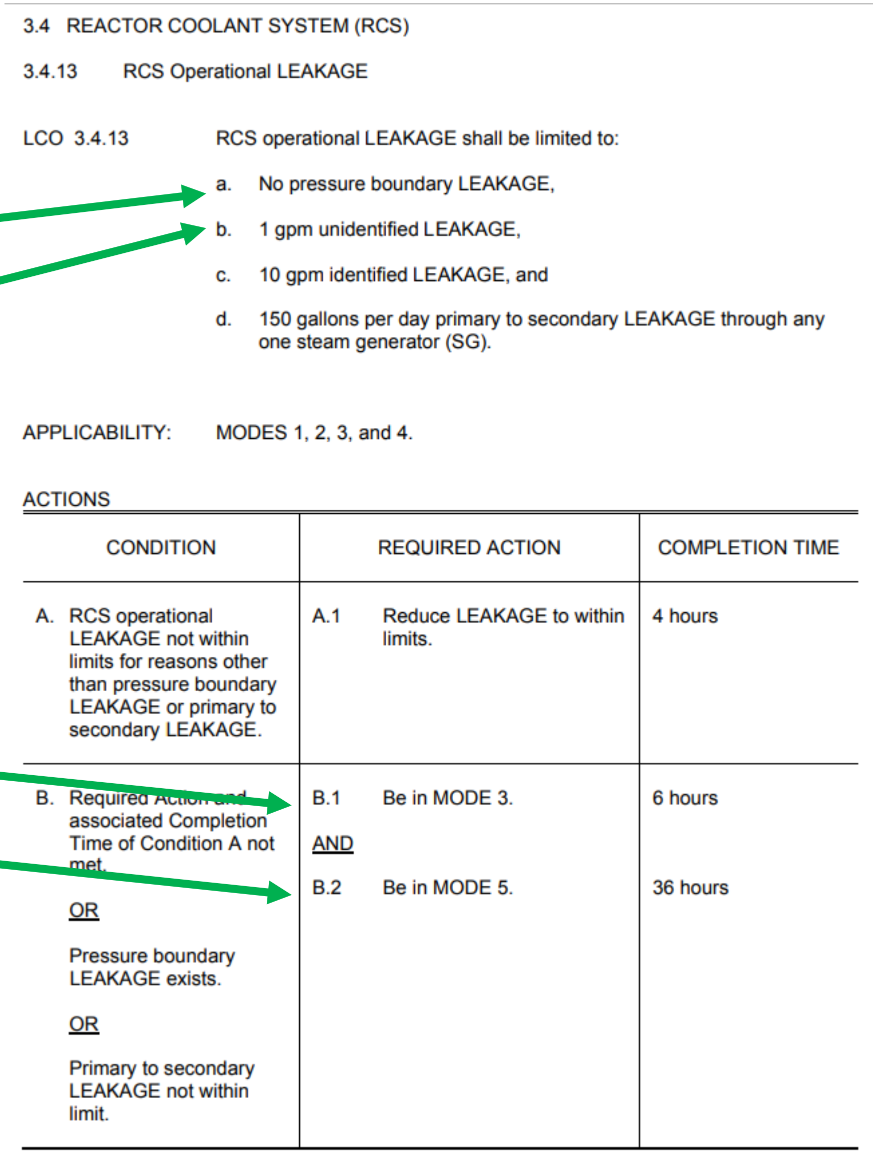
- Limiting Condition for Operation (LCO)
  - No RCPB leakage
  - Unidentified Leakage <1 gpm

<u>Required Action</u>:

Mode 3 within 6 hours

Mode 5 within 36 hours

- Periodic surveillance to verify LCO met



3.4 REACTOR COOLANT SYSTEM (RCS)

3.4.13 RCS Operational LEAKAGE

LCO 3.4.13 RCS operational LEAKAGE shall be limited to:

a. No pressure boundary LEAKAGE,

b. 1 gpm unidentified LEAKAGE,

c. 10 gpm identified LEAKAGE, and

d. 150 gallons per day primary to secondary LEAKAGE through any one steam generator (SG).

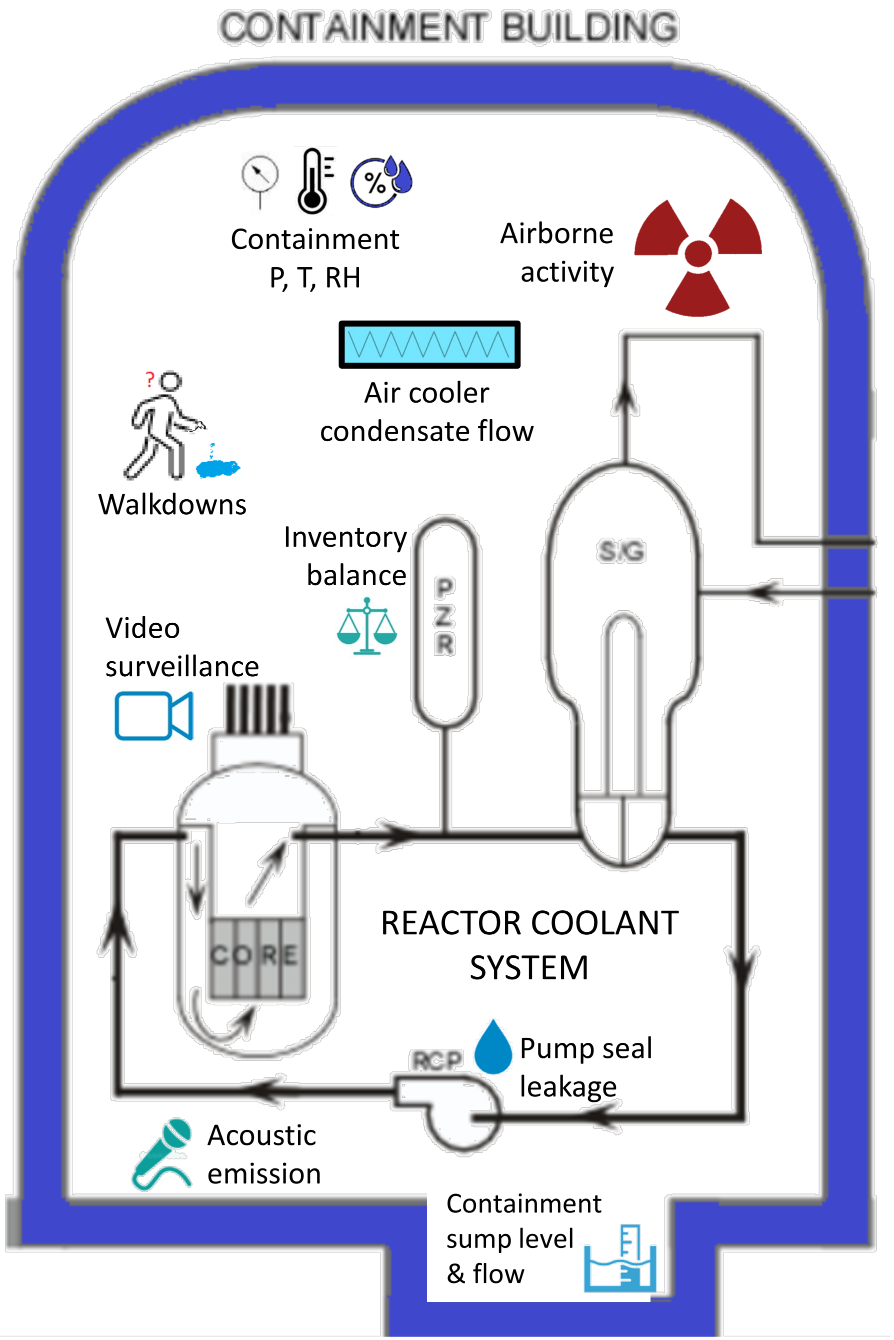
APPLICABILITY: MODES 1, 2, 3, and 4.

ACTIONS

CONDITION	REQUIRED ACTION	COMPLETION TIME
A. RCS operational LEAKAGE not within limits for reasons other than pressure boundary LEAKAGE or primary to secondary LEAKAGE.	A.1 Reduce LEAKAGE to within limits.	4 hours
B. Required Action and associated Completion Time of Condition A not met. <u>OR</u> Pressure boundary LEAKAGE exists. <u>OR</u> Primary to secondary LEAKAGE not within limit.	B.1 Be in MODE 3. <u>AND</u> B.2 Be in MODE 5.	6 hours 36 hours

Leak Detection

- Regulatory Guide 1.45, “Guidance on Monitoring and Responding to Reactor Coolant System Leakage”
  - Unidentified leak rate > 0.05 gpm detection/quantification
  - Response time (excluding transport time) of no more than 1 hr for leak rate of 1 gpm
  - Leakage Monitoring Parameters
    - Inventory balance
    - Containment sump level or flow
    - Airborne particulate activity
    - Air cooler condensate flow
    - Airborne gaseous activity
    - Containment pressure, temperature, humidity
    - Acoustic emission
    - Video surveillance
    - Pump seal leakage
    - Makeup flow rate
    - Walkdowns



Characteristics of Potential LOCAs

LOCA Size Category	**1**	**2**	**3**	**4**	**5**	**6**
Double-ended diameter (in)	0.5 to 1.625	1.625 to 3	3 to 7	7 to 14	14 to 31	31
Equiv. single-ended diameter (in)	0.8	2.6	4.8	11.2	22.3	49.5
Double-ended leak rate (gpm)	>100	>1500	>5000	>25k	>100k	>500k
Safety analysis LOCA break size class	Small	Small	Small	Intermediate	Large	Large
Expect LOCA not cause clad burst	Yes	Yes	Yes	Yes	No	No
Expect FFRD exclusion based on LBB	No	No	No	No	Yes	Yes
Piping of that size category	Sensing	Many	ECCS	Surge line	Loop	None
Active component failure	Relief valve	Safety valve	N/A	N/A	N/A	N/A
Passive non-piping failure	Head vent	CRDM		Manway		RPV

Non-Piping Failures

Assessment of Non-Piping Failures

- Components acceptable if:
  - Separated from reactor vessel by pipe equal or smaller than limiting intermediate line that results in no fuel clad rupture
  - Failure of component body
    - Unlikely based on ASME Section III allowable stress vs. pipe – pipe fails first
      - Allowable primary membrane + bending stress for piping is higher (factor of safety is less) that for components to which piping attaches such as valves and vessels
    - Restrained by supports/attachments to less than full offset, reducing leak rate

Failure of Bolted Closures

EPRI NP-5769, April 1988

Degradation and Failure of Bolting in Nuclear Power Plants

- Causes of failures
  - Boric acid corrosion
  - Mechanical/thread damage‡
  - Pitting damage
- Component bolting failure rate
  - Steam generator manway*
  - Pressurizer manway
  - RCP flanges
  - RCP seals

	No. of contiguous failed bolts		
Component	**2**	**3**	**4**
RCP main flange	15	>100	-
16-stud manway	0.2	3	15
20-stud manway	0.1	1	7
10-in. check valve	-	1.7	10

- For failure of one or more contiguous bolts:
  - Change in stress in nearby bolts
  - Resultant leak rate
    - SG manway: for 1 gpm leak rate, ~15% of manway studs must have failed
- Since 1988, threaded faster reliability generally good

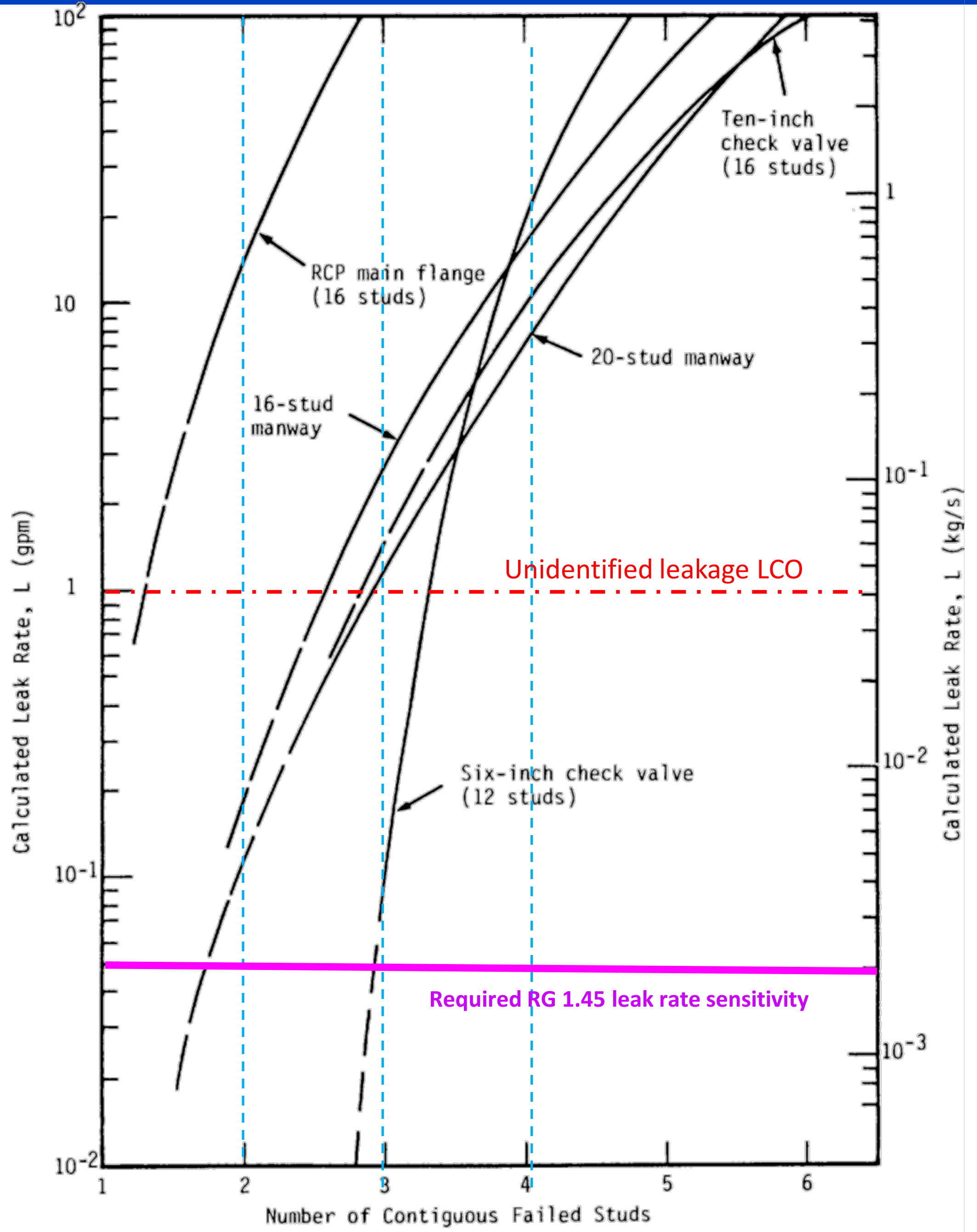


Figure 3-13. Leak Rate Predictions for Different Primary System Closures

‡ Not relevant to in-service pressure retention failure

* Predominantly from galling and mechanical damage, thread damage, and removal damage, exacerbated by rejecting 61 bolts for one event; in general Westinghouse SG manways much better

Margin to Threaded Closure Failure 1

- As more contiguous studs fail, load pattern shifts
- For example, assuming 3 studs failed in a row and then 4th and 5th
    - Load redistributes gradually
    - Failure of several studs does not cause rest to "unzip," causing sudden rupture

No. of Failed Studs	Load on Stud 3	Load on Stud 4	Load on Stud 5	Load on Stud 6	Load on Stud 7	Load on Stud 8
2	1.17	1.08	1.06	1	0.93	-
3	Failed	1.25	1.12	1.05	1	0.88
4	Failed	Failed	1.38	1.17	1.05	1
5	Failed	Failed	Failed	1.52	1.2	1.05

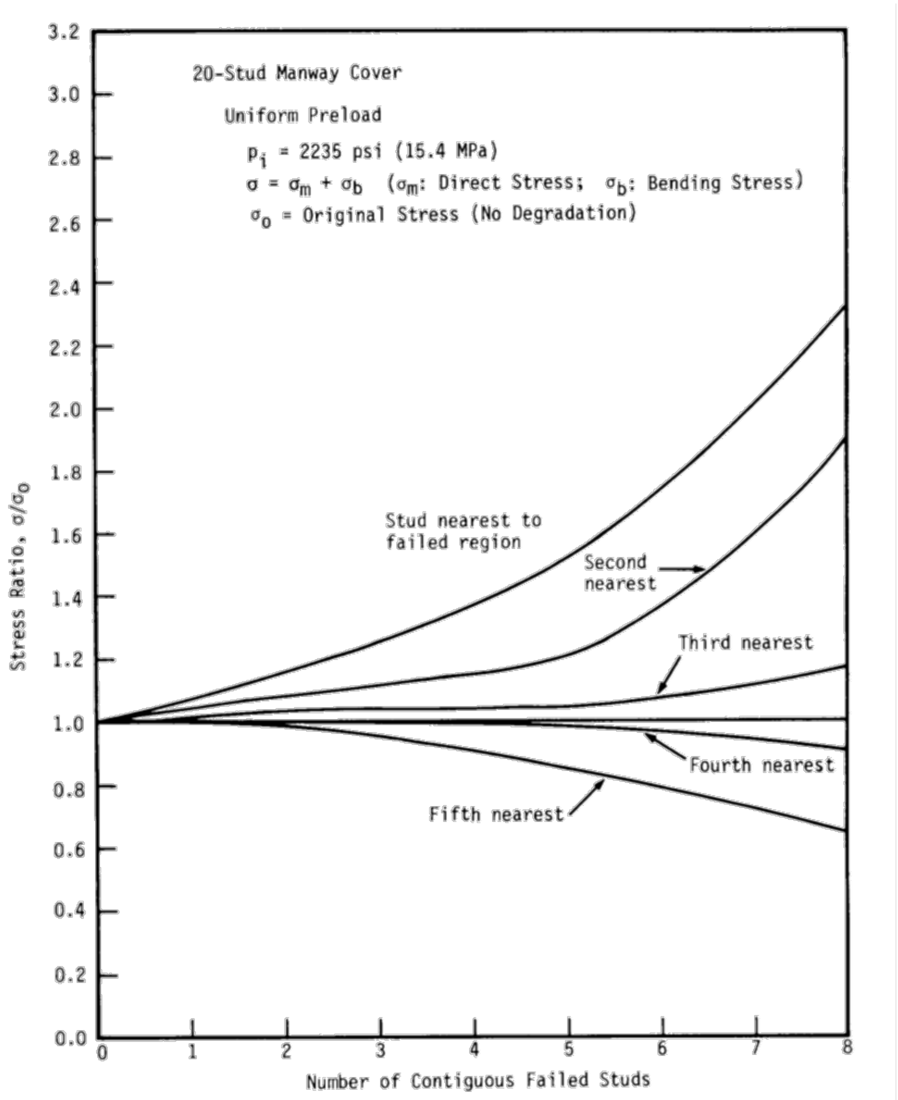


Figure 3-4. Load Redistribution in Five Nearest Studs to Degraded Region in a 20-Stud Manway

Margin to Threaded Closure Failure

At the 1 gpm leak rate for which plant shutdown is required, closures listed in Table 3-3 have at least a factor of 2.2 factor of safety, with the larger ones (manways) having even additional margin

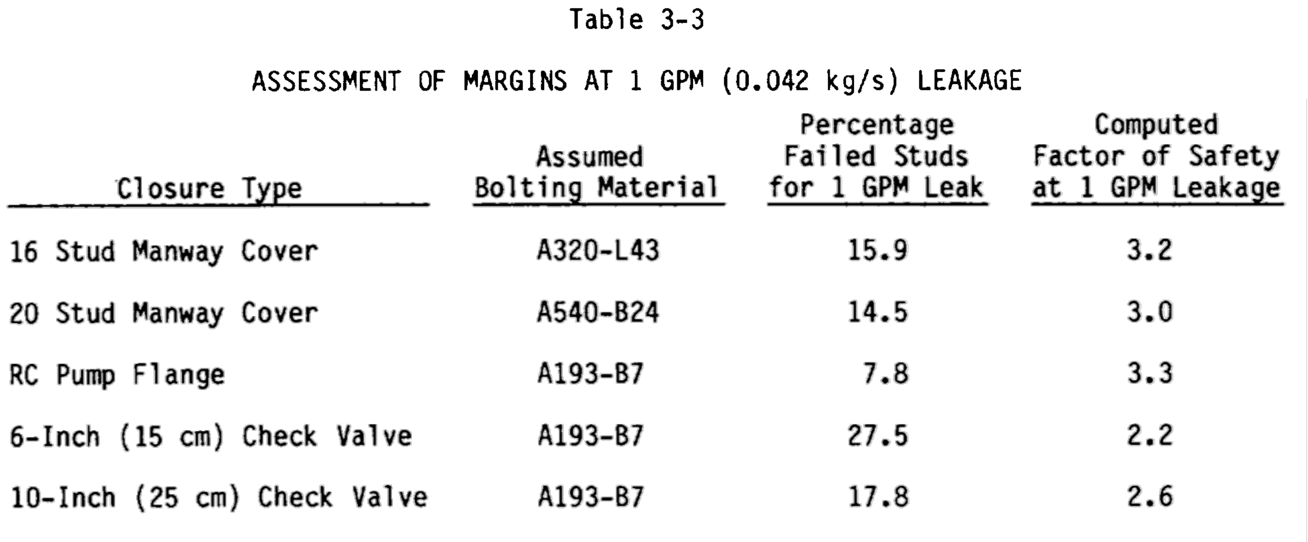


Table 3-3

ASSESSMENT OF MARGINS AT 1 GPM (0.042 kg/s) LEAKAGE

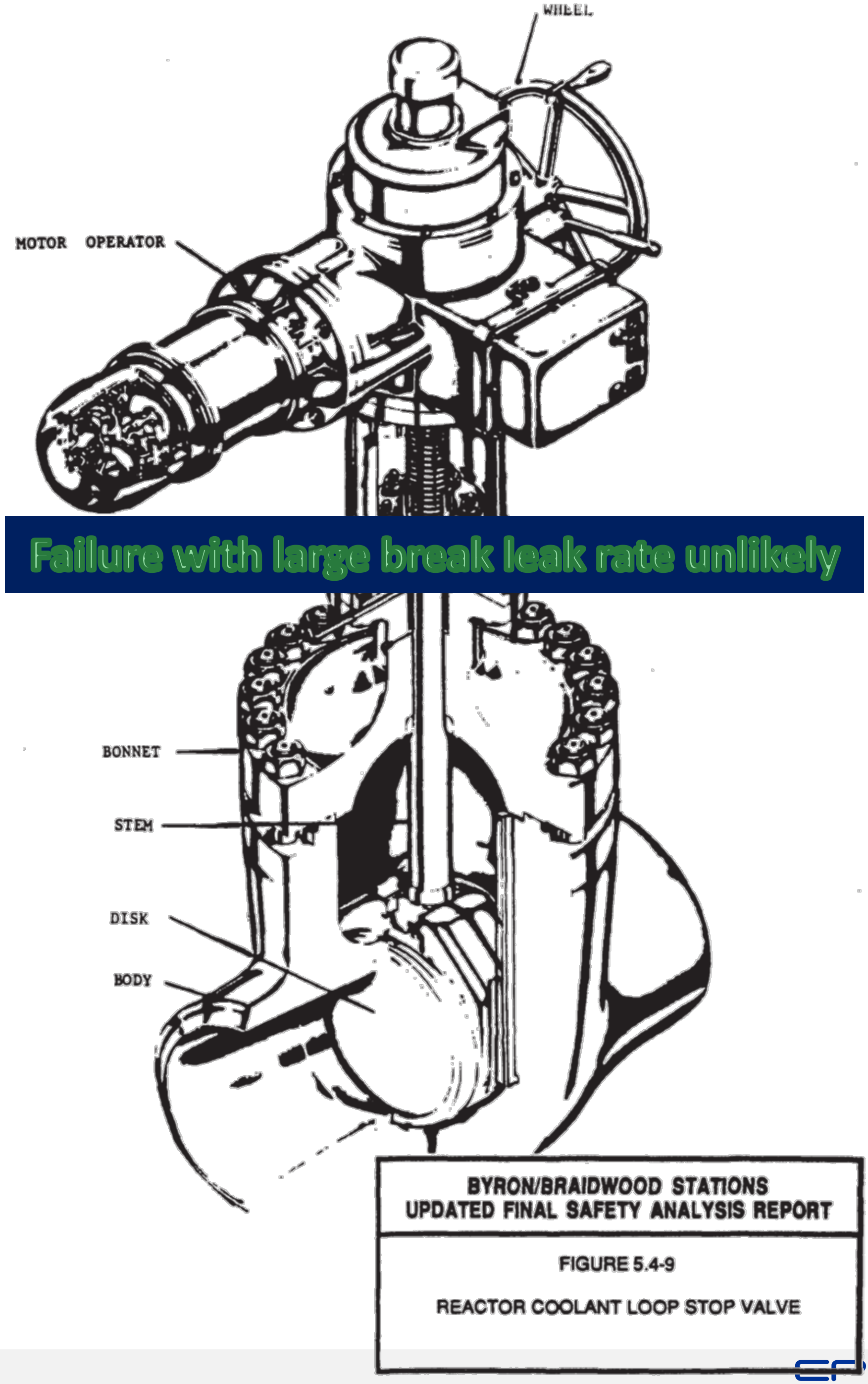
Closure Type	Assumed Bolting Material	Percentage Failed Studs for 1 GPM Leak	Computed Factor of Safety at 1 GPM Leakage
16 Stud Manway Cover	A320-L43	15.9	3.2
20 Stud Manway Cover	A540-B24	14.5	3.0
RC Pump Flange	A193-B7	7.8	3.3
6-Inch (15 cm) Check Valve	A193-B7	27.5	2.2
10-Inch (25 cm) Check Valve	A193-B7	17.8	2.6

Resolution of GSI-29 – Bolting Degradation

- In NUREG-1339 “Resolution of Generic Safety Issue 29: Bolting Degradation or Failure in Nuclear Power Plants,” the NRC concluded that NP-5769, combined with other industry and NRC actions were adequate to resolve GSI 29, "Bolting Degradation or Failure in Nuclear Power Plants“
  - NRC did note that fastener integrity needs to be procedurally controlled
- Although NP-5769 was issued almost 35 years ago, subsequent experience with bolting has been good, benefiting from the many actions undertaken by industry and the NRC.
  - EPRI has issued and updated several guides on proper inspection and maintenance practices (e.g., *Bolted Joint Fundamentals*, 3002015824, Revision 1, EPRI Nuclear Materials Applications Center)

Reactor Coolant Loop Stop Valve

- Failure modes/locations
  - Bonnet
    - Margin to failure (EPRI NP-5769)
    - Does not fully dislodge – disk assembly remains
      - Flow area small
    - Completely separated – disk remains
      - Flow area small
    - Completely separated – disk ejected
      - Flow area: ID x disk assembly thickness ~ 300 in^2
  - Valve body
    - Solid forging/casting (no welds)
    - Ductile material
    - Inspected per ASME Section XI
    - Lower allowable stress – piping will fail first
    - Even if ruptured, separation unlikely



Failure with large break leak rate unlikely

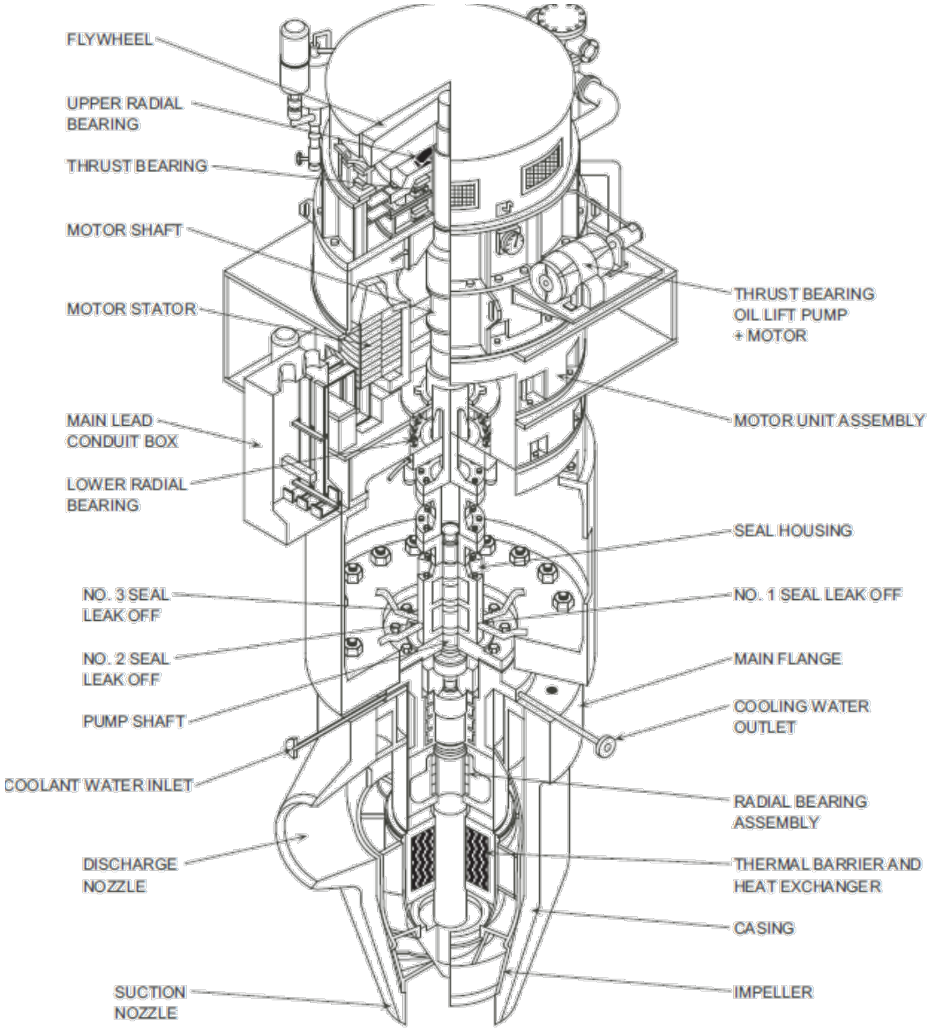
BYRON/BRAIDWOOD STATIONS
UPDATED FINAL SAFETY ANALYSIS REPORT

FIGURE 5.4-9

REACTOR COOLANT LOOP STOP VALVE

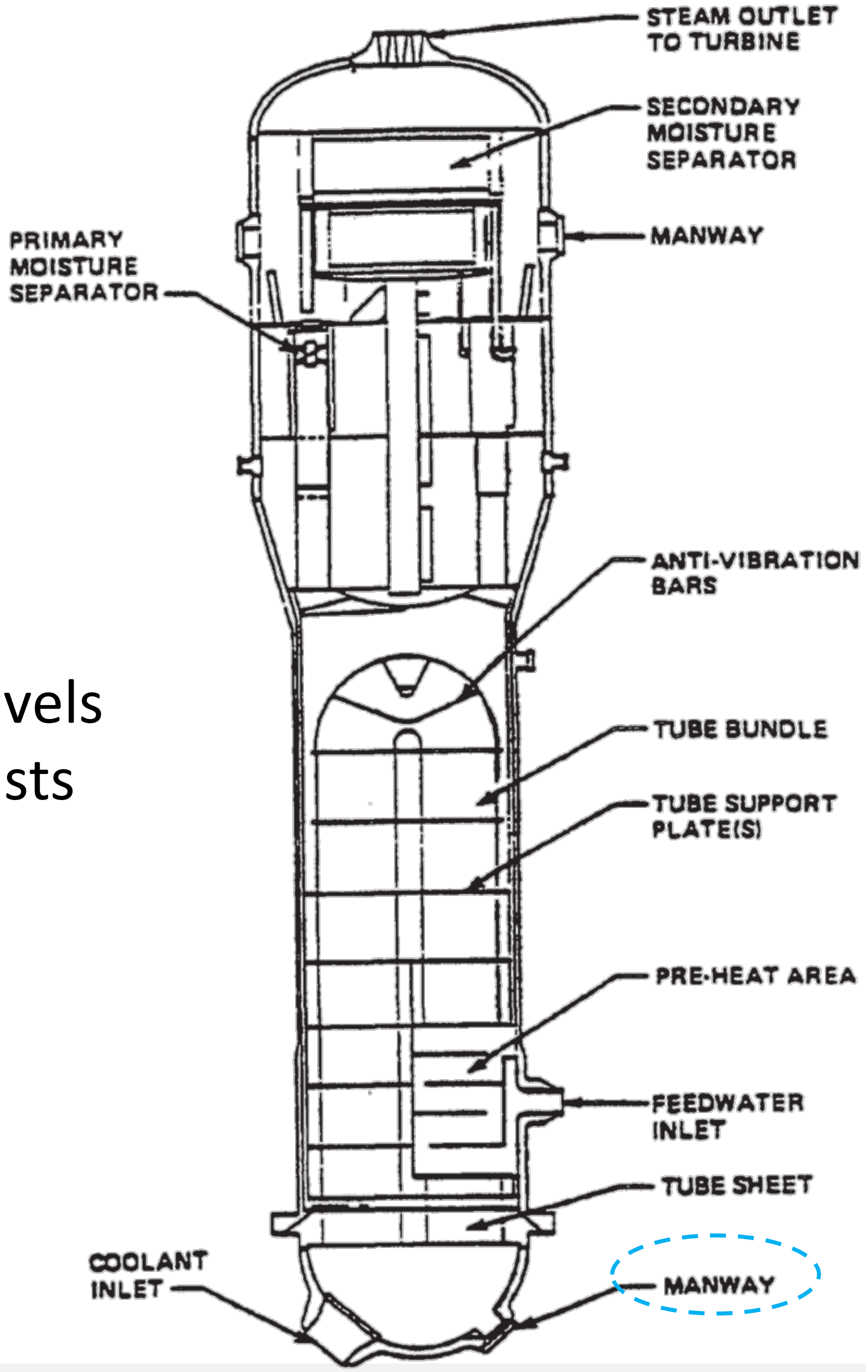
Reactor Coolant Pump

- Failure modes/locations
  - Seal housing bolting
    - Motor above: shaft cannot eject
    - Small flow area
  - Main flange bolting
    - Attached to supports;
      casing cannot move down
    - Even if motor off and shaft out, flow area limited by radial bearing and thermal barrier to less than about 100 in^2
  - Pump casing cracking
    - Wall exceeds piping thickness: failure unlikely
    - Cannot move up
    - Lower casing supported by two pipes, which limit separation which would need to exceed about one inch for flow area > surge line break



Steam Generators

- Westinghouse SG primary side manways
  - Two manways, 21 in. or 16 in. ID
- EPRI NP-5769 report:
  - SG manway fasteners most problematic of closures
    - Most instances do not affect strength
    - Statistics because of one-time event involving 61 stuck fasteners
- WCAP-16465-NP, PWROG Standard RCS Leakage Action Levels and Response Guidelines for PWRs, 9/2005, Table 10.1-1 lists a single manway (pzr) leak event:
  - Detected during power operation by particulate activity
  - Confirmed by inventory balance and chemical analysis
  - Leak rate 0.07 to 0.275 gpm



Summary

- Expect to demonstrate acceptability of not including FFRD in LOCA analysis:
  - Small and intermediate breaks acceptable: no clad burst using usual LOCA analysis
  - Large break LOCA precluded: LBB analysis shows detectability years before rupture
  - Non-piping failures
    - Bolted closures (e.g., manways, valve bonnets) acceptable: version of LBB behavior
    - Component bodies acceptable: more stress margin than piping, large gaps unlikely
    - Active component failure flow rates bounded by LOCA analysis of piping failures

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