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Severe Accident Mitigation Strategies Considered for U.S. Mark I Boiling Water Reactors (BWRs)

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Outline of Presentation

- Background
- Events and operator actions considered for extended loss of ac power (ELAP) analyses
- Results showing impacts of various operator actions when dc power is available
- Results for situations where dc power and RCIC fail early
- Insights and conclusions

Background

- This work is informed by ELAP mitigating strategies activities at NRC
  - Order EA-12-049: prevent core damage following beyond-design-basis events
  - Order EA-13-109 on severe accident-capable hardened vent for Mark I and Mark II BWRs
  - Mitigation of beyond design basis events rule
  - Development of the technical basis for the containment protection and release reduction (CPRR) rule for Mark I and Mark II BWRs
- Actions following core damage are also being considered by the BWROG in their SAMGs
- Results presented below show impacts of various operator actions
  - Early venting (before RCIC failure)
  - RPV depressurization after RCIC failure
  - Water injection before vessel failure
  - Venting strategies after core uncovered
  - Water addition and flow control after vessel failure

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Some Events and Operator Actions Considered for ELAP Mitigation Analyses

Events and Actions (~elapsed time)	Core Damaged?	Vessel Failed?	Remarks
DC power lost (0-6 hr); or recharging successful	No	No	Batteries could fail initially or be depleted and not re-charged
Early depressurization of RPV (2-3 hr)	No	No	Cooldown at 80 ºF /hr
Control RPV pressure between 200 to 400 psi (until RCIC fails)	No	No	Maximizes time for RCIC operation
Early venting (4-10 hr)	Maybe	No	Allows a heat removal path
Further depressurize RPV after RCIC failure	Maybe	No	Allows for injection into RPV after RCIC lost
Close vent at core damage	Yes	No	Minimize fission product releases
After RCIC fails, inject into RPV <u>or</u> flood DW	Yes	No	Injection into RPV preferred to arrest core damage. If RPV pressure too high, then injection could occur at vessel failure to reduce releases.
Re-open wetwell vent at primary cont. pressure limit (PCPL)	Yes	Maybe	Maintain containment integrity; possible vent cycling. Some release would occur if vent opened before vessel failure.
Throttle flow and/or close WW vent if WW level too high	Yes	Yes	Spillover height (DW to DC vents) Top of level instrument range. Prevent flooding WW vent
Open DW vent at PCPL	Yes	Yes	Only if WW vent closed. Maintain containment integrity; possible vent cycling
Turn off or reduce flow at high DW level	Yes	Yes	Four feet above DW floor in plant studied

Analysis Assumptions for Case Where Most Likely Operator Actions Taken

- DC power not lost
- Early depressurization of the RPV is successful and pressure controlled between 200 psi and 400 psi
- Early containment depressurization occurs when DW pressure reaches 29.7 psia (not reached prior to RCIC failure in this case).
- RCIC fails when suppression pool temperature exceeds 230 ºF, or RPV pressure falls below 75 psia.
- Operators depressurize RPV after RCIC failure
- After core damage, the WW vent is opened at PCPL (75 psia).
- The operators inject 500 gpm into the RPV at vessel failure and later reduce flow to avoid flooding the WW vent.

Information Available to Operators when dc power is available
(reliable instruments facilitate success)

- Water level in the vessel
- RPV pressure
- Containment pressure
- Water level in torus
- Radiation levels

Results and Insights When No External Water Added

Event Timing (hr)	MELCOR 2.1 (MAAP 5.03) Results
RCIC fails when SP temperature is 230 ºF	9.6 (8.9)
Early venting at 29.7 psia	N/A (N/A)
RPV depressurized when RCIC fails	Yes (Yes)
Core uncovers	12.4 (11.2)
Core damage begins	13.7 (11.5)
Containment vented at 75 psia	14.9 (16.4)
RPV lower head fails; no water addition	23.0 (22.9)
Drywell head flange leakage	27.1 (none)
Drywell liner melt-through	31.4 (23.3)
Cesium release fraction at 72 hr	1.94E-02 (1.49E-02)

- **RPV depressurized below 200 psi after RCIC fails at 9-10 hr**
  - **2-4 hr may be available to inject into RPV to prevent core damage**
  - **Up to 13 hr available to inject into RPV to prevent vessel failure (VF)**
- **Venting through wetwell occurs before VF**
  - **Considerable Cs release to environment through WW vent occurs before VF**
- **DW head flange leakage and liner melt-through may occur**

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Results and Insights When Most Likely Operator Actions Taken

Event Timing (hr)	MELCOR 2.1 (MAAP 5.03) Results
RCIC fails and RPV depressurized	9.6 (8.9)
Core uncovers	11.9 (11.2)
Core damage begins	13.2 (11.5)
Containment vented at 75 psia	14.4 (16.4)
Lower head dries out	18.2 (17.7)
RPV lower head fails	23.4 (22.9)
Water addition begins	23.4 (22.9)
Drywell head flange leakage	None (none)
Drywell liner melt-through	None (none)
Wetwell vent closed	N/A (N/A)
Drywell vent opened	N/A (N/A)
Time interval from RCIC failure to LH dryout	8.6 (8.8)

- **DW head flange leakage and liner melt-through prevented by external water addition**
- **At least an 8-9 hour time window for injection into RPV to prevent vessel failure**

RPV not Depressurized Until SRV Seizure

Event Timing (hr)	MELCOR 2.1 (MAAP 5.03) Results
RCIC fails and RPV depressurized	9.6 (8.9)
Core uncovers	11.9 (12.0)
Core damage begins	13.7 (12.4)
Containment vented at 75 psia	14.9 (17.3)
SRV sticks open	16.9 (16.8)
Lower head dries out	18.2 (17.7)
RPV lower head fails	23.0 (20.3)
Water addition begins	23.0 (20.3)
Drywell head flange leakage	None (none)
Drywell liner melt-through	None (none)
Time interval from SRV failure to LH dryout	1.3 (0.9)

- **Not depressurizing after RCIC failure results in later venting and earlier vessel failure.**
- **Less time is available for injection to prevent vessel failure (about an hour).**

Influences of Early Venting and Depressurizing RPV After RCIC Failure on In-Vessel Recovery Potential

(calculations with MAAP 5.03)

Event Times, hr	No Early Venting	Early Venting at 13 psig	Early Venting at 10 psig	Early Venting at 5 psig	No Early Venting, No RPV depressurization at RCIC failure
Early Venting	N/A	8.4	6.9	*3.5*	N/A
RCIC Fails	8.9	9.8	12.4	13.6	8.9
Operators Depressurize RPV	8.9	9.8	12.4	13.6	**N/A**
Start of Core Damage (close vent if open)	11.5	11.6	15.2	15.4	12.4
WW Venting at PCPL	16.4	19.9	24.1	24.5	17.3
SRV Seizure (RPV Depressurizes)	N/A	N/A	N/A	N/A	16.8
Lower Head Dries Out	17.7	18.1	22.0	23.3	17.7
Vessel Fails	22.9	22.4	26.5	27.7	20.3
Time Interval from RPV Depr. to LH dry-out	8.8	8.3	9.6	9.7	**0.9**

Early venting prolongs RCIC and creates more time to inject in-vessel, provided that the RPV is depressurized after RCIC failure.
Failure to close vent before core damage results in much higher releases.

Cases Where Batteries Depleted in 4 Hours (Calculations with MAAP 5.03)

Event Timing (hr)	RCIC Fails in 4 hr, Inj. At VF		RCIC Fails at 230 F		
	SRV Fails (800 lifts)	Recirc. Line Failure	SRV Fails (1500 lifts), Inj.at VF	Recirc. Line Failure	
				Inj. at VF	Inj. 200 psi
RCIC fails	4.0	4.0	10.4	10.4	10.4
SRV sticks open	9.6	N/A	11.6	N/A	N/A
Core damage begins	6.3	6.3	12.0	12.3	12.3
Recirc. Line fails	N/A	9.3	N/A	15.5	15.5
Containment vented at 75 psia	13.1	9.3	16.7	15.5	15.7
Lower head dries out	9.8	9.9	16.3	16.7	N/A
RPV lower head fails	12.9	13.4	20.9	20.5	N/A
Water addition begins	12.9	13.4	20.9	20.5	15.8

It is likely that RCIC will keep running after battery depletion. Then, there is a good chance that in-vessel retention will be successful.

No DC Power Cases
(Calculations with MAAP 5.03)

Event Timing (hr)	Black Start at 2 hr		Black Start at 3 hr		
	RPV Inj. at VF	RPV Inj. at 200 psi	SRV Fails (seizure), Inj.at VF	Recirc. Line Failure	
				Inj. at VF	Inj. LH dry-out
Core damage begins	0.6	0.6	0.6	0.6	0.6
SRV fails open (seizure)	4.2	4.2	3.0	N/A	N/A
Recirc. Line failure	N/A	N/A	N/A	2.8	2.8
RCIC fails (after BS)	11.3	11.3	9.6	4.5	4.5
Containment vented at 75 psia	16.6	20.0	15.8	3.0	3.0
Lower head dries out	17.3	N/A	19.3	4.6	4.6
RPV lower head fails	22.2	N/A	24.2	6.5	N/A
Water addition begins	22.2	15.6	24.2	6.5	4.6

A tight window (2 hours or so) is available for successful RCIC black start. Temperature-induced recirculation line failure can thwart operator attempts to provide late water addition.

Summary of Results and Insights from the CPRR Technical Basis Analysis

- A combination of venting and water addition is required to maintain containment structural integrity.
- Water addition, either into the RPV or into the Drywell, acts to minimize fission product releases.
- Wetwell venting and consequent early fission product releases occurred before vessel failure in most of the sequences.
  - Fission products are effectively scrubbed in the suppression pool.
- Fission products released from core debris after vessel failure can be further reduced by water added from an external source.
  - Little difference between RPV injection and DW flooding because most of the release occurs before vessel failure.
- Cases where flow not controlled led to conditions where the WW vent had to be closed and the DW vent opened, causing rapid changes in suppression pool and drywell water levels.
- Vent cycling, particularly before vessel failure, can reduce fission product releases.

Summary of Results and Insights from Additional MAAP 5.03 Analyses

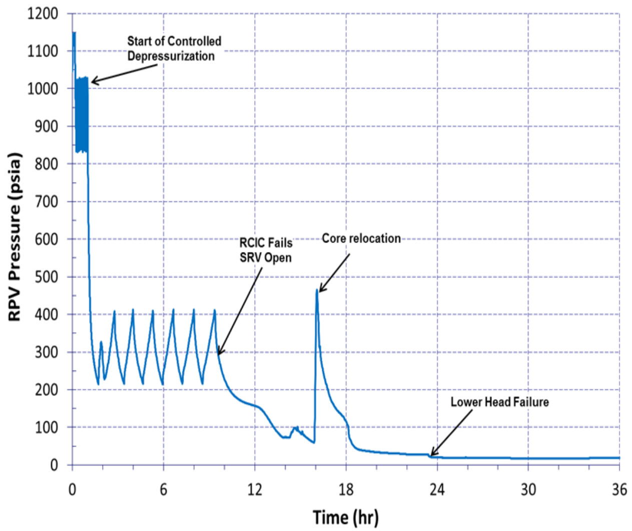
- MELCOR 2.1 and MAAP 5.03 agree quite well for all cases run by both.
- Early venting prolongs RCIC and creates more time to inject in-vessel, provided that the RPV is depressurized after RCIC failure.
- If the RPV is depressurized sufficiently before core damage, then timely water injection into the RPV can arrest core damage, reduce fission product release, and prevent vessel failure
- For cases with no dc power, black starting RCIC could allow enough time to vent the wetwell and provide water from an external source.
  - Depends on RPV depressurization, such as by recirculation line creep rupture or a stuck-open SRV
- For cases where batteries are depleted early, RCIC would most likely keep running (such as at Fukushima Unit 2) without control at high RPV pressure until failure at high suppression pool temperature.
  - External water could be supplied after RPV depressurization, such as by recirculation line creep rupture or a stuck-open SRV.

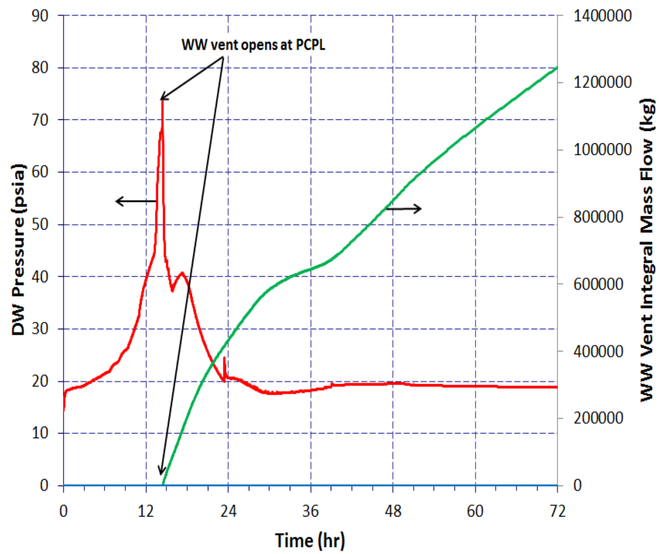
BACKUP SLIDES

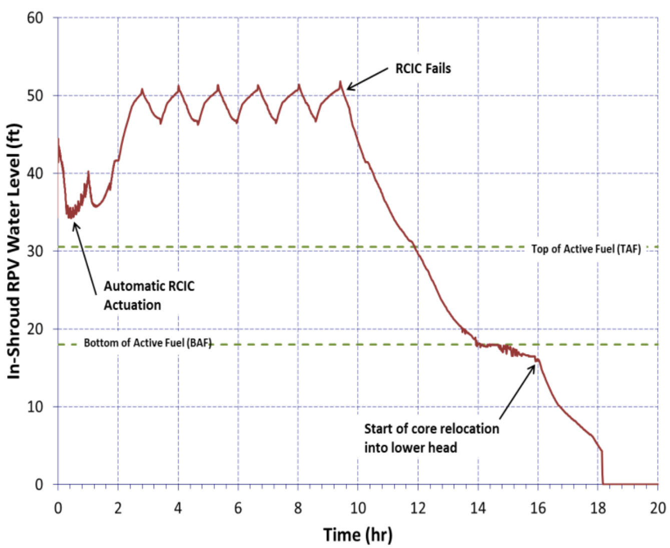
Representative Results of Responses to an ELAP With DC Power Available (from CPRR Rule Technical Basis Development)

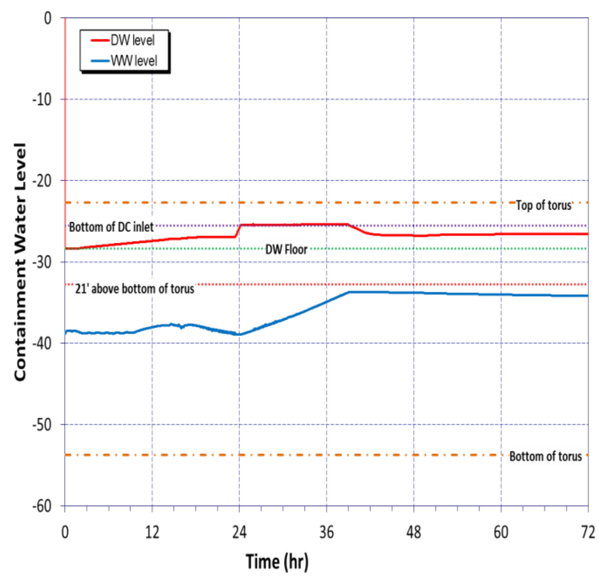
Event Timing (hr)	MELCOR 2.1 (MAAP 5.03) Results							
RCIC fails at 230 ºF suppression pool temperature, Venting at PCPL, WW venting only except for Case 10	Depr. at RCIC failure, No water addition	Depr. at RCIC failure, Inject into RPV when level at BAF	Depr. at RCIC failure, Inject into RPV at VF	SRV sticks open, Inject into RPV at VF	SRV sticks open, vent cycling, Inject into RPV at VF	SRV sticks open, Inject into RPV at VF, WW and DW venting	Depr at RCIC failure, Flood DW at VF	SRV sticks open, Flood DW at VF
MELCOR Case	**1**	**9IVR**	**9**	**8**	**15**	**10**	**25**	**23**
RCIC fails	9.6 (8.9)	9.6 (8.9)	9.6 (8.9)	9.6 (8.9)	9.6 (8.9)	9.6 (8.9)	9.6 (8.9)	9.6 (8.9)
Early venting	N/A (N/A)	N/A (N/A)	N/A (N/A)	N/A (N/A)	N/A (N/A)	10.7 (9.2)	N/A (N/A)	N/A (9.2)
RPV depressurized when RCIC fails	Yes (Yes)	Yes (Yes)	Yes (Yes)	No (No)	No (No)	No (No)	Yes (Yes)	No (No)
SRV sticks open	N/A (N/A)	N/A (N/A)	N/A (N/A)	16.0 (16.8)	16.0 (16.8)	16.0 (16.8)	N/A (N/A)	16.0 (16.8)
Core uncovers	12.4 (11.2)	11.9 (11.2)	11.9 (11.2)	11.9 (12.0)	11.9 (12.0)	11.9 (12.0)	11.9 (11.2)	11.9 (12.0)
Core damage begins	13.7 (11.5)	13.2 (11.5)	13.2 (11.5)	13.7 (12.4)	13.7 (12.4)	13.7 (12.4)	13.2 (11.5)	13.7 (12.4)
Containment vented at 60 psig	14.9 (16.4)	~22.5 (16.9)	14.4 (16.4)	14.9 (17.3)	14.9 (17.3)	16.3 (21.2)	14.4 (16.4)	14.9 (21.2)
RPV lower head fails	23.0 (22.9)	none (none)	23.4 (22.9)	23.0 (20.3)	25.5 (20.4)	23.8 (21.1)	23.4 (22.9)	23.0 (21.1)
Water addition begins	none (none)	13.5 (12.5)	23.4 (22.9)	23.0 (20.3)	25.5 (20.4)	23.8 (21.1)	23.4 (22.9)	23.0 (21.1)
Drywell head flange leakage	27.1 (none)	none (none)	none (none)	none (none)	none (none)	none (none)	none (none)	none (none)
Drywell liner melt-through	31.4 (23.3)	none (none)	none (none)	none (none)	none (none)	none (none)	none (none)	none (none)
Wetwell vent closed	N/A (N/A)	N/A (N/A)	N/A (N/A)	N/A (N/A)	N/A (N/A)	41.2 (41.2)	N/A (N/A)	N/A (N/A)
Drywell vent opened	N/A (N/A)	N/A (N/A)	N/A (N/A)	N/A (N/A)	N/A (N/A)	54.3 (59.3)	N/A (N/A)	N/A (N/A)
Cesium release fraction at 72 hr	1.94E-02 (1.49E-02)	~3.0E-05 (1.10E-04)	6.12E-03 (9.83E-03)	1.49E-02 (1.94E-03)	6.05E-03 (1.36E-03)	7.26E-03 (1.00E-03)	6.60E-03 (9.80E-03)	1.54E-02 (1.04E-03)

RPV and Containment Pressures and Levels: Measureable Quantities (MELCOR 2.1)

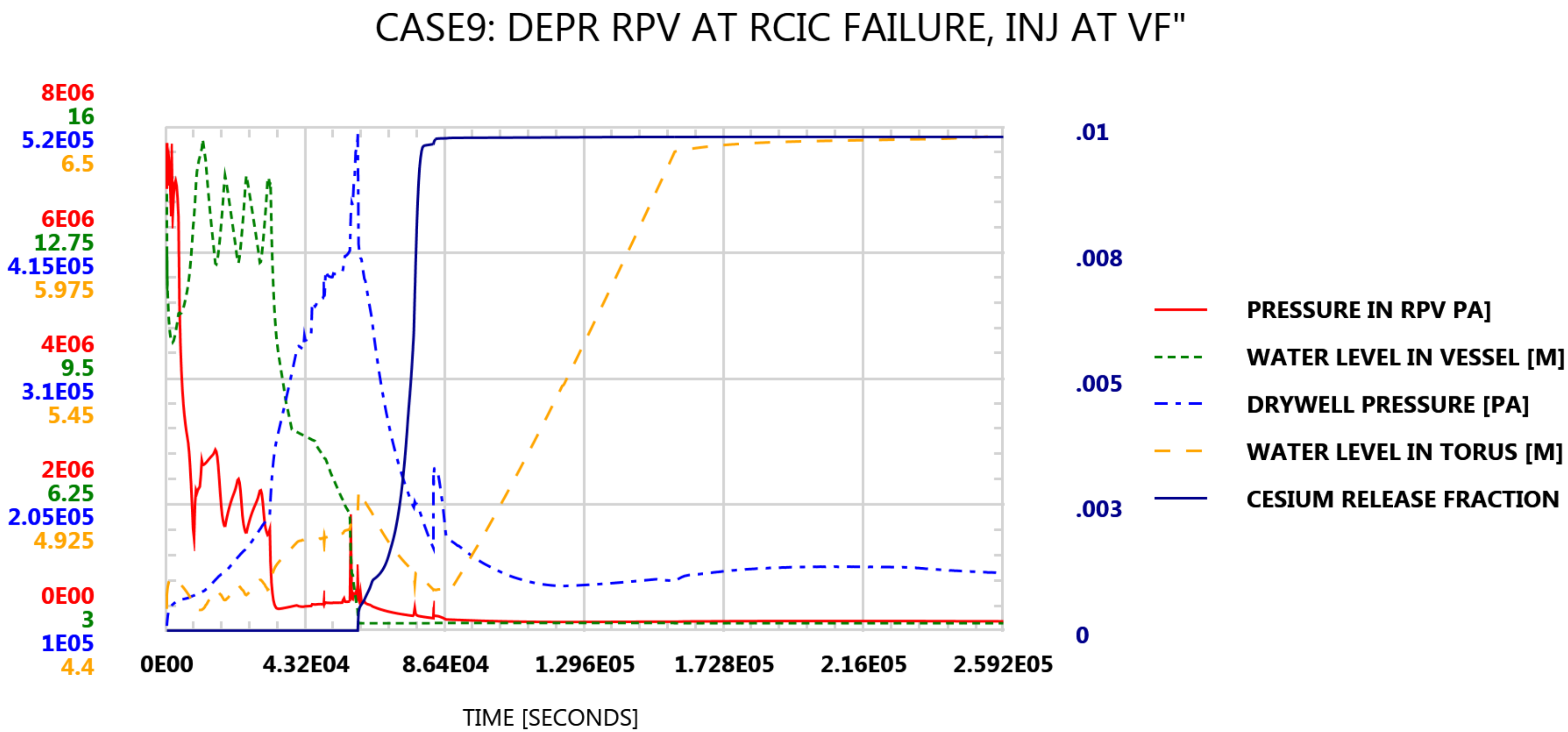






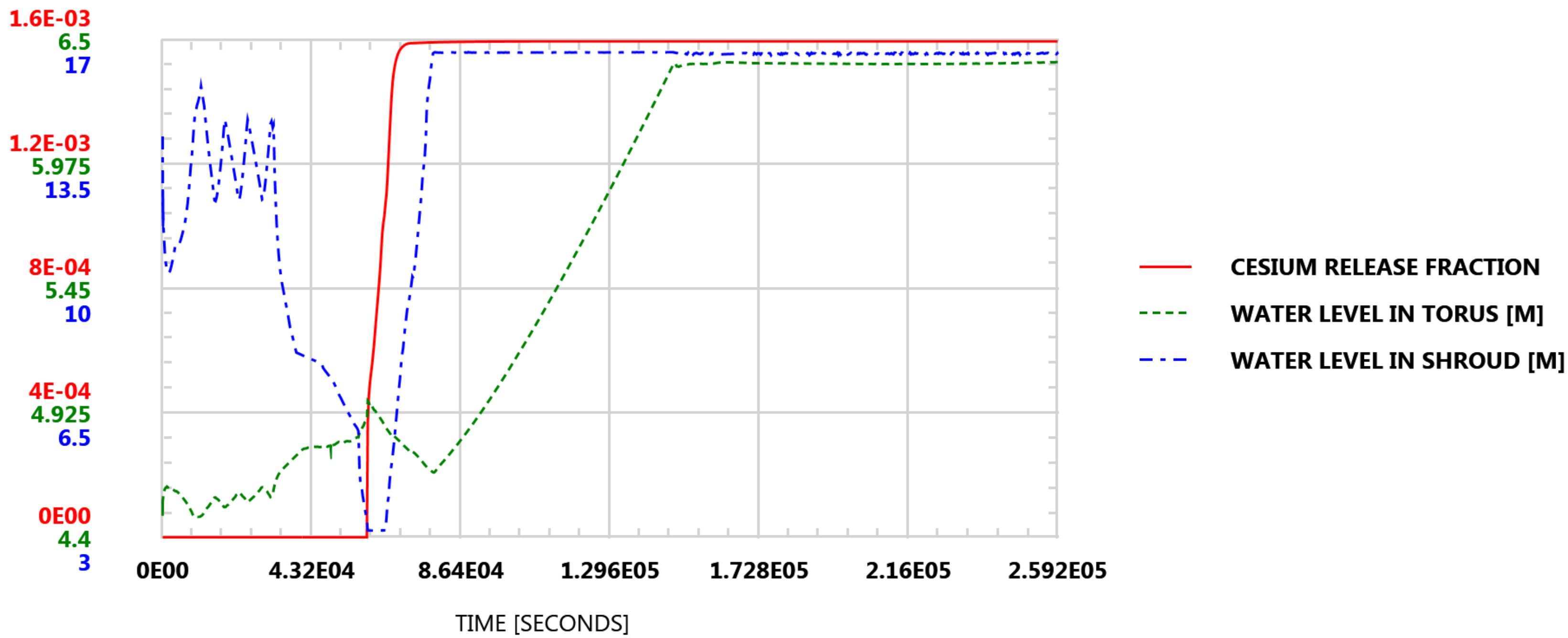


RPV and Containment Pressures and Levels: Measureable Quantities (MAAP 5.03)



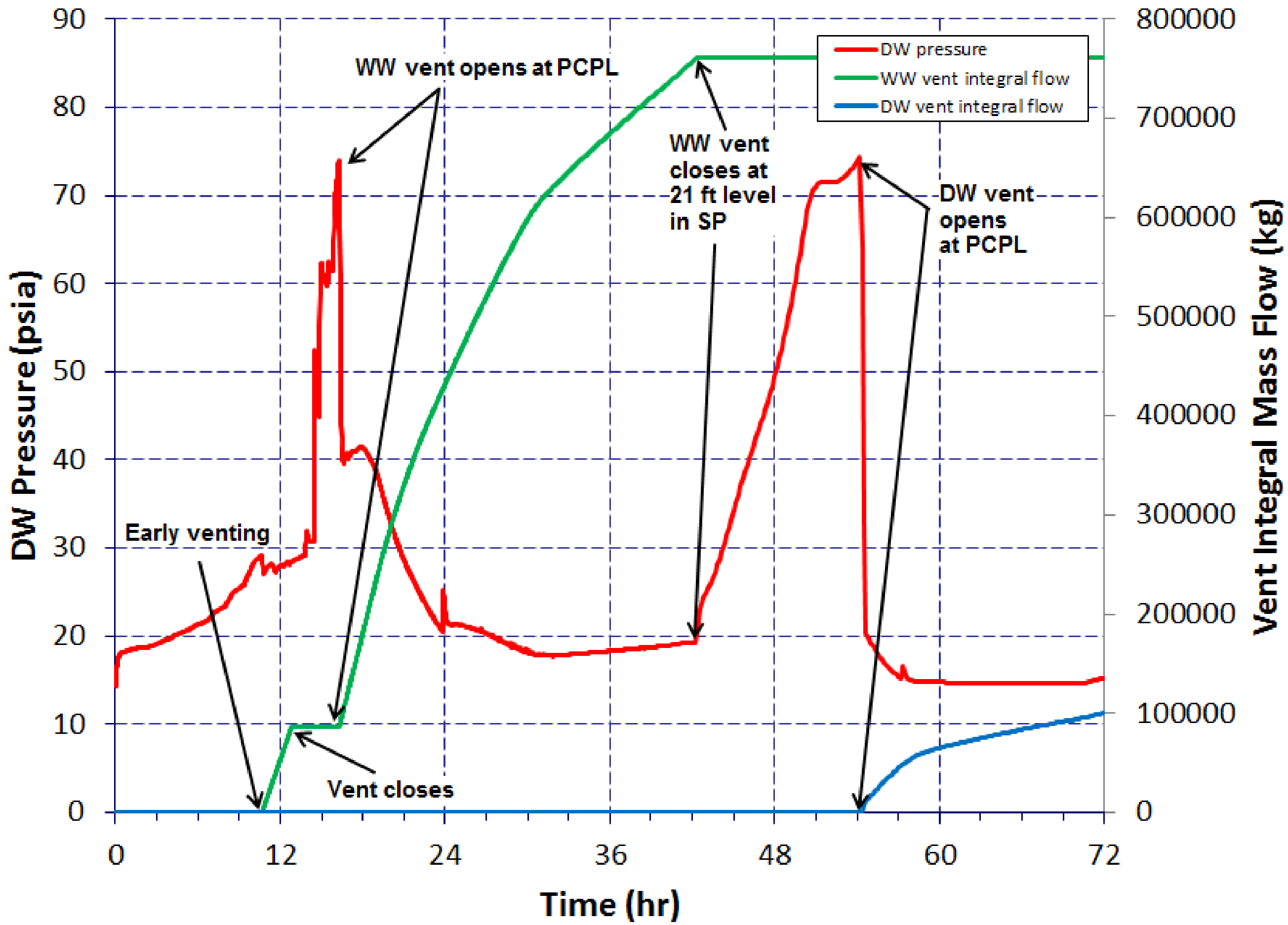
Results and Insights from In-vessel Recovery Study

"CASE9-IVR3: INJECT 500 GPM/100 GPM INTO RPV AFTER INITIAL WATER EVAPORATION



- **Injection early enough can prevent vessel failure.**
- **Torus water level increases once water level in RPV reaches the steam lines.**
- **Injection prior to dry-out of the lower head is likely to result in in-vessel recovery.**

Mark I containment pressure and integral mass flow for WW and DW venting (MELCOR 2.1)



Mark I containment water level for WW and DW venting (MELCOR 2.1)