High Burnup Fuel Source Term Accident Analysis
Boiling-Water Reactor Follow-On Calculations

ACRS FUELS, MATERIALS, AND STRUCTURES SUBCOMMITTEE BRIEFING

November 19, 2024

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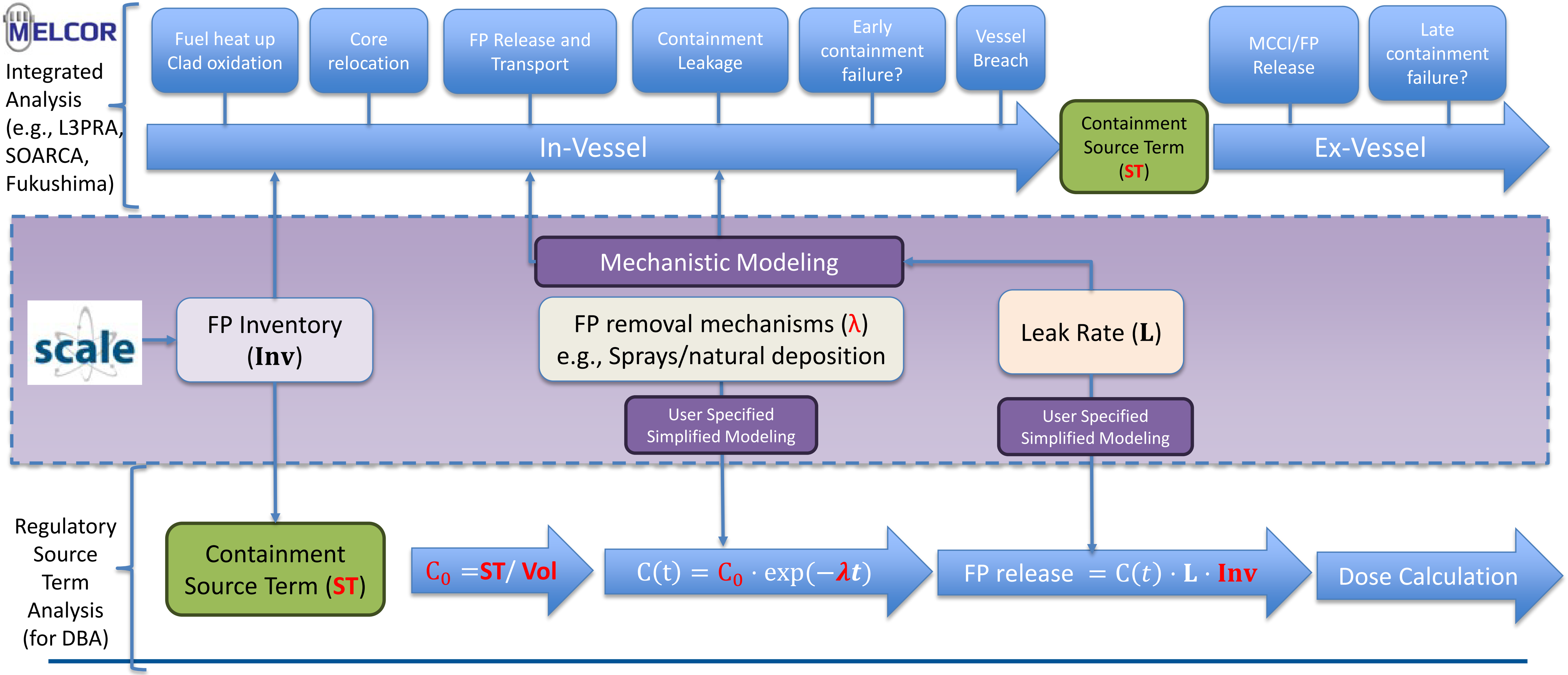
Outline

- Background and Motivation
- Source Term Methodology
- Multi-region source terms for BWRs
- Example HBU Inventories
- Steam line removal rates for downstream codes

Background and Motivation

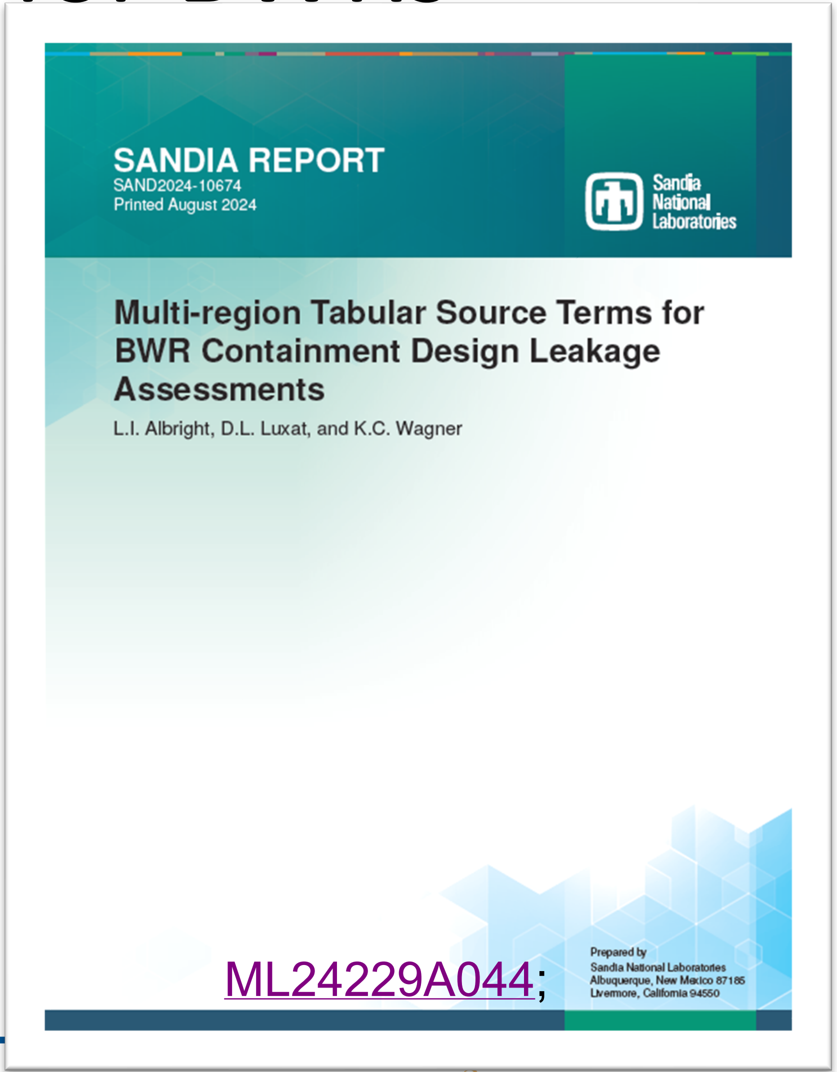
- *The High Burnup (HBU) Peer Review panelists commented on the potential impact of the suppression pool on the containment source term.*
- *Table 5-16 of SAND2023-01313 provides the boiling-water reactor (BWR) containment release fractions including and excluding the suppression pool.*
- *Supplemental investigations following the peer review in BWRs:*
  - *Investigate fission product concentration variation between different regions of the reactor system and containment since some release pathways bypass the suppression pool (i.e., main steam line).*
  - *Modified the two (Peach Bottom, Grand Gulf) full-scale BWR input decks to better capture aerosol behavior in the containment and steam line.*
  - *Performed a set of BWR source term calculations.*
  - *Proposed methodology for a multi-region (pathway-specific) BWR source term.*

Source Term Methodology



Multi-Region Source Term for BWRs

- Containment Source Term (**ST**)
- Broke the source term into three parts:
  - Suppression pool (SP)
  - Containment atmosphere
  - Main Steam Line (MSL)
- The first two STs are derived from SAND2023-01313 results
- The MSL ST is developed from new calculations documented in SAND2024-10674


SANDIA REPORT
SAND2024-10674
Printed August 2024

Sandia National Laboratories

Multi-region Tabular Source Terms for BWR Containment Design Leakage Assessments

L.I. Albright, D.L. Luxat, and K.C. Wagner

ML24229A044;

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Illustration of BWR Modeling Practices

Area with refined modeling

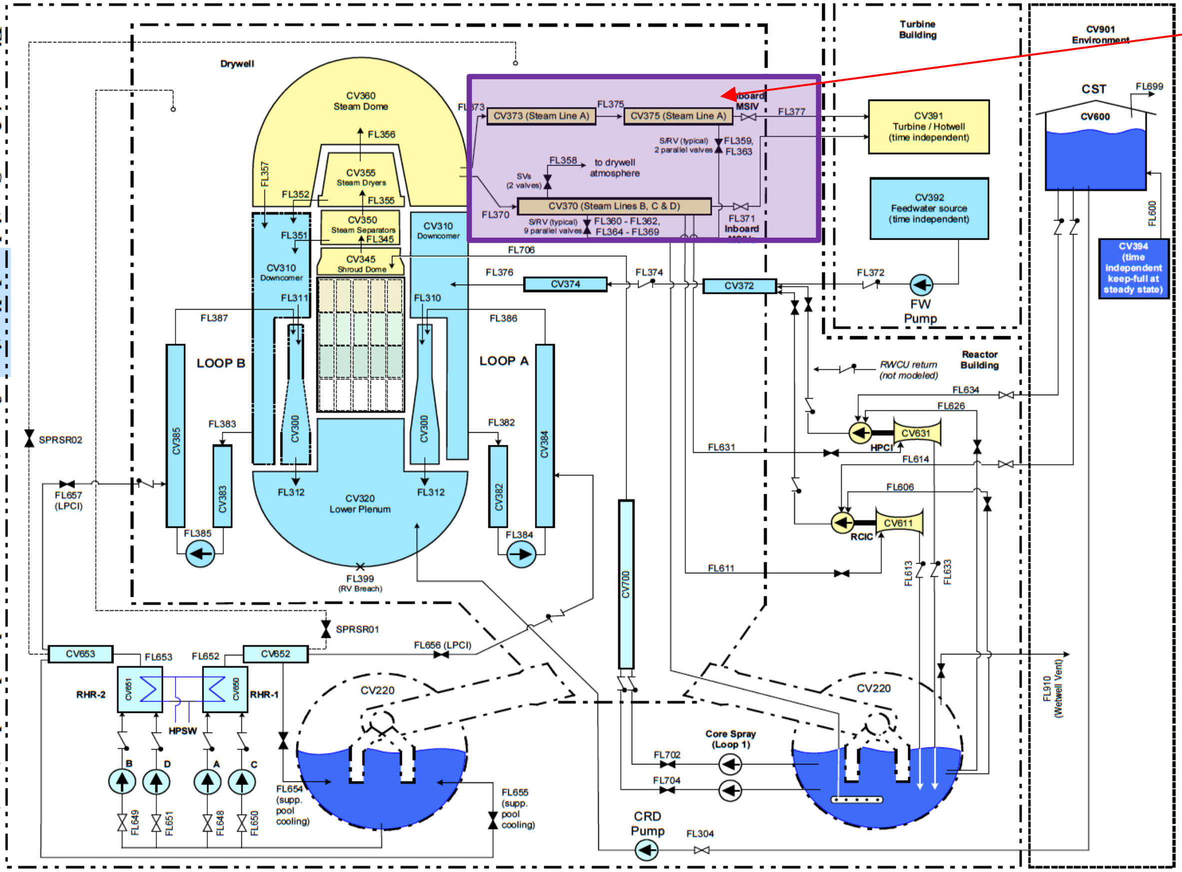
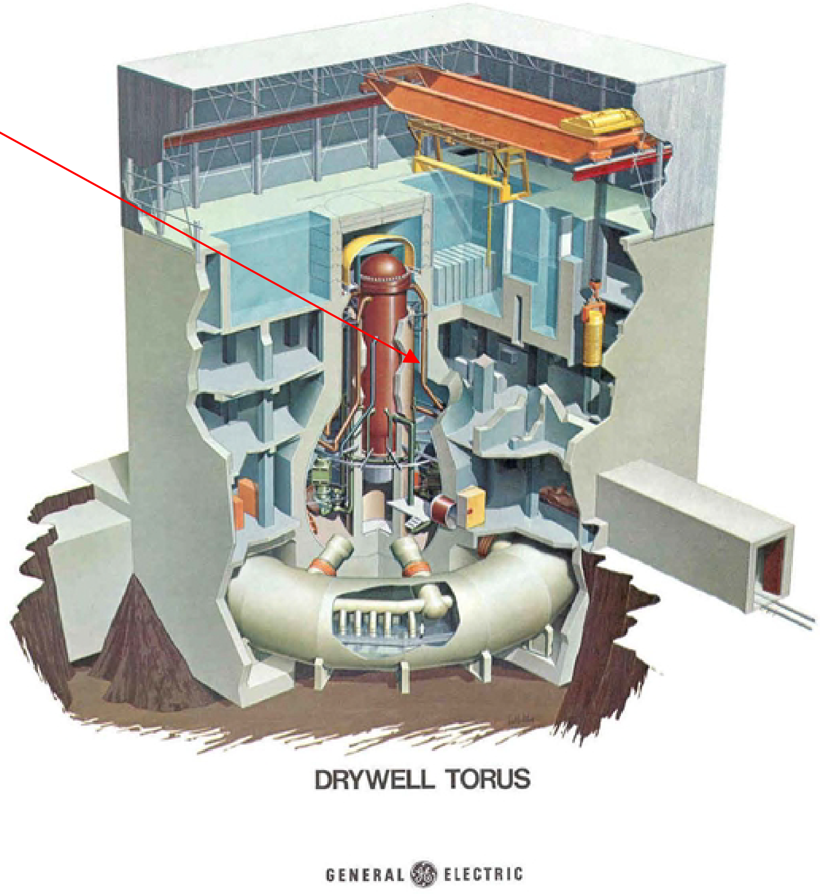
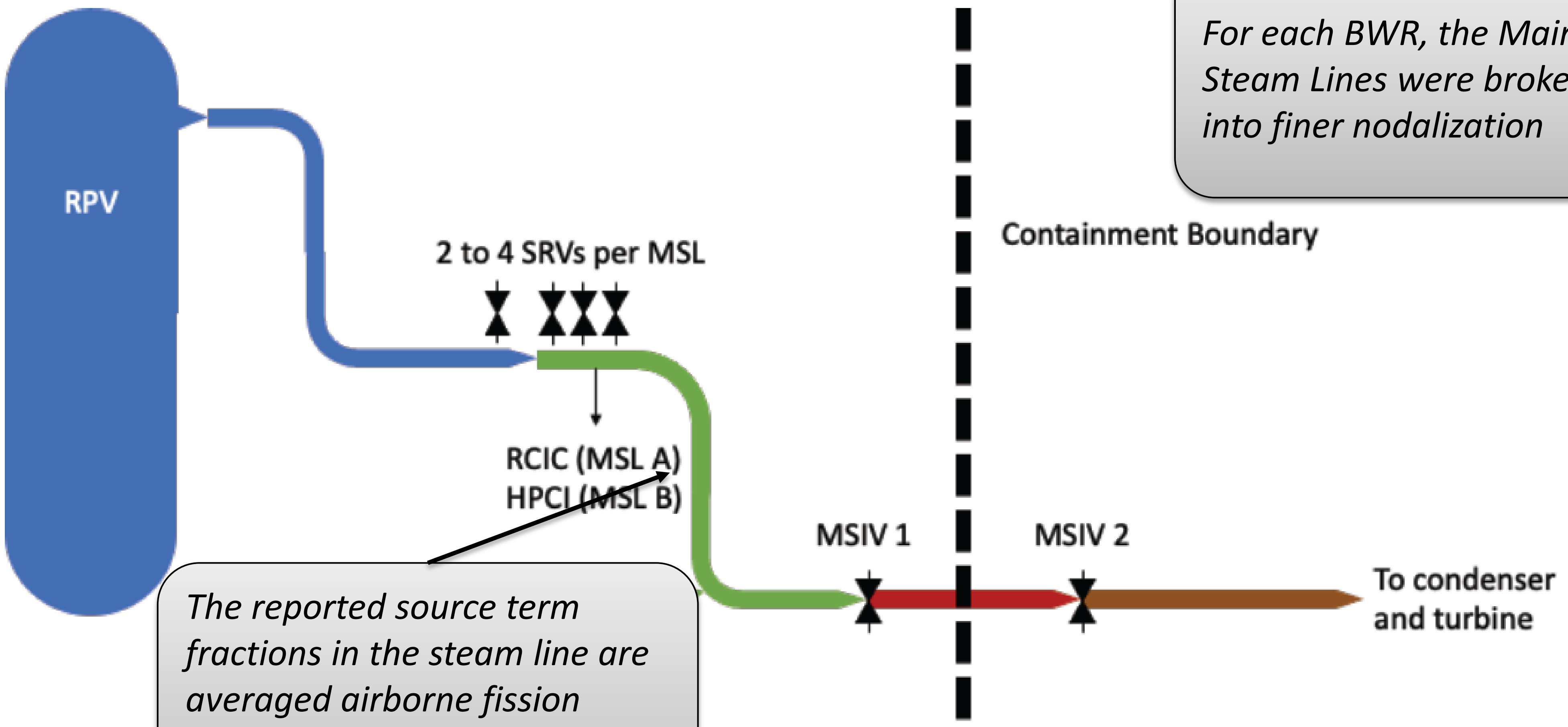


Figure 4-2 Spatial nodalization of reactor pressure vessel and coolant system

Peach Bottom



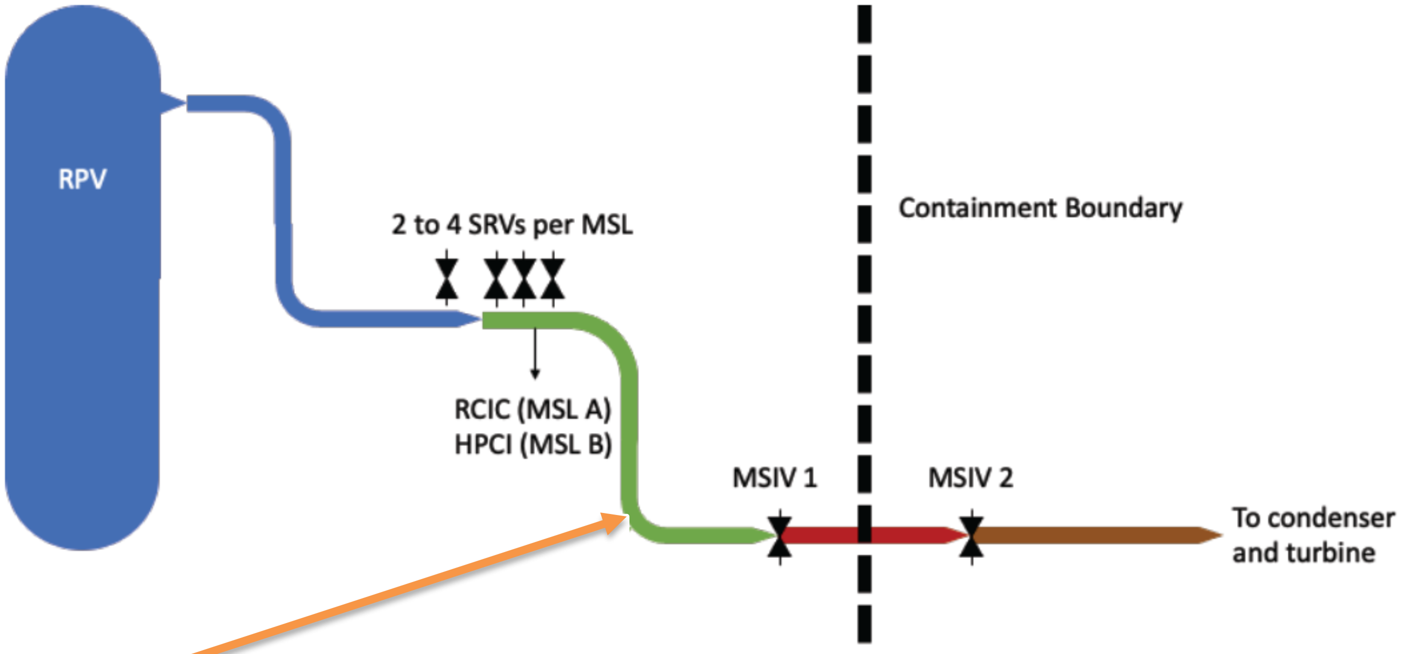
New BWR Main Steam Line (MSL) Modeling



For each BWR, the Main Steam Lines were broken up into finer nodalization

The reported source term fractions in the steam line are averaged airborne fission products in the green portion.

Proposed BWR Multi-Region Source Term



	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	<1e-9	2.4e-7
Mo Group	3.3e-9	3.0e-6
Lanthanides	<1e-9	<1e-9
Ce Group	<1e-9	<1e-9

*: 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 (for gap and early in-vessel phases)*
- *Time averaged over each phase duration (i.e. gap, early in-vessel, etc.)*
- *RADTRAD would take this as a constant concentration*

BWR Source Term (ST) Inventory Fractions

Metric	Gap Release Phase			Early In-vessel Phase		
Region	Main Steamline*	Suppression Pool**	Containment Atmosphere**	Main Steamline*	Suppression Pool**	Containment Atmosphere**
Noble Gases	2.9×10^{-5}	$< 1.0 \times 10^{-6}$	1.6×10^{-2}	1.1×10^{-3}	$< 1.0 \times 10^{-6}$	9.5×10^{-1}
Halogens	5.6×10^{-6}	5.0×10^{-3}	1.3×10^{-6}	5.1×10^{-5}	6.5×10^{-1}	6.0×10^{-2}
Alkali Metals	5.1×10^{-6}	5.0×10^{-3}	1.2×10^{-6}	1.3×10^{-5}	3.1×10^{-1}	6.0×10^{-3}
Te Group	3.2×10^{-6}	3.0×10^{-3}	$< 1.0 \times 10^{-6}$	2.7×10^{-5}	5.2×10^{-1}	3.8×10^{-2}
Ba/Sr Group	6.1×10^{-7}	6.0×10^{-4}	$< 1.0 \times 10^{-6}$	2.4×10^{-7}	4.7×10^{-3}	3.0×10^{-4}
Ru Group	$< 1.0 \times 10^{-9}$	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$	2.4×10^{-7}	6.0×10^{-3}	7.4×10^{-6}
Mo Group	3.3×10^{-9}	1.9×10^{-5}	$< 1.0 \times 10^{-6}$	3.0×10^{-6}	1.2×10^{-1}	1.0×10^{-4}
La Group	$< 1.0 \times 10^{-9}$	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-9}$	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$
Ce Group	$< 1.0 \times 10^{-9}$	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-9}$	$< 1.0 \times 10^{-6}$	$< 1.0 \times 10^{-6}$
Phase Duration [h]	0.70			6.7		

*: time-averaged airborne fission product inventory fraction – intended to be held constant for the duration of the accident phase in downstream analyses. A lower minimum threshold is used for time-averaged metrics.

**: cumulative release fraction – intended to be released completely by the end of a given accident phase in downstream analyses.

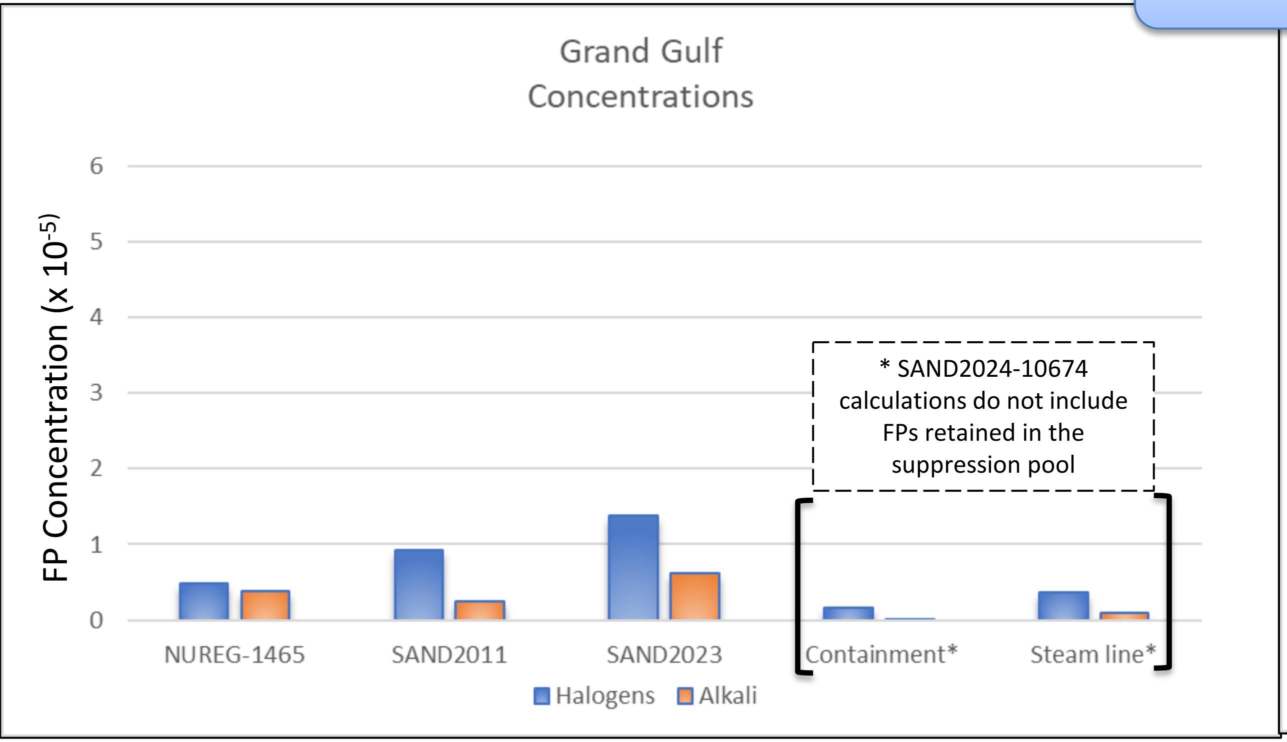
Suppression pool and containment atmosphere source terms are derived from SAND2023-01313 [1].

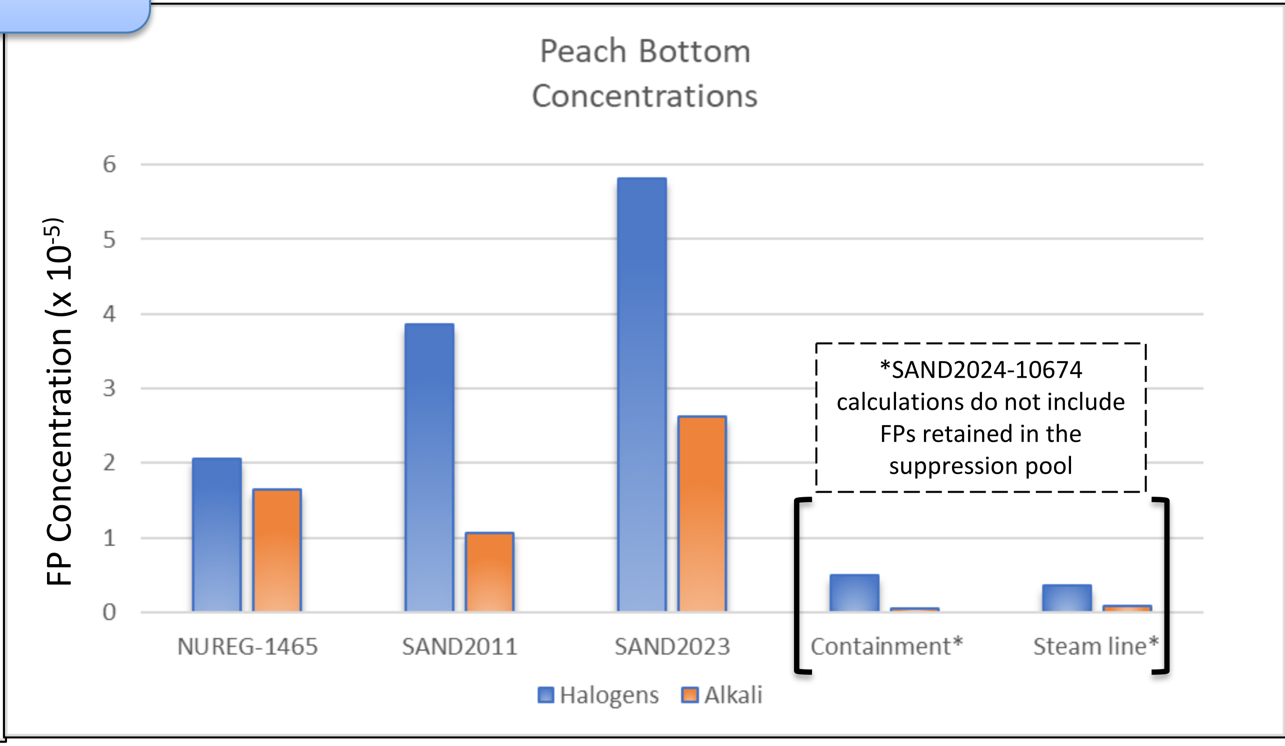
BWR Source Term (ST) Inventory Fractions – Early In-Vessel

Radionuclide Group	RG1.183 (rev0)	RG1.183 (rev1)	SAND2023	Pool (SAND2023 Table 5-16)	Containment (SAND2023 Table 5-16)	Steam Line (SAND2024-10674)
Noble Gases	9.50E-01	9.60E-01	9.50E-01	0.00E+00	9.50E-01	1.1E-03
Halogens	2.50E-01	5.40E-01	7.10E-01	6.50E-01	6.00E-02	5.1E-05
Alkali Metals	2.00E-01	1.40E-01	3.20E-01	3.10E-01	6.00E-03	1.3E-05
Te Group	5.00E-02	3.90E-01	5.60E-01	5.20E-01	3.80E-02	2.7E-05
Ba/Sr Group	2.00E-02	5.00E-03	5.00E-03	4.70E-03	3.00E-04	2.4E-07
Ru Group	3.00E-03	2.70E-03	6.00E-03	6.00E-03	7.40E-06	2.4E-07
Mo Group	3.00E-03	3.00E-02	1.20E-01	1.20E-01	1.00E-04	3.0E-06
Lanthanides	2.00E-04	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-9
Ce Group	5.00E-04	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-9

BWR Example Fission Product (FP) Concentrations (C_0)

$C_0 = ST / Vol$



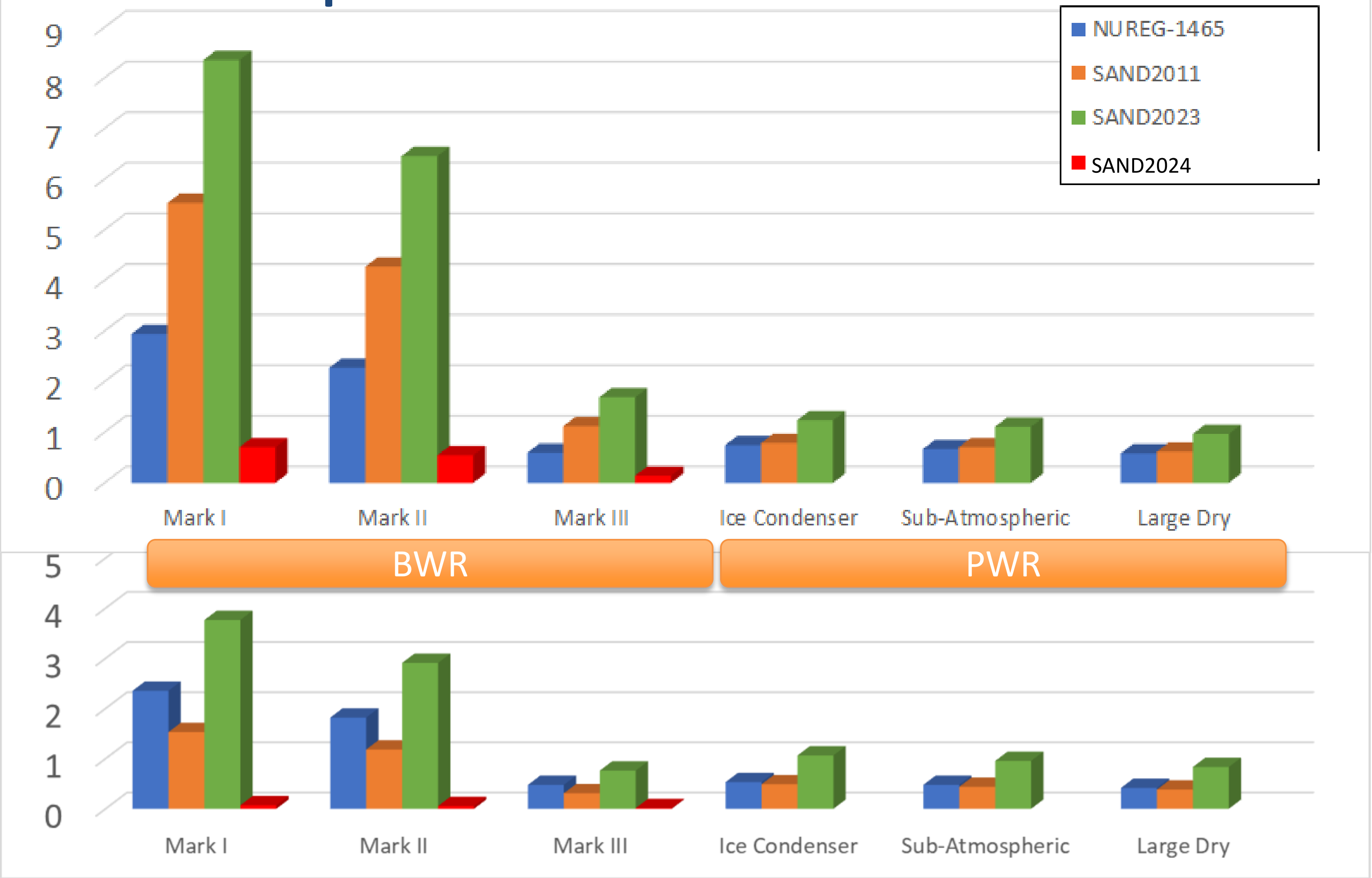


BWR/PWR Example Containment Concentrations

Halogen (Iodine) x 1E-5

$C_0 = \mathbf{ST / Vol}$

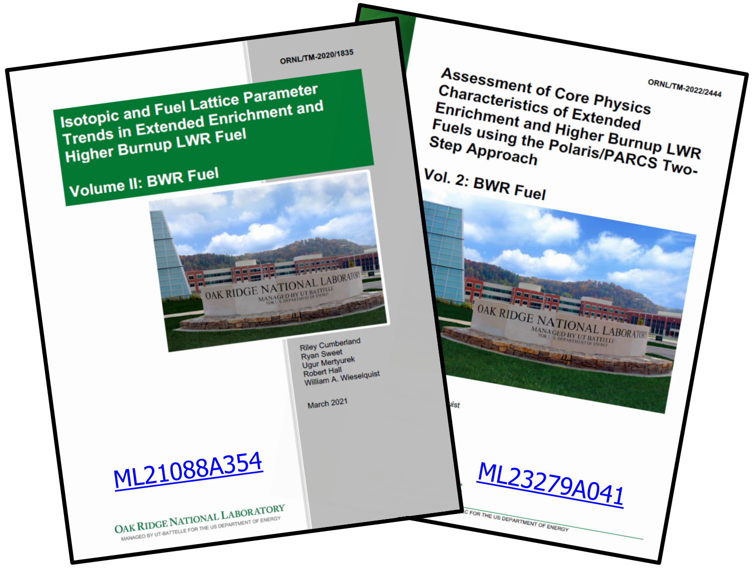
Alkali Metals (Cesium) x 1E-5



Typical containment volumes from *Figure 4.1-1 in NUREG/CR-6042, Rev. 2*

Example HBU Inventories

- Fission Product Inventory (**Inv**)
- Created representative inventories for a high burnup core
- Used SCALE to generate inventories with representative fuel cycle
  - *Fuel & core designs based on SCALE ATF/HBU/EE Project*



Example HBU Inventories - PWRs

Objective
Increase cycle length from 18 months to 24 months

Input Data to Fuel Cycle Estimator	Baseline	HBU/EE
Power (MW_{th})	2893	2893
Initial Enrichment (%)	4.65	5.25
Cycle Length (months)	18	24
Fresh / Once-burned / Twice-burned	56 / 56 / 45	72 / 72 / 13
Core Avg. end of cycle BU (MWd/MTU)	43.5	48.3
Avg. Assembly discharge BU (MWd/MTU)	60.7	71.6

Impact on
Radionuclide Inventories

Radionuclide Group	Baseline Activity (Bq)	HBU/EE Activity (Bq)	Rel. Change (%)
Halogens (I)	**2.53E19**	**2.53E19**	**~0**
Alkali Metals (Cs)	**3.09E18**	**3.24E18**	**5**
Chalcogen (Te)	**8.35E18**	**8.33E18**	**~0**

Example HBU Inventories - BWRs

Objective
Reduce feed batch fraction

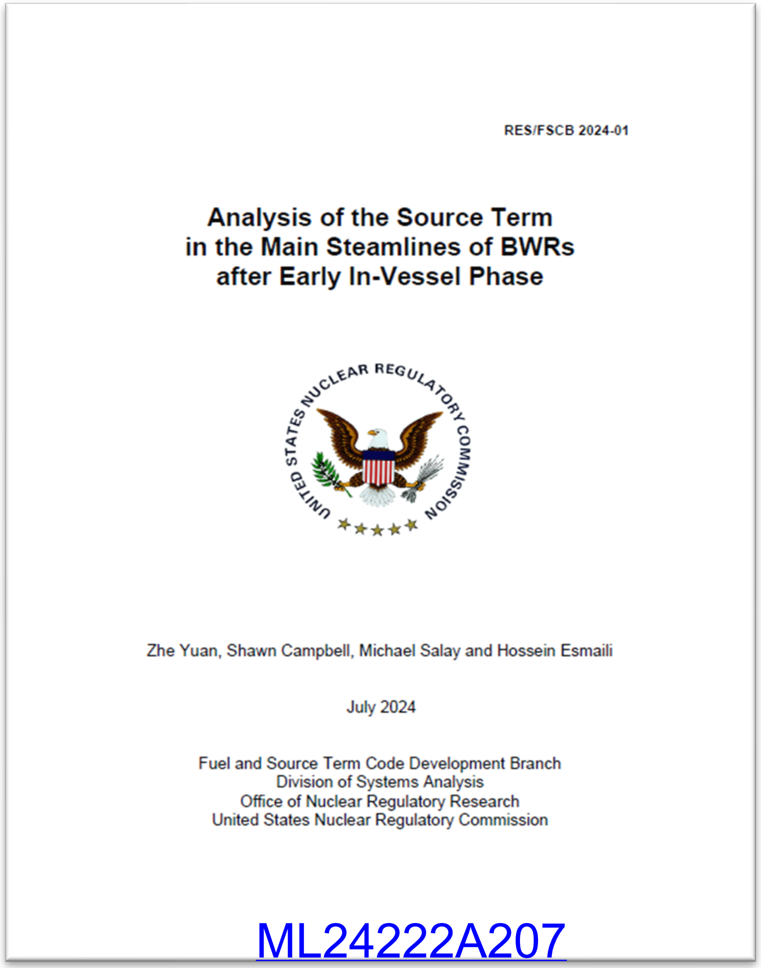
Input Data to Fuel Cycle Estimator	Baseline	HBU/EE
Power (MW_{th})	4016	4016
Initial Enrichment (%)	4.45	5.30
Cycle Length (months)	24	24
Fresh / Once-burned / Twice-burned	316 / 316 / 132	260 / 260 / 244
Core Avg. end of cycle BU (MWd/MTU)	36.2	41.4
Avg. Assembly discharge BU (MWd/MTU)	52.6	58.0

Impact on
Radionuclide Inventories

Radionuclide Group	Baseline Activity (Bq)	HBU/EE Activity (Bq)	Rel. Change (%)
Halogens (I)	**3.54E19**	**3.54E19**	**~0**
Alkali Metals (Cs)	**4.46E18**	**4.78E18**	**7**
Chalcogen (Te)	**1.16E19**	**1.15E19**	**~0**

Removal Rates in the Steam Line

- FP removal mechanisms upstream of containment boundary
- For gap and early in-vessel phases, removal rates are already accounted for in SAND2024-10674 formulation
- After early-in vessel phase, question was raised how to account for removal in the long-term dose assessment with downstream codes
- Used existing NUREG2206 analysis to ascertain a reasonable removal rate in the steam line and documented results in RES/FSCB2024-01


RES/FSCB 2024-01

Analysis of the Source Term in the Main Steamlines of BWRs after Early In-Vessel Phase

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July 2024

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ML24222A207

BWR Multi-Region Source Term Removal Mechanism

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

Proposed BWR Multi-Region Source Term

- **Model**

MELCOR model from the SOARCA studies (NUREG/CR 7110 and 7155)

- **Reference:**

J. Barr, S. Basu, H. Esmaili and M. Stutzke, “Technical Basis for the Containment Protection and Release Reduction Rulemaking for BWRs with Mark I and Mark II Containments”, Office of Nuclear Regulatory Research, US NRC, NUREG-2206, March 2018.

- **Case selections**

RUN MATRIX REV 9 (10/15/2014) - Mark I

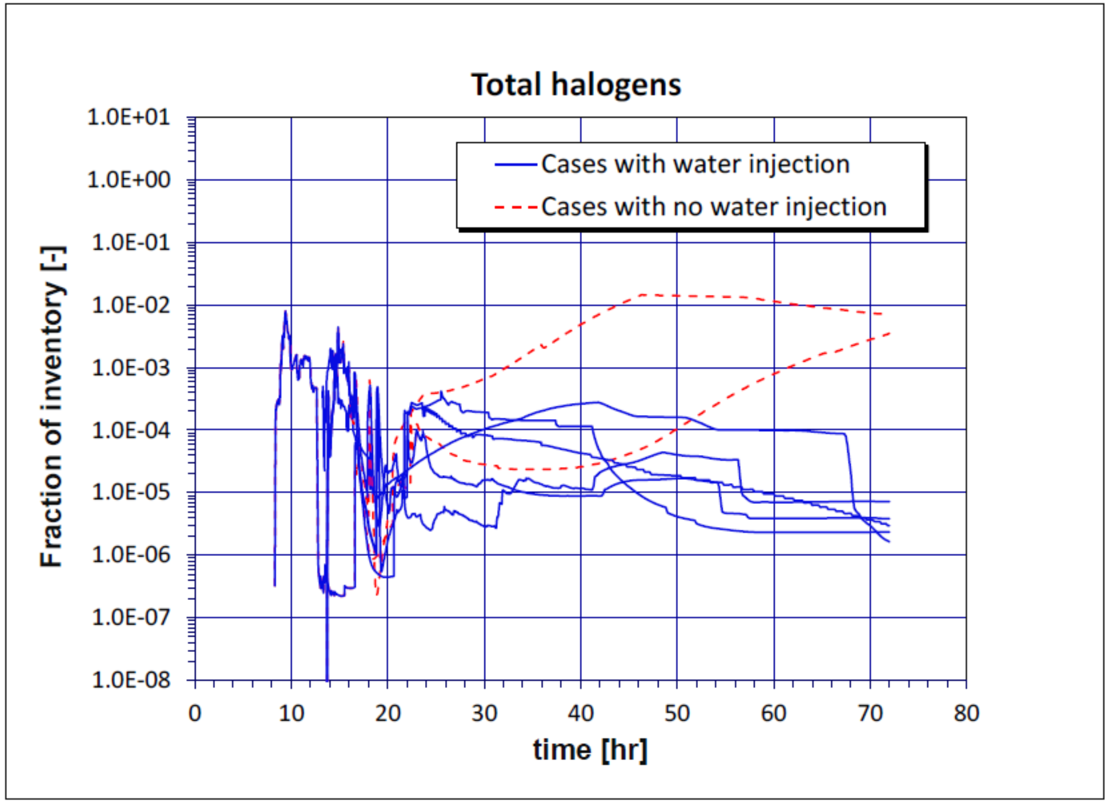
		Pre Core Damage																Post Core Damage															
		DC Power			RCIC Operation									Anticipatory Venting				Flex Operation					SRV Operation		Containment Venting						DW Head Seal	
		Availability (hr)			RCIC Availability (hr)			RCIC Suction		Failure Temp (F)		Open SRV after		Setpoint (psig)		Allow after RCIC		Injection @ LH		WW Level Control Injection			Allow SRV stuck		Mode		Location		Setpoint		Fail @ 700F	
Option	Case	0	4	72	0	4	16	SP	CST	230	240	No	Yes	15	5	Yes	No	RPV	DW	Stop @ 21'	Throttle @ 21 '	Continuous	Thermal seizure - fraction open	Seizure on # cycles?	Open	Cycle (10/20 psid)	Initial	Switchover	PCPL	PSP	Yes	No
1	1			X			X	X		X		X		X			X						100%	Enabled	X		WW		X		X	
1	3		X			X		X		X		X		X			X						No	Disabled	X		WW		X		X	
2A	10			X			X	X		X		X		X		X		X				X	100%	Enabled	X		WW	DW	X		X	
2A	11			X			X	X		X			X	X			X	X				X	100%	Enabled	X		WW	DW	X		X	
2B	18			X			X	X		X		X		X		X		X				X	100%	Enabled		10/10	WW	DW	X		X	
2B	16			X			X	X		X		X		X			X	X				X	100%	Enabled		20/-	WW	DW	X		X	
2A	42		X			X		X		X		X		X			X	X				X	No	Disabled	X		WW	DW	X		X	

Notes
0 DC power means there is no RPV pressure control, so should start like a SBO and remains so
10/10 means both WW and DW cycle at 10 psid
20/- means allow WW cycling at 20 psid but DW is not cycling and remains open

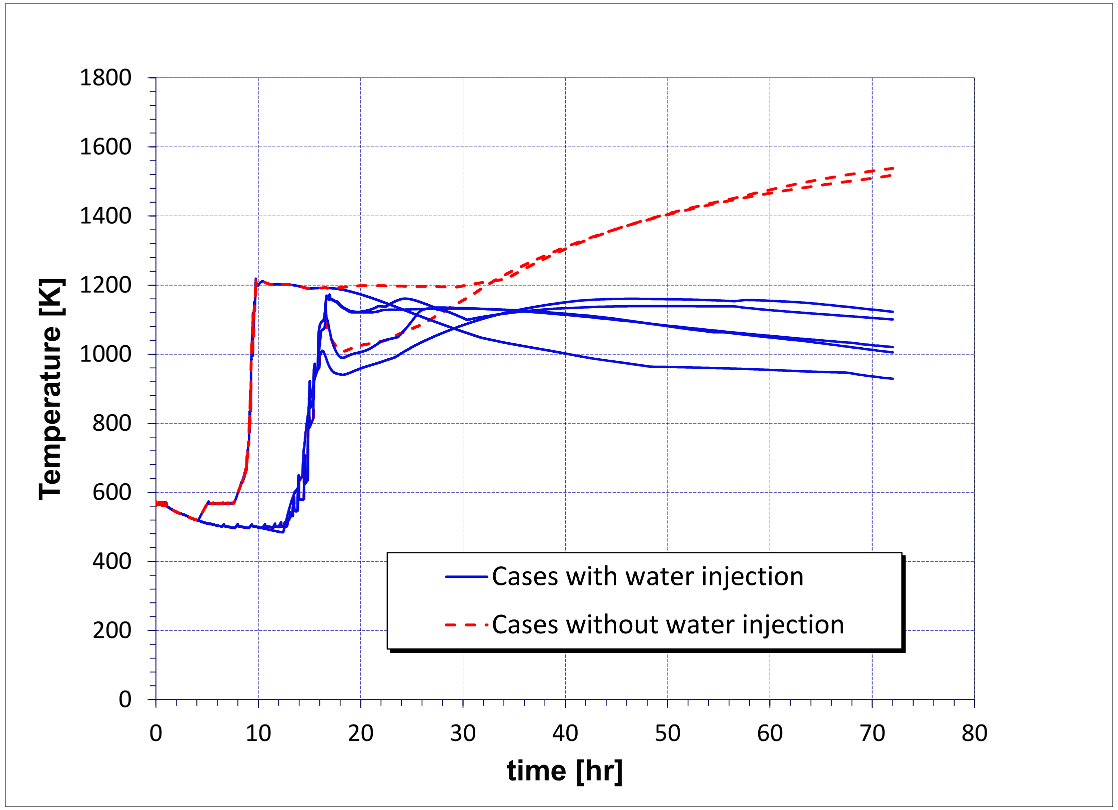
Note: 1) Two cases without water injection and five cases with water injection are selected.
2) The FLEX water is injected to the RPV shroud-dome.

Proposed BWR Multi-Region Source Term

Fraction of airborne halogens in steam line

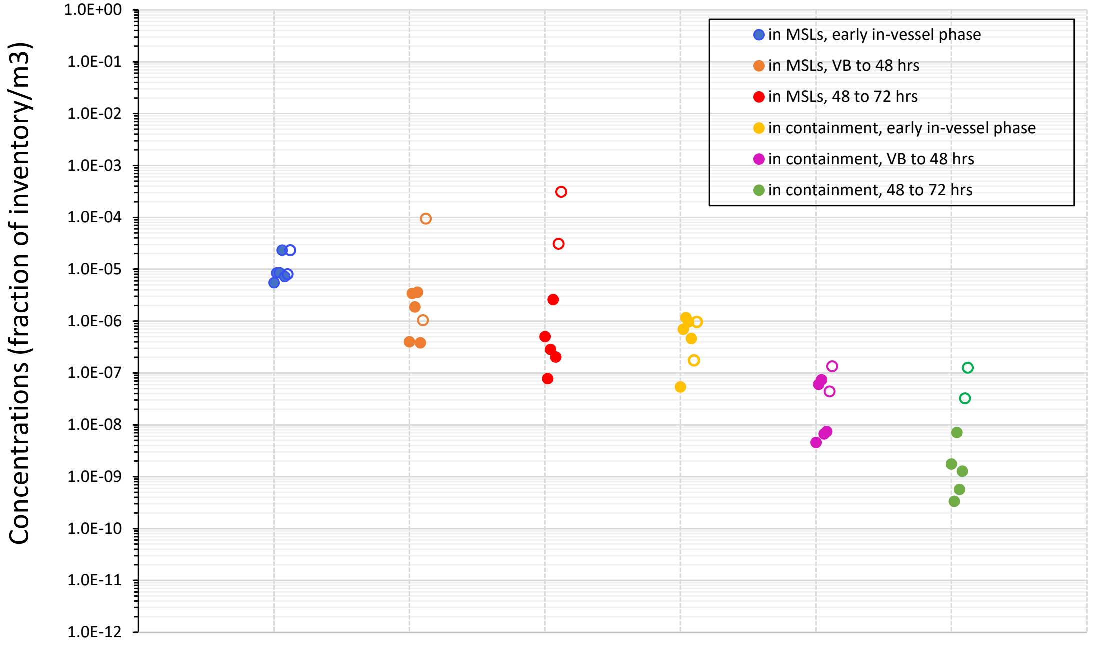


Maximum MSL wall temperatures

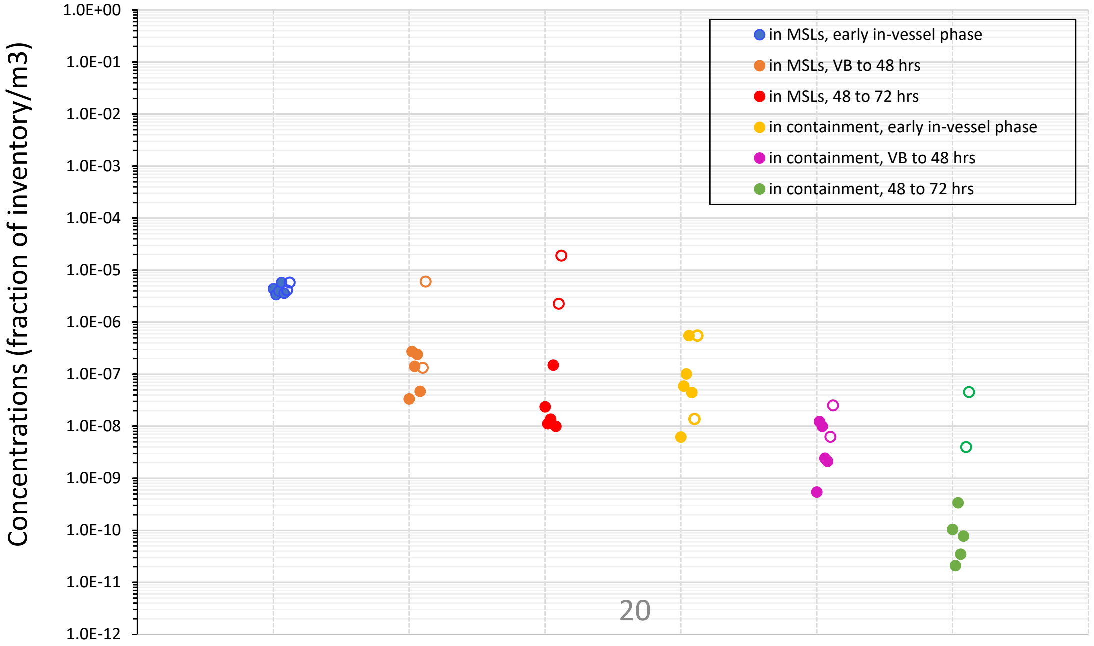


Proposed BWR Multi-Region Source Term

Total halogens time-averaged airborne concentration

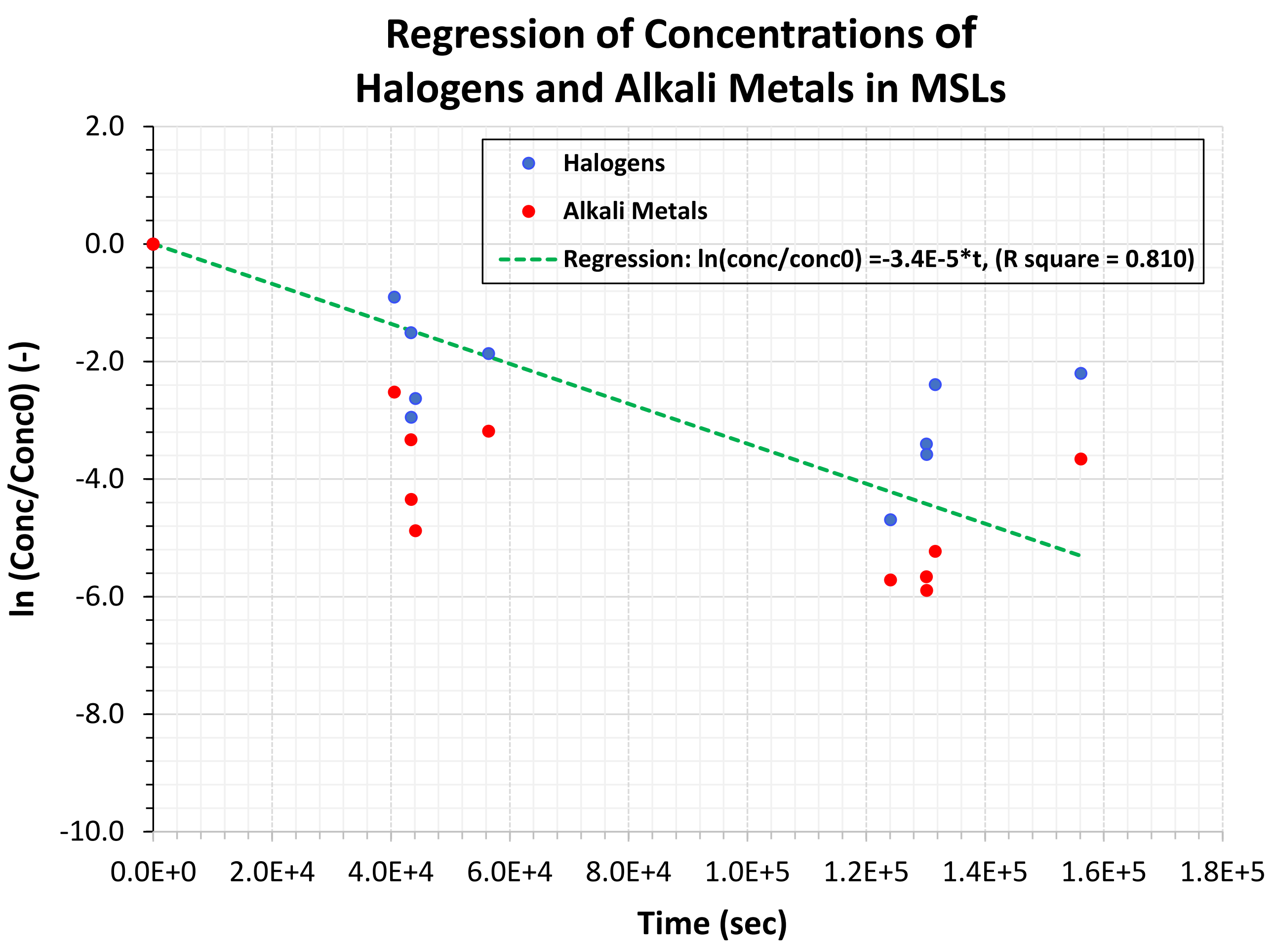


Total alkali metals time-averaged airborne concentration



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

Proposed BWR Multi-Region Source Term



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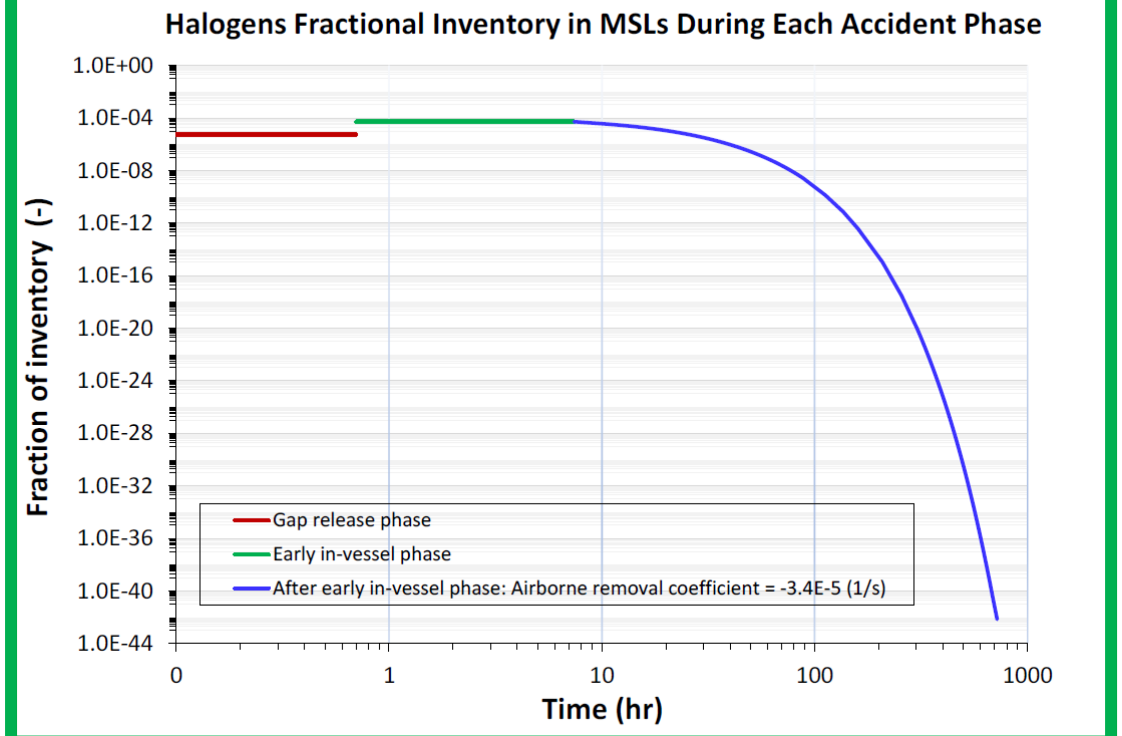
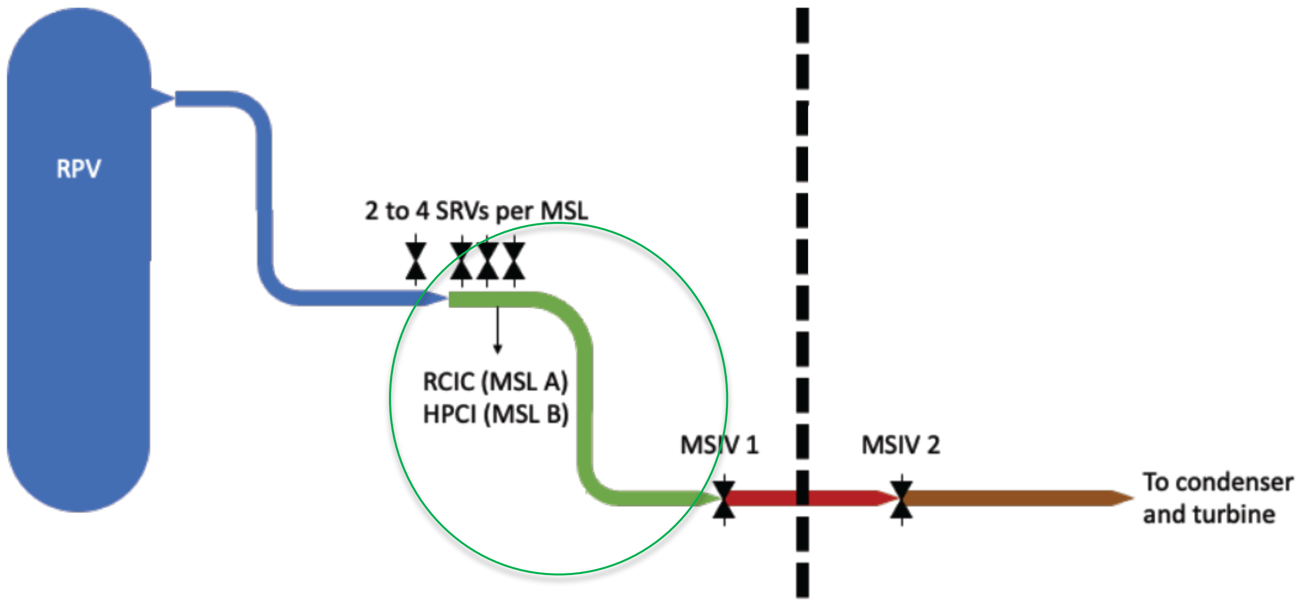
Proposed BWR Multi-Region Source Term





Steam Line Source Term (**ST**) is a function of t

$C_0(t)$ =**ST(t)**/ **Vol**

Conclusions and Next Steps

– Refined modeling provides better estimation of fission product distribution in the steamline.
  - Concentration in the steam line is distinct from that of containment.

– Significant retention of fission products were predicted in the suppression pool.

– A multi-region, pathway specific source term is being applied for BWRs in DG-1425 (RG1.183 rev2).

– Plan to apply MELCOR to inform better estimates of fission product removal mechanisms in containment for the simplified tools used in regulatory applications.

Backup Slides

Acronyms

Bq	Becquerel	MWt	Megawatt thermal
BWR	boiling-water reactor	PWR	pressurized water reactor
DBA	design-basis accident	RCIC	reactor core isolation cooling
FP	fission product	RG	(NRC) regulatory guide
GE	General Electric	RPV	reactor pressure vessel
HALEU	high-assay low-enriched uranium	SOARCA	State-of-the-Art Reactor Consequence Analyses
HBU	high burnup		
HPCI	high pressure coolant injection	SRV	safety relief valve
MSIV	main steam line isolation valve	ST	source term
MSL	main steam line	TCV	turbine control valve
GWd/MTU	gigawatt-days per metric ton of uranium	TSV	turbine stop valve
		W	Westinghouse

Table 5-16 Derived BWR release fractions including and excluding the suppression pool inventory for all core variations (60 GWd/MTU, 80 GWd/MTU, LEU and HALEU).

	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	Including Suppression Pool Inventory	Excluding Suppression Pool Inventory
Noble Gases	0.016	0.016	0.95	0.95	1	1
Halogens	0.005	1.30E-06	0.71	0.06	0.87	0.2
Alkali Metals	0.005	1.20E-06	0.32	0.006	0.35	0.039
Te Group	0.003	<1.0e-6	0.56	0.038	0.78	0.26
Ba/Sr Group	0.0006	<1.0e-6	0.005	0.0003	0.048	0.042
Ru Group	<1.0e-6	<1.0e-6	0.006	7.40E-06	0.006	0.0001
Mo Group	1.90E-05	<1.0e-6	0.12	0.0001	0.13	0.002
Lanthanides	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-6	3.70E-05	3.60E-05
Ce Group	<1.0e-6	<1.0e-6	<1.0e-6	<1.0e-6	0.003	0.003