MAAP Alternate Source Term Research in Support of RG 1.183 Revision 2

ACRS Meeting

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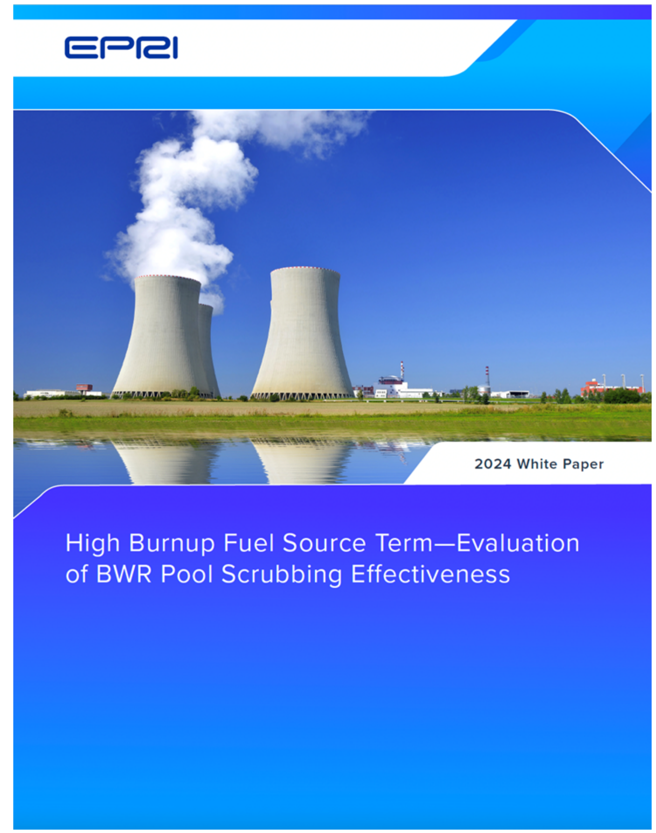
Background

- NRC is preparing to issue Regulatory Guide 1.183 Revision 2 which reflects updated source terms to be used by the industry
- Design Basis Source Terms are based on MELCOR analysis documented in SAND2023-01313.
- Updated source terms, also observed in RG 1.183 Rev. 1, show a significant increase over those documented in RG 1.183 Rev. 0 which were based on NUREG-1465
- As highlighted in SAND2023-01313, the increase in source term is primarily due to increase in scenarios that result in depressurization of the primary system during early in-vessel release phase.
- For BWRs, this is due to a SRV sticking open due to elevated temperatures, resulting in a direct release into the suppression pool.
- For PWRs, this is due to hot leg creep rupture with direct release into containment.

Confirmatory analysis performed by EPRI

High Burnup Source Term – Pool Scrubbing White Paper (3002029329)

- White paper performed confirmatory assessment of source term release fractions and phase durations using MAAP for Mark I and Mark III BWRs
- Evaluated the impact of scenario weighting on reported source terms by considering two plant-specific PRA models
- Demonstrated that MAAP would predict similar suppression pool retention as MELCOR and that no single sensitivity was driving the results



Publicly available for download

Scope of EPRI Research

- Task 1 – Development of candidate MAAP input and parameter files for BWR and PWR plants documented in SAND2023-01313
- Task 2 – Calculate baseline release fractions and phase durations
- Task 3 – Re-characterization of source term estimates based on best-estimate sequence contribution
- Task 4 – Perform sensitivity studies for realistic definition of release duration
- Task 5 – Develop industry white paper for publication
- Task 6 – Evaluate BWR MSIV pathway-specific source terms

BWR Accident Scenarios (Ref: SAND2023-01313)

Table 1 - Boiling Water Reactor High Burnup Accident Sequence Matrix (Ref: SAND2023-01313)

Case	Plant	Initiating Event	DC Power	Coolant Injection	RPV Pressure at Vessel Breach	Containment Failure	Other
1A	Peach Bottom	STSBO	No	None	Low Stuck-open SRV	Drywell liner melt OR drywell head flange leakage*	
~~1B~~	~~Peach Bottom~~	~~STSBO~~	~~No~~	~~None~~	~~Low~~ ~~Stuck-open SRV~~	~~Drywell liner melt~~	
~~1C~~	~~Peach Bottom~~	~~STSBO~~	~~No~~	~~None~~	~~Low~~ ~~Stuck-open SRV~~	~~Drywell head flange leakage~~	~~Basaltic concrete*~~
1D	Peach Bottom	STSBO	No	None	High	Drywell liner melt	
2A	Peach Bottom	LTSBO	8 hours	RCIC only	Low Stuck-open SRV	Drywell liner melt	
~~2B~~	~~Peach Bottom~~	~~LTSBO~~	~~8 hours~~	~~RCIC only~~	~~Low~~ ~~Stuck-open SRV~~	~~Drywell head flange leakage~~	
~~2C~~	~~Peach Bottom~~	~~LTSBO~~	~~8 hours~~	~~RCIC only~~	~~Low~~ ~~Stuck-open SRV~~	~~Overpressure of torus~~	
3	Peach Bottom	SBLOCA	Yes	None	Low LOCA	Drywell head flange leakage	Small break in main steam line
4	Peach Bottom	LBLOCA	Yes	None	Low LOCA	Drywell liner melt	Recirculation suction line LOCA
5A	Grand Gulf	STSBO	No	None	Low Stuck-open SRV	Early H2 burn at Vessel Breach	H2 burn also causes failure of drywell wall
5B	Grand Gulf	STSBO	No	None	High	Early H2 burn at Vessel Breach	H2 burn also causes failure of drywell wall
~~5C~~	~~Grand Gulf~~	~~STSBO~~	~~No~~	~~None~~	~~Low~~ ~~Stuck-open SRV~~	~~Late~~ ~~Overpressure~~	
6A	Grand Gulf	LTSBO	8 hours	RCIC only	Low Stuck-open SRV	Early H2 burn at Vessel Breach	H2 burn also causes failure of drywell wall
~~6B~~	~~Grand Gulf~~	~~LTSBO~~	~~8 hours~~	~~RCIC only~~	~~Low~~ ~~Stuck-open SRV~~	~~Late~~ ~~Overpressure~~	
7	Grand Gulf	ATWS	Yes	Yes	Low ADS	Prior to Onset of Core Damage	MSIV closure
8	Grand Gulf	LBLOCA	Yes	RCIC only	Low LOCA	Late Overpressure	Recirculation suction line LOCA

*: Different from (Leonard, Gauntt, & Powers, 2007).

PWR Accident Scenarios (Ref: SAND2023-01313)

Table 4-2 Pressurized Water Reactor High Burnup Accident Sequence Matrix

Case	Plant	Initiating Event	ECCS	AFW	Containment Spray	Fan Cooler	Cavity Flood	RCP Seal Leak	Containment Failure
1A	Surry	STSBO	No	No	No	No			
1B	Surry	SBLOCA	No	Yes	No*	No*			
1C	Surry	LBLOCA	Injection-mode available	Yes	No*	No			
1D	Surry	STSBO	No	No	No	No		No	
~~1F~~	~~Surry~~	~~SBLOCA~~	~~No~~	~~Yes~~	~~No*~~	~~No*~~			~~Early~~
4A	Sequoyah	RCP Seal LOCA	No	TDAFW-Controlled	Inj.	Yes	Yes	Yes	
~~4B~~	~~Sequoyah~~	~~RCP Seal LOCA~~	~~No~~	~~TDAFW-Controlled~~	~~Inj.~~	~~Yes~~	~~No~~	~~Yes~~	
~~4C~~	~~Sequoyah~~	~~RCP Seal LOCA~~	~~Inj.~~	~~MDAFW (requires ECCS)~~	~~Yes~~	~~Yes~~		~~Yes~~	
4D	Sequoyah	STSBO	No	TDAFW-Uncontrolled	No	No			
4E	Sequoyah	STSBO	No	No	No	No			Early
4F	Sequoyah	LBLOCA	No	TDAFW-Controlled	No	Yes			
4G	Sequoyah	SBLOCA	No	No	No	No			

*: Different from (Ashbaugh, Leonard, Longmire, Gauntt, & Powers, 2010).

Fission Product Groups

Table 2 – Fission Product Groups (Ref: Table 1-2 SAND2023-01313)

Group	MELCOR Group Name	Elements	MAAP Group
1	Noble Gases	Xe, Kr	Group 1 – Nobles (Xe + Kr)
2	Halogens	I, Br	Group 2 – CsI + RbI[1]
3	Alkali Metals	Cs, Rb	Group 6 – Cs[2]
4	Tellurium Group	Te, Sb, Se	Group 3 – TeO_2
5	Barium/Stront ium	Ba, Sr	Group 7 - BaO
6	Noble Metals	Ru, Rb, Pd, Mo, Tc, Co	Group 5 – RuO_2
7	Lanthanide s	La, Zr, Nd, Eu, Nb, Pm, Pr, Sm, Y, Cm, Am	Group 8 – La_2O_3
8	Cerium Group	Ce, Pu, Np	Group 9 – CsO_2

Notes:

1. For the reference plant input, CsI is assumed to represent 100% of this group. Rb is not included in this group and therefore the release fractions represent are those of Iodine only.
2. Output represents the Cs as included in CsI and Cs_2MoO_4. Per SAND2023, CsOH is assumed to be 0.0. The release fractions reported are therefore the total Cs released divided by the initial Cs mass.

BWR results and comparison to SAND2023

- Base MAAP results – equal weighting for 16 accident scenarios
- PRA weighted MAAP results – weighting factors based on two BWR plant-specific PRAs

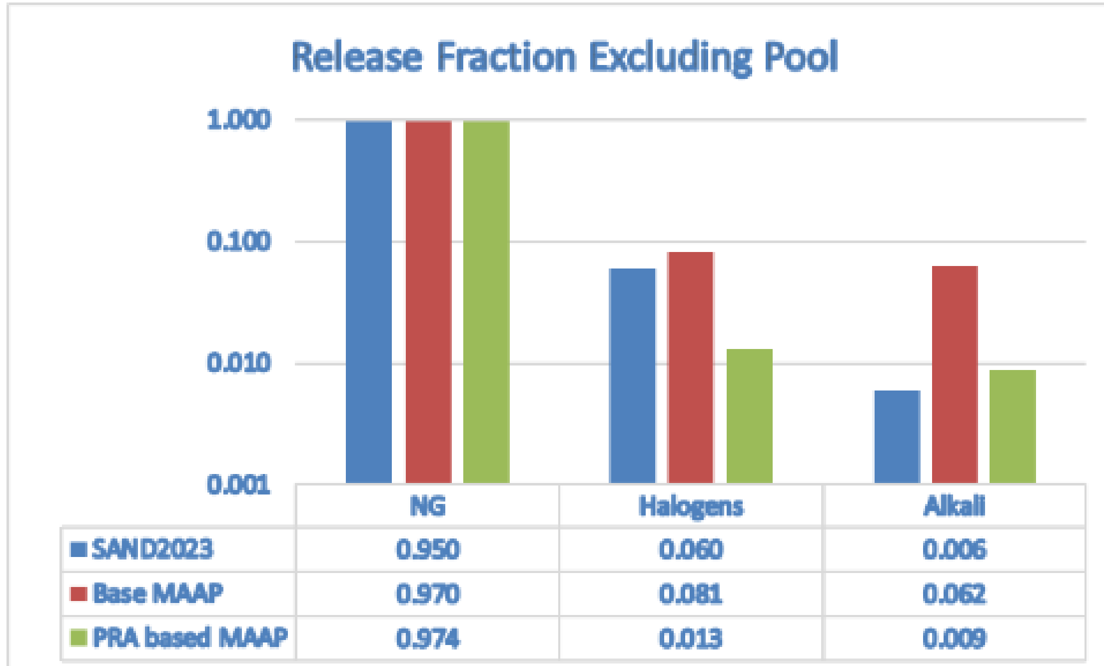
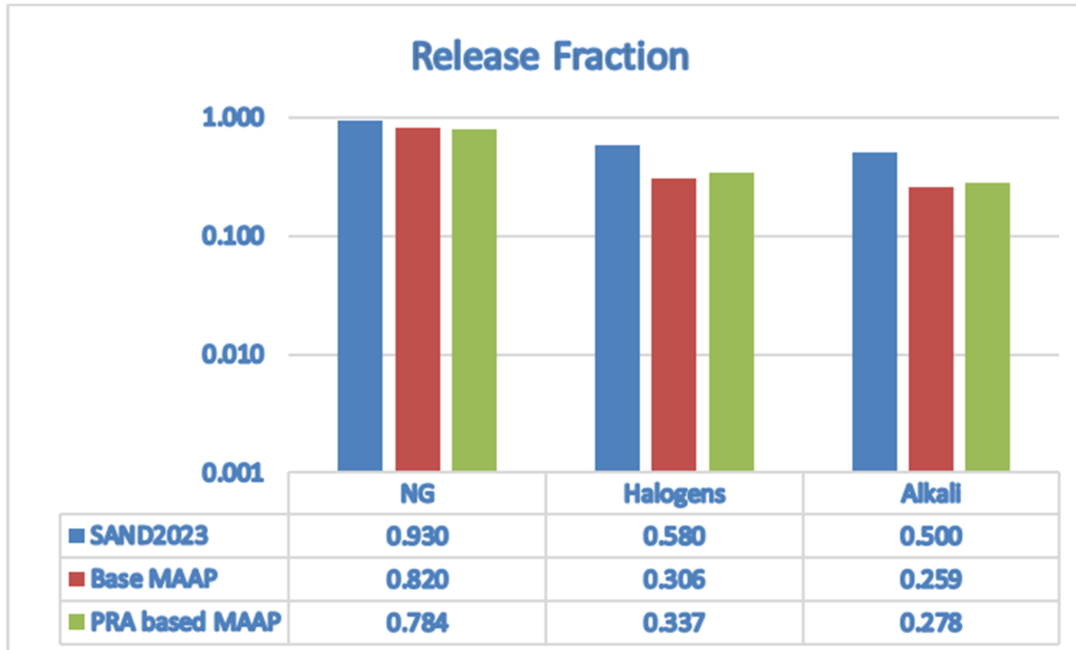


Figure 1 – MAAP/MELCOR Comparison for Key Fission Product Groups

Duration (hr)	SAND2023	Base MAAP
Gap	0.7	0.6
Early In-vessel	6.7	3.9

PWR results and comparison to SAND2023

- Base MAAP results – equal weighting for 12 accident scenarios
- PRA weighted MAAP results – weighting factors based on PWR plant-specific PRAs



Duration (hr)	SAND2023	Base MAAP
Gap	1.3	2.2
Early In-vessel	4.0	3.6

Insights from BWR MAAP Analysis

- Original analysis assumed equal weighting of all 16 sequences
- Current analysis reflects initiating event contribution for plant-specific PRAs
  - Smaller contribution from LOCAs
  - Consistent treatment for high pressure scenarios (~5% of non-LOCAs) for Mark I
- LOCA contributors show lower fission product fraction in suppression pool as expected
- Reduced contribution from scenarios which bypass suppression pool using best-estimate PRA results
  - Order of magnitude increase in suppression pool retention of halogens relative to equally weighted scenarios

MAAP results support the technical basis developed in the SAND2023 report

BWR Sensitivity study

- Parameter selection based on results from Severe Accident Uncertainty Quantification and Analysis Using the Modular Accident Analysis Program (MAAP), EPRI 3002020762
- Work performed in support of international Management and Uncertainties of Severe Accidents (MUSA)
- Additional cases run to investigate timing of SRV opening

Insights from Sensitivity Study

- SRV opening timing
  - Very early opening allows for larger fraction of fission products to be transported to suppression pool
  - Prior to SRV opening, significant transport of fission products to the pool via SRV cycling
- Parameter variations
  - Consistent results support SAND2023 values for releases to containment & retention in suppression pool

Update from May 1, 2024 Public Meeting – ML24120A350

Proposed BWR Pathway-Specific Source Term (Cont'd)

Total Containment Source Term

Containment Source Term (ST)

Radionuclide Group	Containment (SAND2023 Table 5-16)
Halogens	6.00E-02
Alkali Metals	6.00E-03
Te Group	3.80E-02

No proposed change to process in calculating the dose.

MSIV Source Term (ST)

Radionuclide Group	Steam Line (*Preliminary* Follow-on Calcs)
Halogens	5.1E-05
Alkali Metals	1.3E-05
Te Group	2.7E-05

- Steam line ST table already takes FP deposition into account so credit should not be taken for deposition between the reactor vessel and first MSIV during early in-vessel phase.
- Possible approaches after early in-vessel phase:
  1. Keep concentration constant
  2. Apply a removal rate informed by additional analyses

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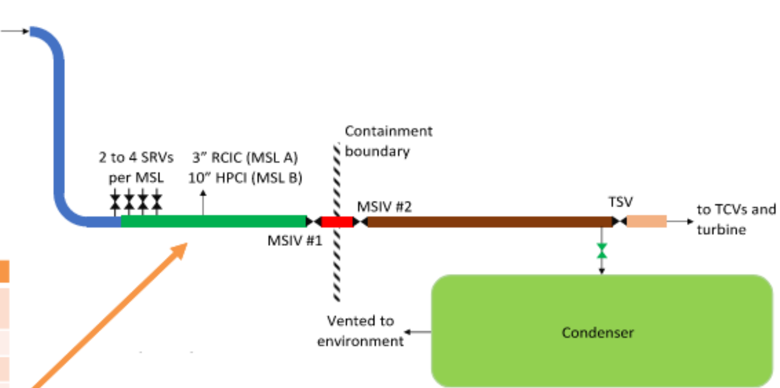
Update from May 1, 2024 Public Meeting – ML24120A350

Proposed BWR Pathway-Specific Source Term

Information presented Jan 9 public workshop

	Steamline	
Release Phase	Gap Release* 0.0h – 0.7h	Early In-vessel* 0.7h – 7.4h
Noble Gases	2.9e-5	1.1e-3
Halogens	5.6e-6	5.1e-5
Alkali Metals	5.1e-6	1.3e-5
Te Group	3.2e-6	2.7e-5
Ba/Sr Group	6.1e-7	2.4e-7
Ru Group	2.2e-11	2.4e-7
Mo Group	3.3e-9	3.0e-6
Lanthanides	3.6e-16	1.0e-11
Ce Group	3.7e-16	8.4e-12

*: inventory fraction held constant across the phase duration



- *The release fractions in the steam line are for the green portion (downstream of first SRV, upstream of MSIV)*
- *Airborne aerosols only, already takes into account the removal of fission products*
- *Time averaged over each phase duration (i.e. gap, early in-vessel, etc.)*
- *RADTRAD would take this as a constant concentration over the gap and early in-vessel phases*

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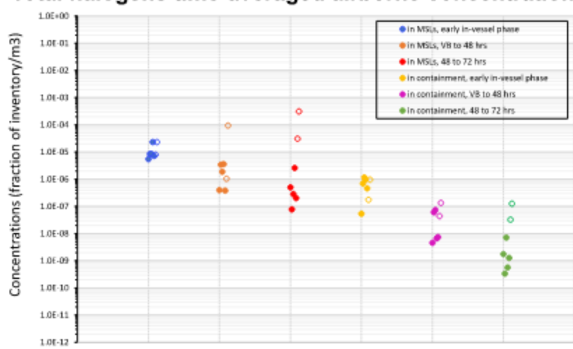
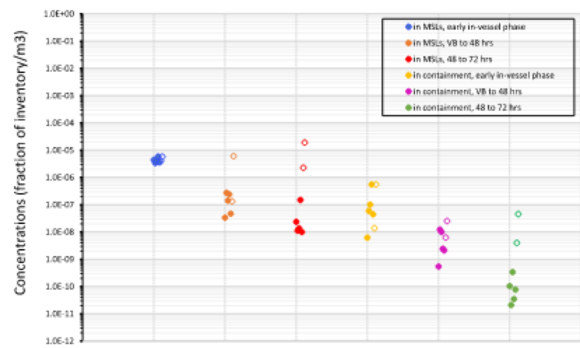
Update from May 1, 2024 Public Meeting – ML24120A350

Proposed BWR Pathway-Specific Source Term (Cont'd)

Total halogens time-averaged airborne concentration





Note: The hollow marks indicate the cases where water injection to the RPV dome shroud did not occur

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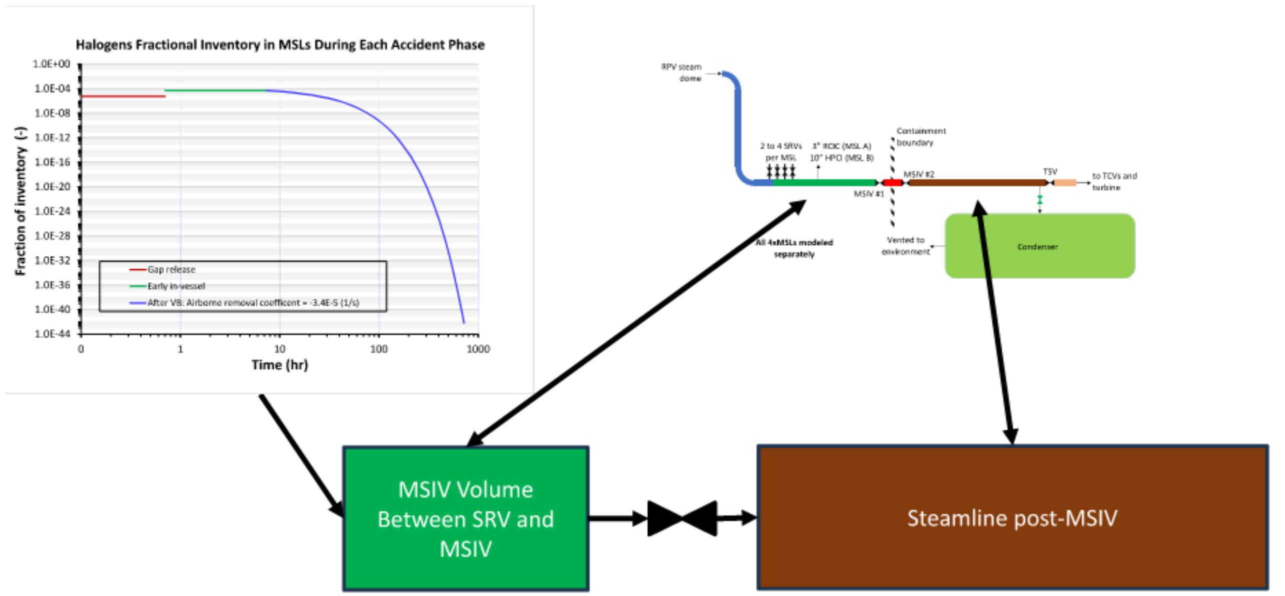
Update from May 1, 2024 Public Meeting – ML24120A350

Proposed BWR Pathway-Specific Source Term (Cont'd)



Use existing methodology (akin to RG1.183 rev1)

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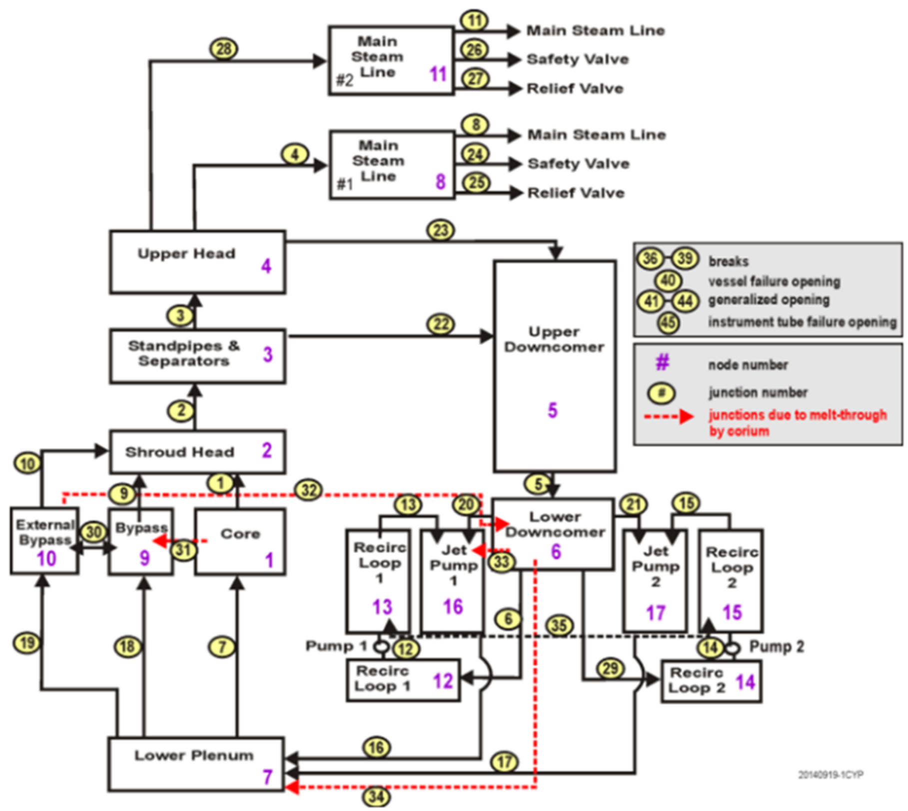
MAAP Main Steam Line (MSL) Analysis

– Represent entire steam line using MAAP RCS Node 8



Results Comparison

- Case 10 from NUREG-2206
- Time-averaged concentrations of Halogens (fraction/m^3)
  - NRC values approximated from ML24120A350
- MAAP results agree with NRC showing similar reduction in fission product concentration over time

Time Phase	NRC (ML24120A350)	MAAP MSL Node 8
Early In-vessel (EI)	1.0E-05	3.7E-05
EI – 48 hrs	1.0E-06	1.3E-06
48-72 hrs	5.0E-07	1.4E-07

EPRI MAAP Analysis of MSL

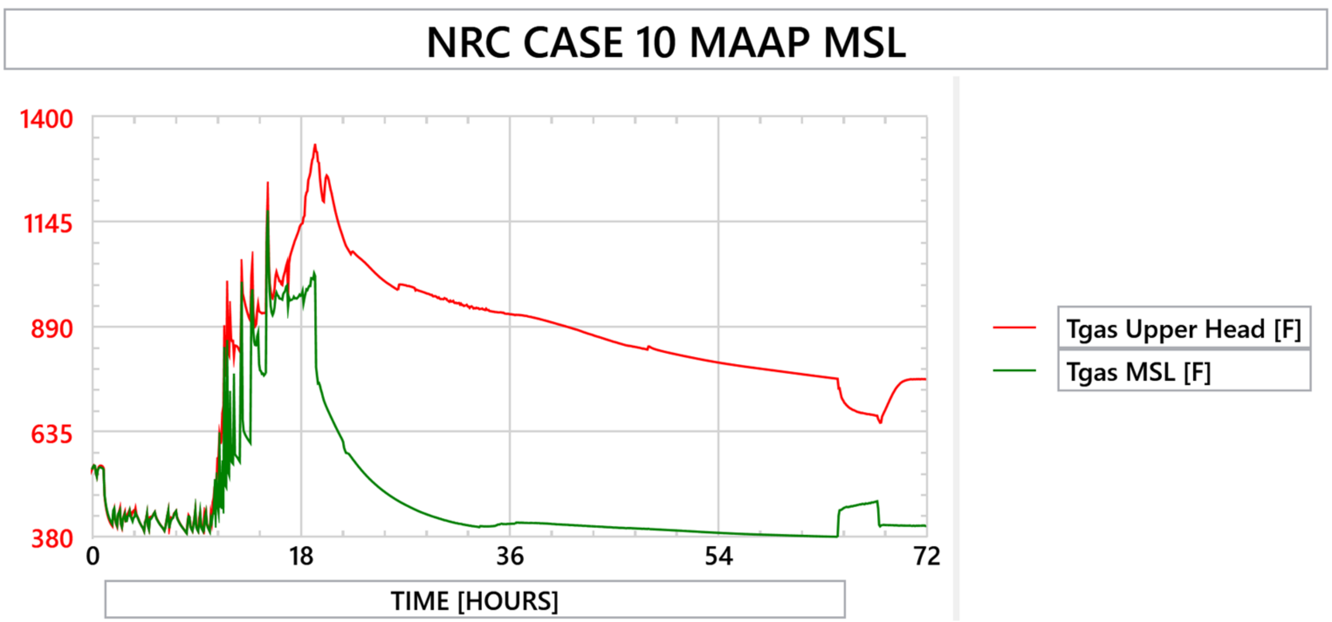
Table 3-4 Timing of key events for Mark I Case 10 (Ref: NUREG-2206)

Event Timing (hr)	Case 10 MELCOR	Case 10 MAAP
Start of ELAP	0.0	0.0
Operators first open SRV to control pressure	0.17	0.17
Low-level 2 and RCIC actuation signal	0.18	0.003[1]
Operators open SRV to control pressure (200-400 psig)	1.0	1.0
RCIC flow terminates (230 °F pool temp)	9.6	7.9
Anticipatory venting at 15 psig	10.6	8.4
SRV sticks open or operators open SRV after RCIC fails	16.0	14.5[2]
Downcomer water level reaches TAF	12.0	10.5
First hydrogen production	13.7	11.4
First fuel-cladding gap release	13.7	11.2
Start of containment venting at 60 psig	16.3	15.8
Relocation of core debris to lower plenum	15.5	15.6
RPV lower head dries out	18.9	16.0
RPV lower head fails grossly	23.1	20.5
Supp pool level > 21 ft	42.2	38.1
Drywell vent open at 60 psig	54.3	61.2
Halogens Concentration (frac/m3) – early in-vessel	1.0E-05[3]	3.7E-05[4]
Halogens Concentration (frac/m3) – VB-48 hrs	1.0E-06	1.3E-06
Halogens Concentration (frac/m3) – 48-72 hrs	5.0E-07	1.4E-07
Calculation terminated	72	72
Selected Results		
Debris mass ejected (1000 kg)	287	336
In-vessel hydrogen generated (kg)	1232	1046

Note 1: MAAP exhibits an initial drop in level causing RCIC actuation.
Note 2: Assumed stuck open SRV was 4 hours after TAF, based on MELCOR results.
Note 3: Average concentrations approximated from ML24120A350
Note 4: MAAP fission product group #2, CsI in MSL Node 8

MSL Temperature Response

- Temperatures remain low due to water injection to RPV after vessel breach
- No revaporization of deposited CsI



Containment Aerosol Removal Rate

- Appendix A, Section 3.2 of RG 1.183 Rev. 0 states that the "reduction in airborne radioactivity in the containment by natural deposition within the containment may be credited". NUREG/CR-6189 cited

- RG 1.183 Rev 1 has changed the language used with regard to aerosol deposition in containment and states "…the aerosol reductions calculated in NUREG/CR-6189 are inconsistent with the characteristics of the revised source terms. However, the methods used in NUREG/CR-6189 may be credited on a case-by-case basis if they are adjusted to incorporate the revised MHA LOCA source term in this revision of Regulatory Guide (RG) 1.183. When these adjusted NUREG/CR-6189 methods are used, the DBA analyses should use the 10^{th}-percentile values unless otherwise justified."

NUREG/CR-6189

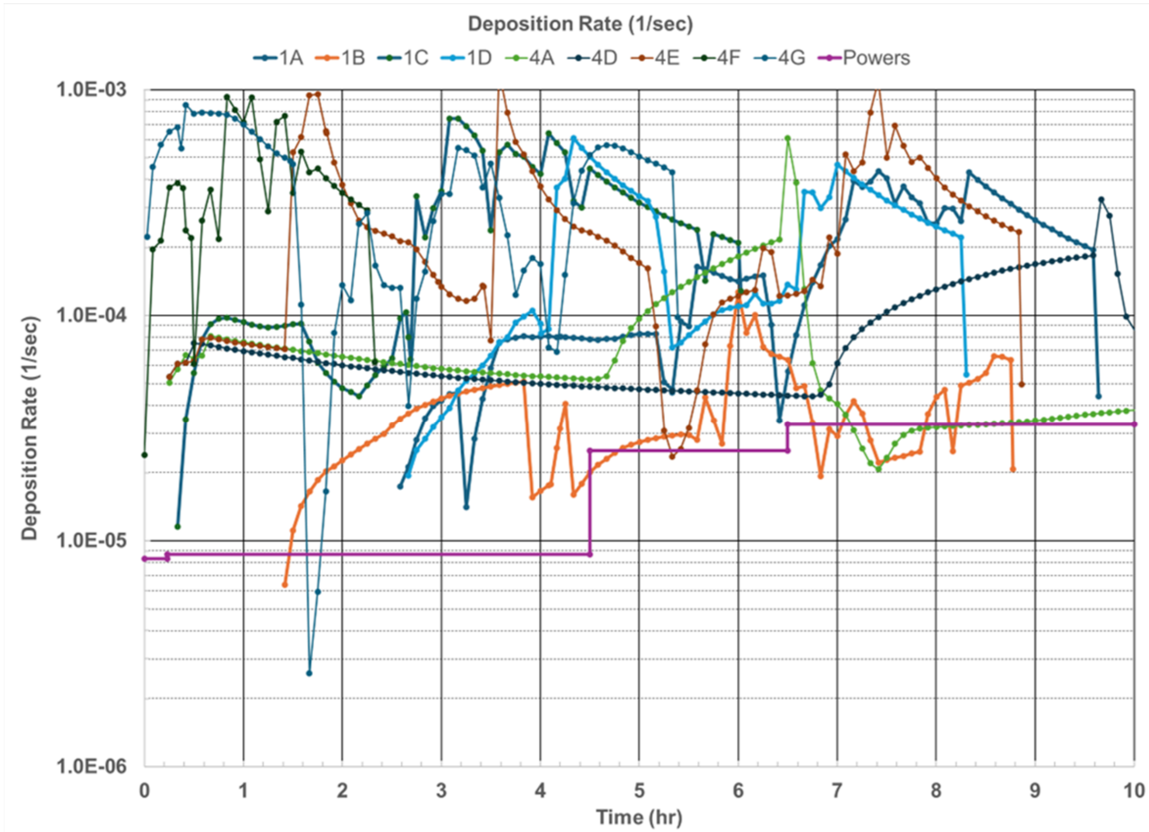
- Addresses basic aerosol physics
- However, source term and phase durations based on NUREG-1465
- Table 36 of NUREG/CR-6189 provides correlation coefficients for 10th percentile values
- RG 1.183 Rev 1 selected for source term and phase durations

	Start Time (hrs)	Rate (sec-1)
Gap	0.0	7.36E-06
Early In-Vessel	0.23	8.16E-06
Gap + Early In-Vessel[1]	4.5	2.33E-05
Gap + Early In-Vessel[1]	6.5[2]	2.97E-05
Gap + Early In-Vessel[1]	16.5[2]	2.38E-05

Note 1: NUREG/CR-6189 assumed no ex-vessel or late in-vessel releases due to assumed water covering core debris ex-vessel.

Note 2: Consistent with NUREG/CR-6189, the ex-vessel and late in-vessel release phases were 2 hours and 10 hours respectively

Deposition Rates for PWR Scenarios vs NUREG/CR-6189



The use of NUREG/CR-6189 can be utilized to provide containment deposition rates

Summary

- MAAP results support source terms and durations developed in SAND2023-01313
  - Confirms importance of considering suppression pool scrubbing in BWR
- Uncertainty analysis confirms significance of BWR SRV seizure and PWR hot leg creep rupture
  - Targeted sensitivity analysis shows small impact on results
- MAAP results confirm NRC proposed treatment for pathway-specific source term for MSIV leakage analysis
- Use of NUREG/CR-6189 remains a viable method to estimate long term aerosol deposition in containment

Questions?

Backup Slides

BWR Results and comparison to SAND2023 – Equal Weighted

Table 5-16 SAND2023-01313

	Gap Release		Early In-vessel			Total (end of 72 hours)	
Release Category	Including Suppression Pool Inventory	Excluding Suppression Pool Inventory	Including Suppression Pool Inventory	Excluding Suppression Pool Inventory	Pool DF	Including Suppression Pool Inventory	Excluding Suppression Pool Inventory
Noble Gases	1.60E-02	1.60E-02	9.50E-01	9.50E-01	1.0	1	1
MAAP	2.85E-02	2.85E-02	9.67E-01	9.67E-01	1.0		
Halogens	5.00E-03	1.30E-06	7.10E-01	6.00E-02	11.8	0.87	0.2
MAAP	2.25E-02	5.70E-03	7.42E-01	8.63E-02	8.6		
Alkali Metals	5.00E-03	1.20E-06	3.20E-01	6.00E-03	53.3	0.35	0.039
MAAP	4.93E-04	2.16E-04	6.29E-01	7.61E-02	8.3		
Te Group	3.00E-03	<1.0e-6	5.60E-01	3.80E-02	14.7	0.78	0.26
MAAP	2.83E-05	2.20E-05	5.11E-01	3.45E-02	14.8		
Ba/Sr Group	6.00E-04	<1.0e-6	5.00E-03	3.00E-04	16.7	0.048	0.042
MAAP	2.18E-06	1.68E-06	3.20E-02	4.27E-03	7.5		
Ru Group	<1.0e-6	<1.0e-6	6.00E-03	7.40E-06	810.8	0.006	0.0001
MAAP	7.23E-09	7.01E-09	9.77E-02	9.15E-03	10.7		
Mo Group	1.90E-05	<1.0e-6	1.20E-01	1.00E-04	1200.0	0.13	0.002
MAAP	2.66E-06	8.86E-07	1.41E-01	4.74E-03	29.8		
Lanthanides	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-6	NA	3.70E-05	3.60E-05
MAAP	1.80E-11	1.35E-11	2.46E-04	3.30E-05	7.5		
Ce Group	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-6	NA	0.003	0.003
MAAP	7.96E-11	7.91E-11	1.45E-03	2.33E-04	6.2		

Duration (hr)	SAND2023	MAAP
Gap	0.7	0.66
Early In-vessel	6.7	4.04

PWR Results and comparison to SAND2023 – Equal Weighted

Table 3 – PWR Release Fractions; equal weighting of scenarios (Ref: Table ES-1 of SAND2023-01313-01313)

Release Category	Gap Release	Early In-vessel Release
Noble Gases	2.60E-02	9.30E-01
MAAP	2.31E-02	7.84E-01
Halogens	7.00E-03	5.80E-01
MAAP	8.59E-03	3.37E-01
Alkali Metals	3.00E-03	5.00E-01
MAAP	8.40E-04	2.78E-01
Te Group	6.00E-03	5.50E-01
MAAP	2.78E-05	2.97E-01
Ba/Sr Group	1.00E-03	2.00E-03
MAAP	1.84E-06	1.39E-02
Ru Group	<1.0e-6	8.00E-03
MAAP	1.62E-08	4.71E-02
Mo Group	2.00E-05	1.50E-01
MAAP	8.24E-06	4.48E-02
Lanthanides	<1.0e-6	<1.0e-6
MAAP	9.97E-11	1.14E-04
Ce Group	<1.0e-6	<1.0e-6
MAAP	1.11E-11	9.64E-04

Table 4 – PWR Release Durations; equal weighting of scenarios (Ref: Table ES-1 of SAND2023-01313-01313)

Duration (hr)	SAND2023	MAAP
Gap	1.3	2.23
Early In-vessel	4.0	3.60

Input Preparation

- Utilize MAAPv5.06 reference BWR parameter files
- BWR isotopic inventory based on scaling of current default values using Table 2-3 from SAND2023.
  - 80 GWd/MTU 10% wt% enrichment
- Minor adjustments to core dimensions (e.g., pellet diameter, clad thickness)
- Increased core power to be consistent with SAND2023
- Selection of ORNL-BOOTH model per SAND2023 Section 3.2.1.7
- Based on SAND2023, assume 100% remaining Cs (after formation of CsI) will exist as Cs_2MoO_4

Sensitivity Study Parameter Selection

Variable Name	Sensitivity Case #	Parameter Range	BWR Default	Sensitivity Value	Description
FGBYPA	1	0-1	0	1	Flag to identify whether gas flow should be entirely diverted to the external bypass when all core nodes at an axial level are blocked (IGTYP=4)
FCHTUR	2	1.0-5.0	1.53	1	FCHTUR is the churn-turbulent critical velocity coefficient
TSPFAL	3	1000-3113 K	1650 K	2000 K	Temperature used in time-at- temperature correlations for core support plate failure
IGCHF	4	0,1	1	0	This parameter is used to enable or disable the CHF gap boiling model for in-vessel debris cooling
FCSHVP	5	.01-1.0	.1	1.0	Multiplier to vapor pressure of CsOH for vapor-aerosol equilibrium
FCSIVP	6	-100-100	1.0	10.	Multiplier to vapor pressure of CsI for vapor-aerosol equilibrium
FVPREV	7	.01-2.0	1.0	2.0	Multiplier to vapor pressures of CsI and CsOH for revaporization
FPNVMP	8	0,1	0	1	Indicate whether nonvolatile fission products can be released from in-core molten pools
ISIDRL	9	0,1	0	1	Indicates if model for sideward relocation within core is enabled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