Assessment of the Mitigative Strategy using External Coolant Injection for OPR-1000 Plant

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Background & Purpose

- Following the Fukushima accident, a special safety inspection for operating plants has been conducted in Korea
- Inspection results (Ref. H.C.Kim et al., "Inspection and Validation Activities on SAM in Korea" IAEA IEM, March 2014)
  - no imminent risk for the expected maximum potential earthquake and coastal flooding
  - needs to implement the long- and short-term improvements in order to secure safety for natural BDBE.
- On-going safety improvements concerning a severe accident
  - Revising SAMG to enhance their effectiveness
  - Developing low-power and shutdown SAMGs
  - Installation of injection flow paths for emergency cooling water from external sources
  - Installation of PAR
  - Installation of CFVS or depressurizing facilities in C/B

Background & Purpose

- One of the measures to increase the mitigation capability:
  - installing the injection flow paths to provide emergency cooling water of external sources to RCS & SGs
  - cooling water injected using fire engines
- Necessary to develop some guidelines or strategies
  - to cope with an extreme severe accident scenario using the newly installed injection flow paths and fire engines.
- Additional strategies are being incorporated into the existing SAMG by utility.
  - RCS & SG injection using the new injection flow paths & fire engines
- A preliminary assessment is conducted as an independent analysis
  - the effectiveness of the external water injection strategies using fire engines as an ultimate mitigative measure during extreme accident scenarios.

Analysis Methodology

- Applied plant : OPR-1000
  - PWR with a core thermal output of 2815 MWth
- Evaluation Tool : MAAP 5.02
- Analyzed Cases

Case ID	System Availability			Depressurization system
	2ry heat removal (TDAFW & ADV)	External water injection into SGs	External water injection into RCS	
Long term SBO_Unmitigated	Yes (4 hours with DC power)	No	No	N/A
Long term SBO_Mitigated 1		Yes		ADV
Long term SBO_Mitigated 2			Yes	SDS
Short term SBO_Unmitigated	No	No	No	N/A
Short term SBO_Mitigated 1		Yes		ADV
Short term SBO_Mitigated 2			Yes	SDS

Initial & Boundary Condition, Assumption

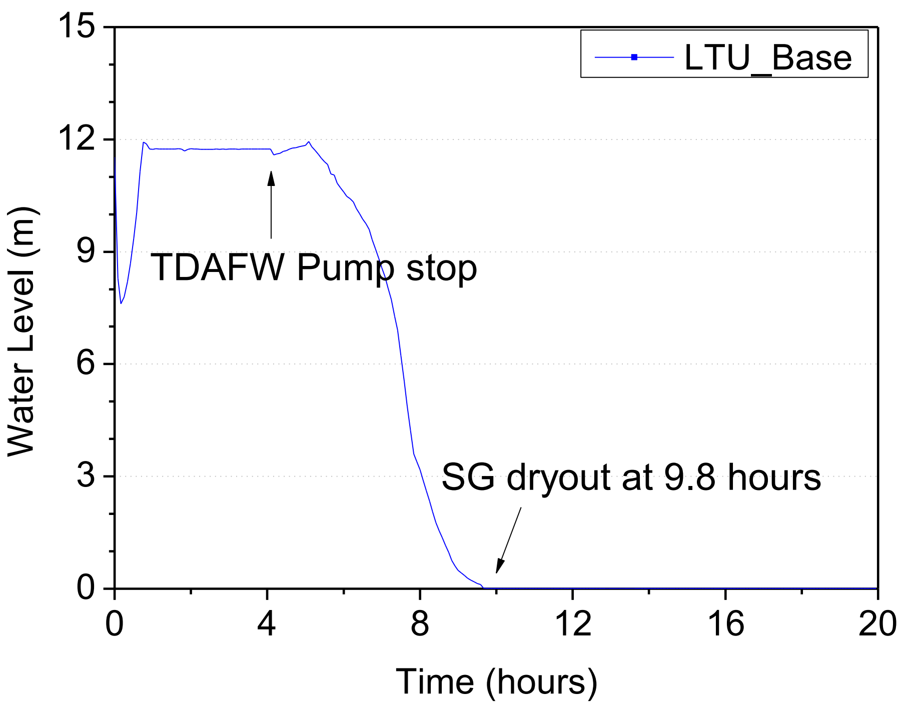
- Long-term SBO
  - Loss of offsite power followed by SBO
  - Reactor trips and the MSIVs close
  - DC buses are available, at minimum loading, used for instrumentation, and TDAFW operation
- Short-term SBO
  - Loss of offsite power followed by SBO
  - Reactor trips and the MSIVs close
  - TDAFW is unavailable
- Mitigative measures to inject water into SGs
  - ADV & Fire engines

Initial & Boundary Condition, Assumption

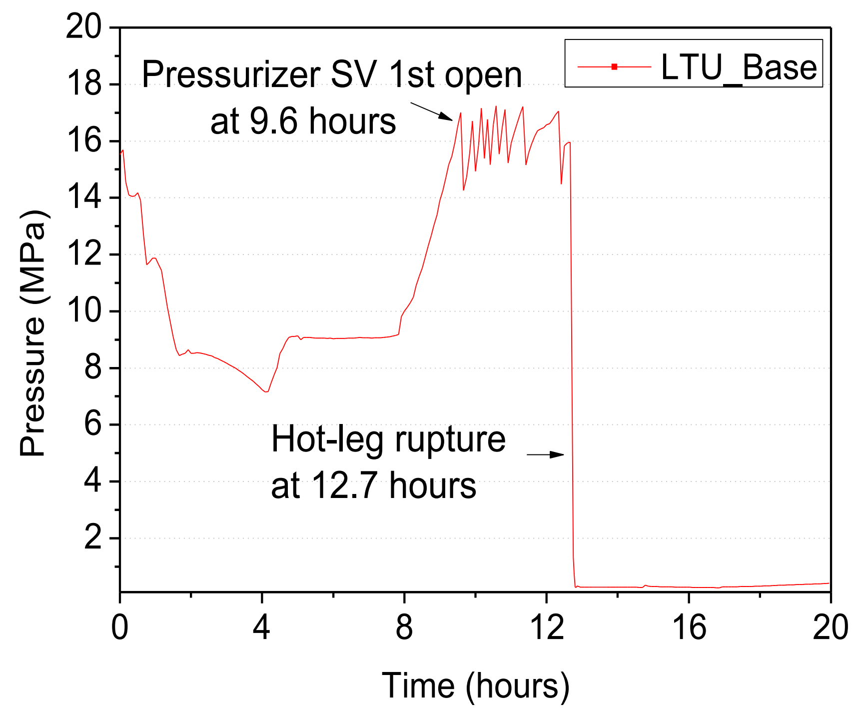
- Mitigative measures to inject water into RCS
  - SDS(safety depressurization system) & Fire engines
  - Even though the SDS still needs AC power, the system is assumed operable during SBO scenario, which can be achievable by any means or other, for example, through the design improvement in the future.
- Passive SITs availability
  - automatically discharge into RCS if the RCS pressure decreases below the SIT pressure (4.31 MPa)
  - RCS pressure is maintained above the SIT injection set point in most sequences, therfore, the SIT injection occurs only after the depressurization of the RCS, vessel breach, or other induced RCS failure.
- RCP Seal Leakage : 15 gpm/RCP

Analysis Results : Long-term SBO

- Long-term SBO_Unmitigated Case (No Injection)



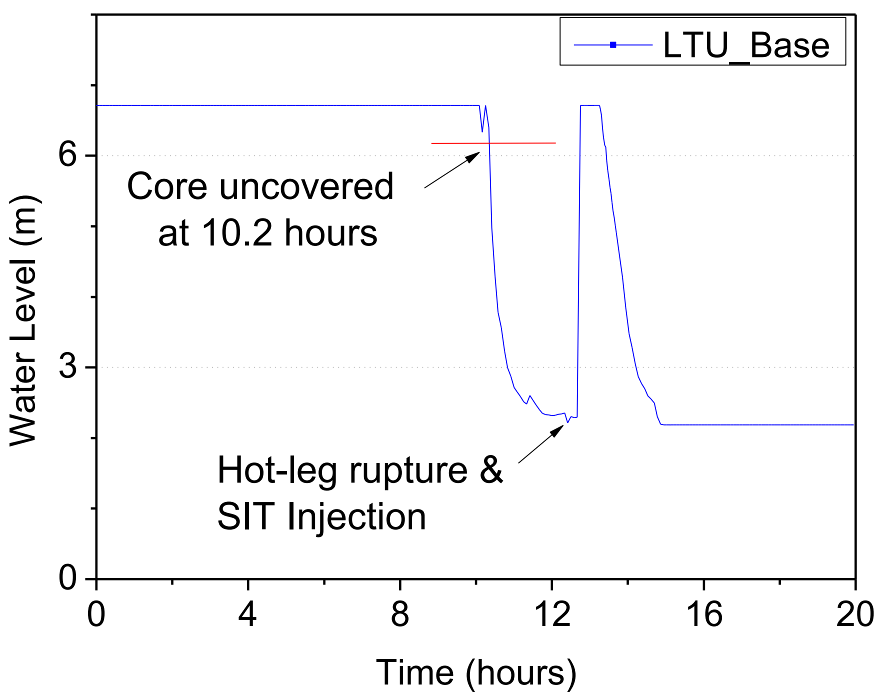
Water level in SG



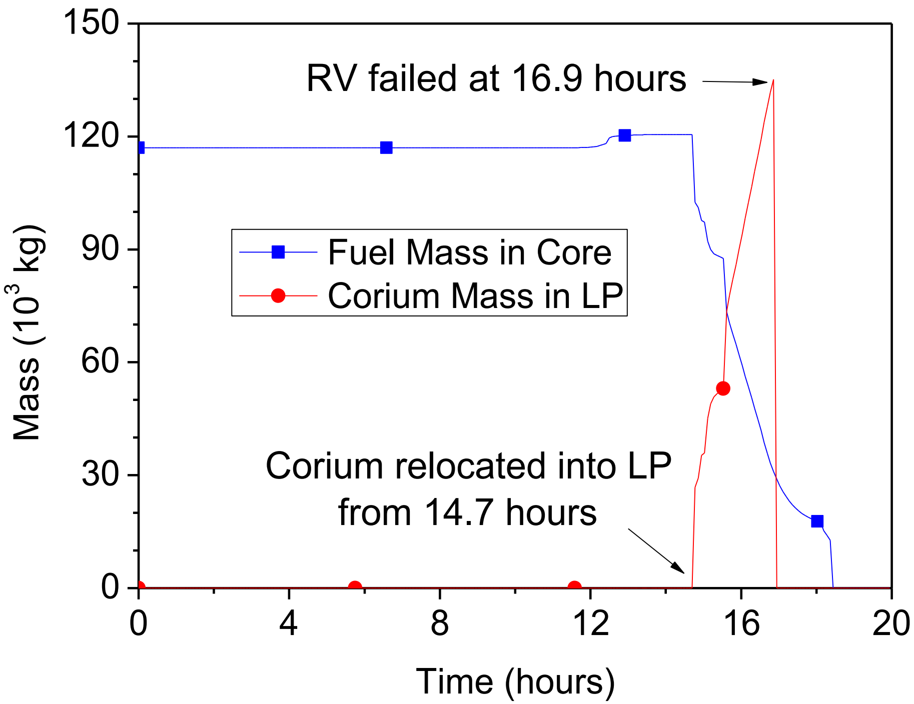
Pressure in RCS

Analysis Results : Long-term SBO

- Long-term SBO_Unmitigated Case (No Injection)



Water level in Rx vessel



Fuel mass in Core & Corium mass in LP

Analysis Results : Long-term SBO

- Long-term SBO_Mitigated 1 (Injection into SGs)

Sequence ID	Assumption		Calculation Results (Event Summary, hours)									
	ADV open											
	# of ADV	Opening time	PSV open	ADV opening	SG makeup	Core uncovery	Core melt start	Hot leg rupture	SIT injection	Corium Relocation into LH	RV failure	CTMT failure
LTU-base	N/A	N/A	9.6	N/A	N/A	10.2	12.3	12.7	12.7	14.7	16.9	109.3
LTM1-1ADV -PSV05	1	PSV open	9.6	9.7	9.8	no uncovery	no melt	no rupture	10.8	no relocation	no failure	no failure
LTM1-1ADV -PSV60	1	PSV open + 1 hr	9.6	10.6	10.1	10.3	no melt	no rupture	16.4	no relocation	no failure	No failure
LTM1-1ADV -PSV180	1	PSV open + 3 hr	9.6	12.6	12.7	10.3	12.4	12.7	12.7	16.7	18.5	118.6

- If one ADV is opened at the time of the PSV first opening (9.6 hours) and the water is injected through a fire engine, it successfully cools down the reactor core and the core uncovery can be prevented.

Analysis Results : Long-term SBO

- Long-term SBO_Mitigated 2 (Injection into RCS)

Sequence ID	SDS open		Calculation Results (Event Summary, second)								
	# of SDS	Opening time	PSV opening	SDS opening	Core uncovery	Core melt start	Hot leg rupture	SIT injection	RCS makeup start	Corium relocation into LH	RV failure
LTU-base	N/A	N/A	9.6	N/A	10.4	12.5	12.7	12.7	N/A	15.3	17.0
LTM2-1SDS00	1	PSV open	9.6	9.6	10.0	16.1	no rupture	10.4	18.6	106.0	no failure
LTM2-2SDS120	2	PSV open +2 hrs	9.6	11.6	10.4	no melt	no rupture	11.8	15.4	no relocation	no failure
LTM2-2SDS180	2	PSV open +3 hrs	9.6	12.6	10.4	12.5	no rupture	12.8	17.7	no relocation	no failure
LTM2-2SDS300	2	PSV open +5 hrs	9.6	14.6	10.4	12.5	12.7	12.7	14.7	no relocation	no failure

- If RCS depressurization starts within two hours after the PSV first opening using two SDS system , the severe core damage can be prevented.

Analysis Results : Long-term SBO

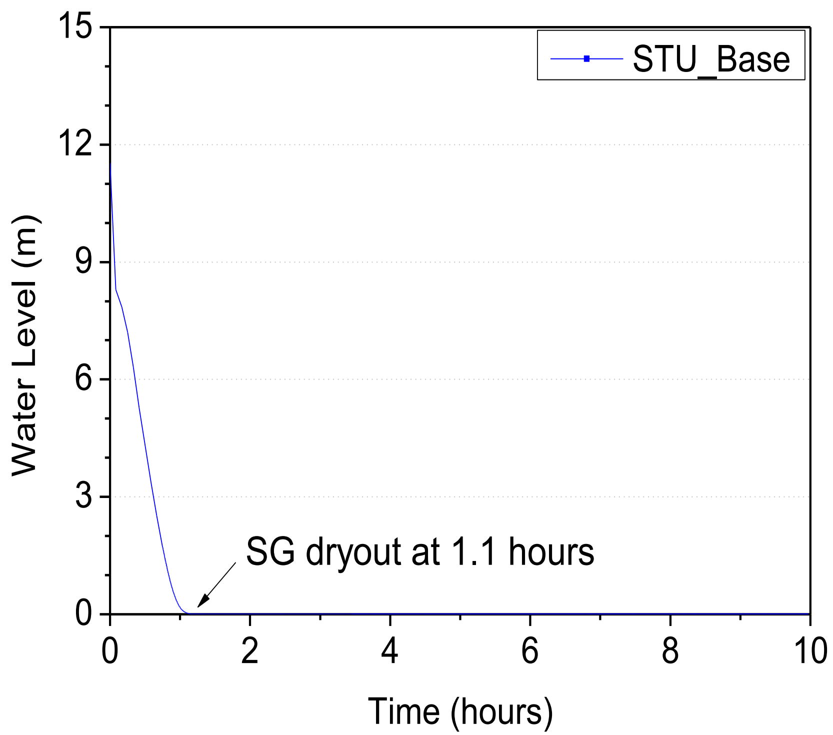
- Long-term SBO_Mitigated 2 (Injection into RCS)
  - Sensitivity of Aggressive SG Cool-down during TD-AFW Injection

	Sequence ID	Assumption		Calculation Results (Event Summary, hours)								
		SDS open										
		# of SDS	Opening time	PSV opening	SDS opening	Core uncovery	Core melt start	Hot leg rupture	SIT injection	Corium relocation into LH	RCS Makeup	RV failure
ADV control by WSGRV0	LTU-base	N/A	N/A	9.6	N/A	10.4	12.5	12.7	12.7	15.3	N/A	17.1
Max-ADV flow (4hr)	LTU-1AD	N/A	N/A	15.6	N/A	16.4	18.7	19.1	0.7	21.7	N/A	23.7
ADV control by WSGRV0	LTM2-2SDS120	2	PSV open +2 hrs	9.6	11.6	10.4	no melt	no rupture	11.8	no relocation	15.4	No failure
Max-ADV flow (4hr)	LTM2-2SDS120-1AD	2	PSV open +2 hrs	15.6	17.6	16.4	no melt	no rupture	0.7	no relocation	19.8	no failure

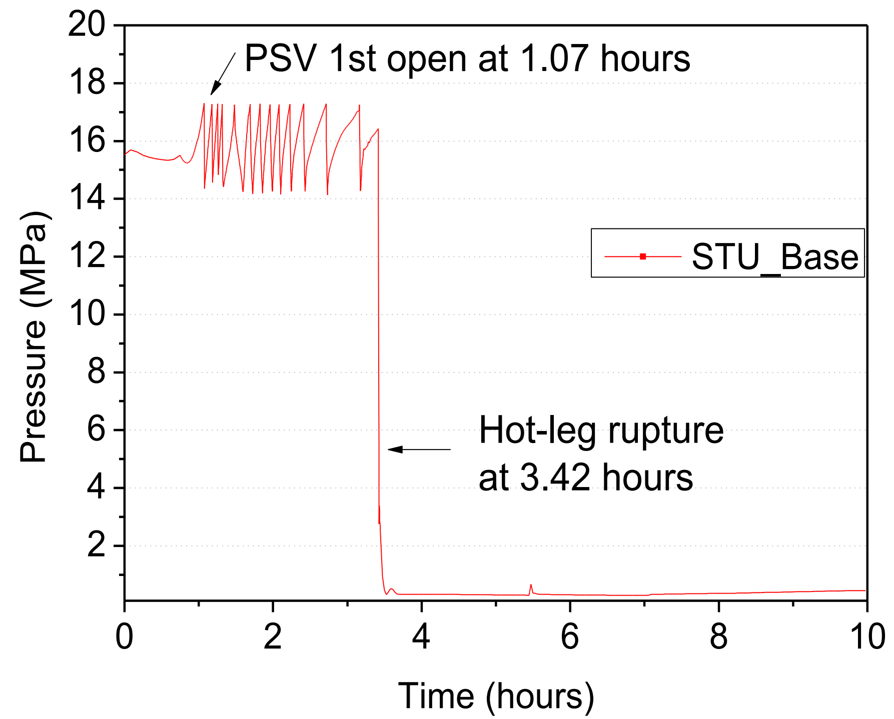
- If the 2ry heat removal rate is maximized during initial 4 hours, the accident progression will be delayed about 6 hours.

Analysis Results : Short-term SBO

- Short-term SBO_Unmitigated Case (No Injection)



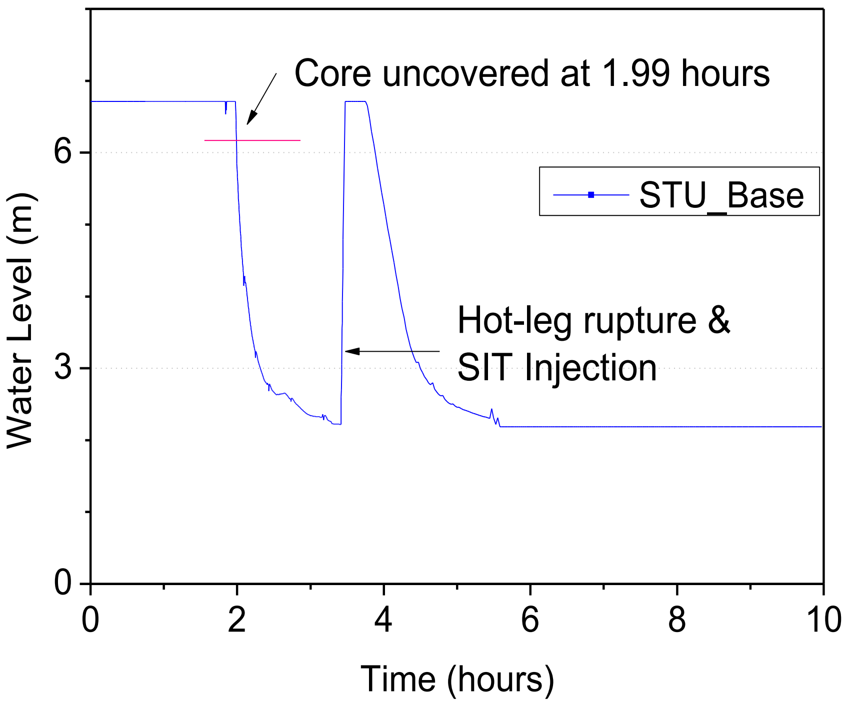
Water level in SG



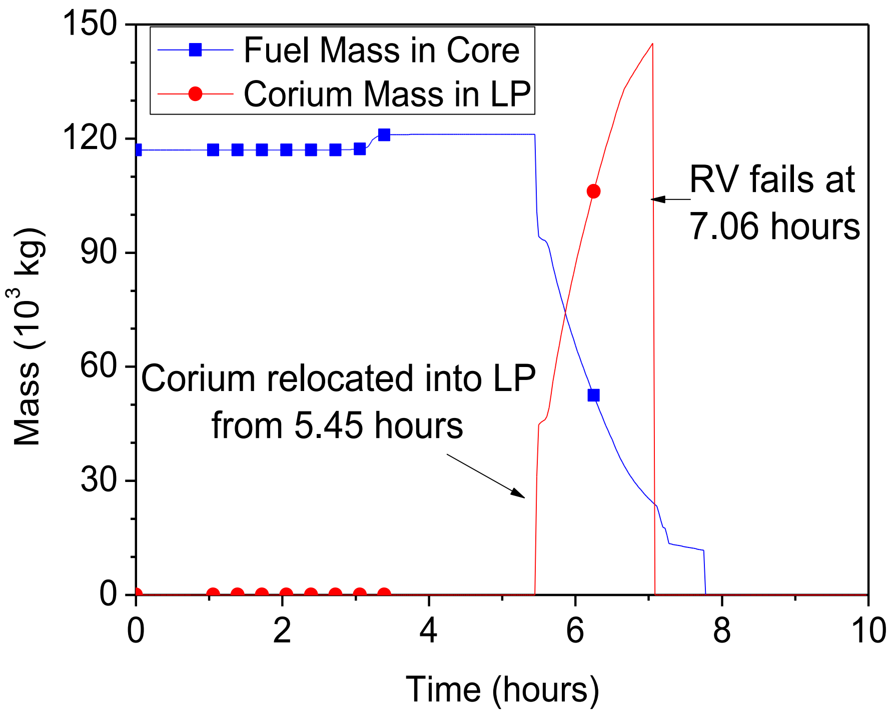
Pressure in RCS

Analysis Results : Short-term SBO

- Short-term SBO_Unmitigated Case (No Injection)



Water level in Rx vessel



Fuel mass in Core & Corium mass in LP

Analysis Results : Short-term SBO

- Short-term SBO_Mitigated 1 (Injection into SGs)

Sequence ID	Assumption		Calculation Results (Event Summary, hours)								
	ADV open										
	# of ADV	Opening time	PSV open	ADV opening time	SG makeup	Core uncovery	Core melt	Corium relocation into LH	SIT injection	RV failure	Hot leg rupture
STU-base	N/A	N/A	1.07	N/A	N/A	1.99	3.16	5.45	3.43	7.06	3.42
STM1-1ADV-PSV05	1	PSV open	1.07	1.16	1.18	no uncovery	no melt	no relocation	10.33	no failure	no rupture
STM1-1ADV-PSV60	1	PSV open +1 hr	1.07	2.07	2.10	2.00	no melt	no relocation	8.41	no failure	no rupture
STM1-1ADV-PSV120	1	PSV open +2 hr	1.07	3.07	3.10	2.00	3.13	6.49	3.50	7.96	3.49
STM1-2ADV-PSV120	2	PSV open +2 hr	1.07	3.07	3.10	2.00	3.13	7.14	3.90	9.27	3.90

- To prevent the severe core damage, ADV should be opened before the PSV first opening + 1 hour.

Analysis Results : Short-term SBO

- Short-term SBO_Mitigated 2 (Injection into RCS)

Sequence ID	Assumption		Calculation Results (Event Summary, hours)								
	SDS open										
	# of SDS	Opening time	PSV opening	SDS opening	Core uncovery	Core melt start	Hot leg rupture	SIT injection	RCS makeup start	Corium relocation into LH	RV failure
STU-base	N/A	N/A	1.07	N/A	1.99	3.16	3.42	3.43	N/A	5.45	7.06
STM2-1SDS00	1	PSV open	1.07	1.10	1.74	2.23	no rupture	2.21	7.43	6.61	no failure
STM2-2SDS60	2	PSV open +1 hr	1.07	2.10	2.00	no melt	no rupture	2.31	5.94	no relocation	no failure
STM2-2SDS120	2	PSV open +2 hr	1.07	3.10	2.00	3.04	no rupture	3.26	6.61	6.79	no failure
STM2-2SDS180	2	PSV open +3 hr	1.07	4.10	2.00	3.04	3.76	3.77	3.78	no relocation	no failure

- If RCS depressurization starts within one hours after the PSV first opening using two SDS system , the severe core damage can be prevented.

Analysis Results : Short-term SBO

- Short-term SBO_Mitigated 2 (Injection into RCS)
  - Sensitivity of Depressurization by Gas Vent System

Sequence ID	Analysis Assumption			Calculation Results (Event Summary, hours)									
	PZR vent		RCS Makeup										
	Flow rate (kg/s)	Opening time	Makeup initiation	PSV opening time(sec)	Vent opening time(sec)	Core uncovery	SIT injection	Core melt start	Corium relocation into LH	RCS makeup start	RV failure	Hot leg rupture
STU-Base	N/A	N/A	N/A	1.07	N/A	1.99	3.43	3.16	5.45	N/A	7.06	3.42
VT-FT-XVT	N/A	N/A	RCS Pr. <1.34 Mpa	1.07	N/A	1.99	3.43	3.16	no relocation	3.81	no failure	3.42
VT-FT-V00	5.25	PSV open	RCS Pr. <1.34 Mpa	1.07	1.10	2.06	4.28	2.99	3.76	4.28	4.27	no rupture

- RCS makeup without depressurization results in the hot-leg rupture (No RV failure)
- RCS makeup with depressurization using the gas vent system results in the RV failure)

Summary and Concluding Remarks

- A preliminary evaluation for the effectiveness of external cooling water injection strategies
  - using fire engines and depressurization systems
  - injection into SGs and RCS are included
  - short-term and long-term SBO sequences are considered
  - The initiation time of the depressurization is focused, which might be a key feature for a successful strategy implementation

- State-of-the-Art Reactor Consequence Analysis of USNRC
  - performed to develop a body of knowledge regarding the realistic outcomes of severe reactor accidents
  - the availability of the vessel injection was assessed to occur at 3.5 hours (NUREG/CR-7110 Vol. 2 : Surry analysis)

Summary and Concluding Remarks

- Effectiveness of external cooling water injection strategies in OPR-1000
  - The strategies are judged not likely to effective for the short-term SBO (based on the SOARCA operator action time)
  - The strategies are very feasible for the long-term SBO
  - The operation of TDAFW system is an important mitigation measure for the successful strategy implementation

Thank you for your attention

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