Diffrences between AMGs for Normal Operations, Shutdown and Spent Fuel Pools

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Presented by
Ivica Basic
APoSS d.o.o.

Overview

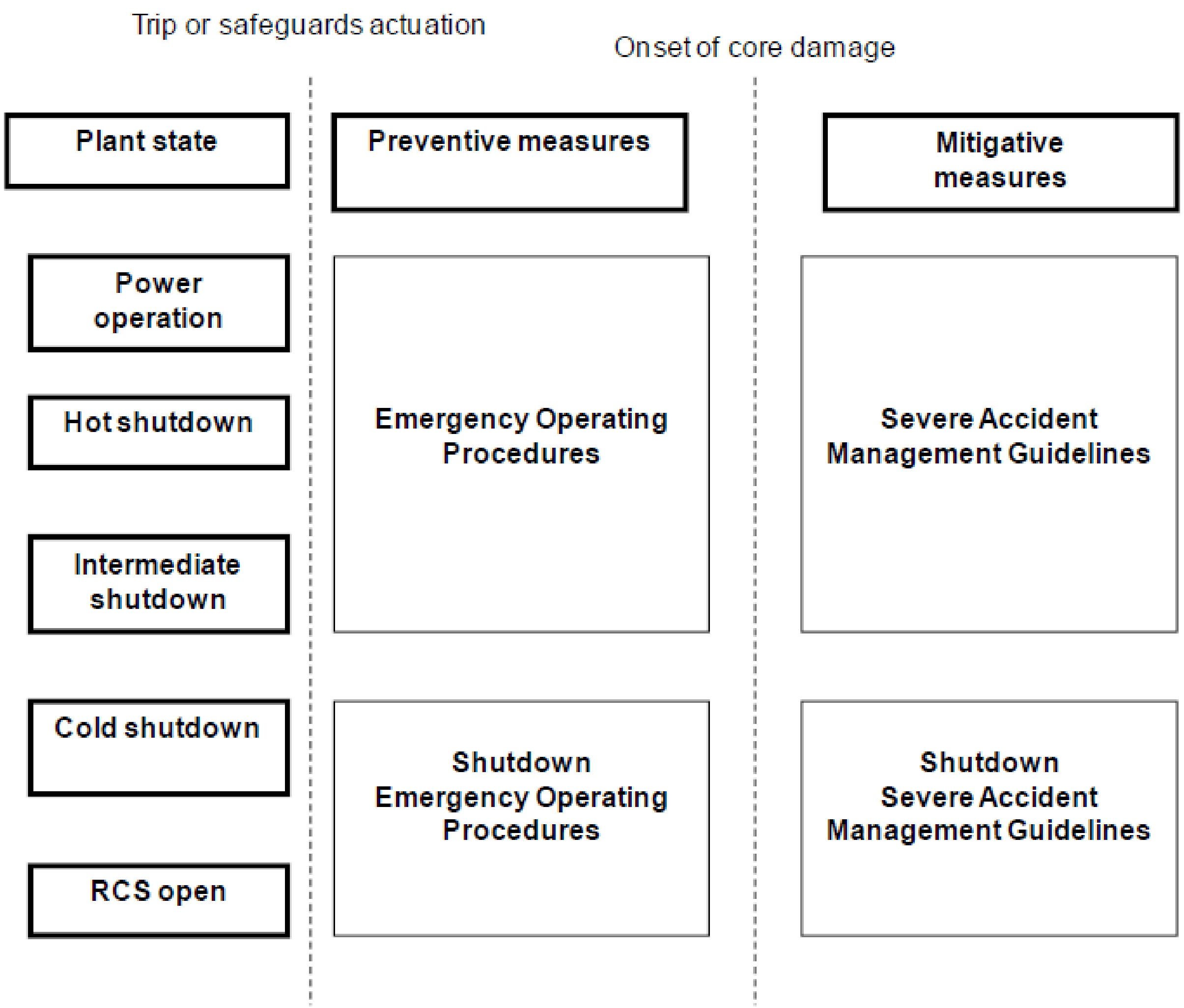
- Introduction
- WOG SSAMG
  - Principles
  - Development (POS examples, t-h analyses examples)
  - Transition
  - Insights
- SAM Measures Verification (MELCOR)
- Conclusions
- References

SAMG

- According to requirements of IAEA Safety Standards “Severe Accident Management Programs for Nuclear Power Plants, NS-G-2.15” appropriate consideration of beyond design basis accidents of nuclear power plants is an essential component of the defence in depth approach used in nuclear safety.

- In early 90-th the Westinghouse Owners Group (WOG) developed the generic Severe Accident Management Guidance (SAMG) **at-power** for PWR plants that are applicable for all plants irrespective of the total core damage frequency and fission product release frequency calculated for the plant.

Introduction

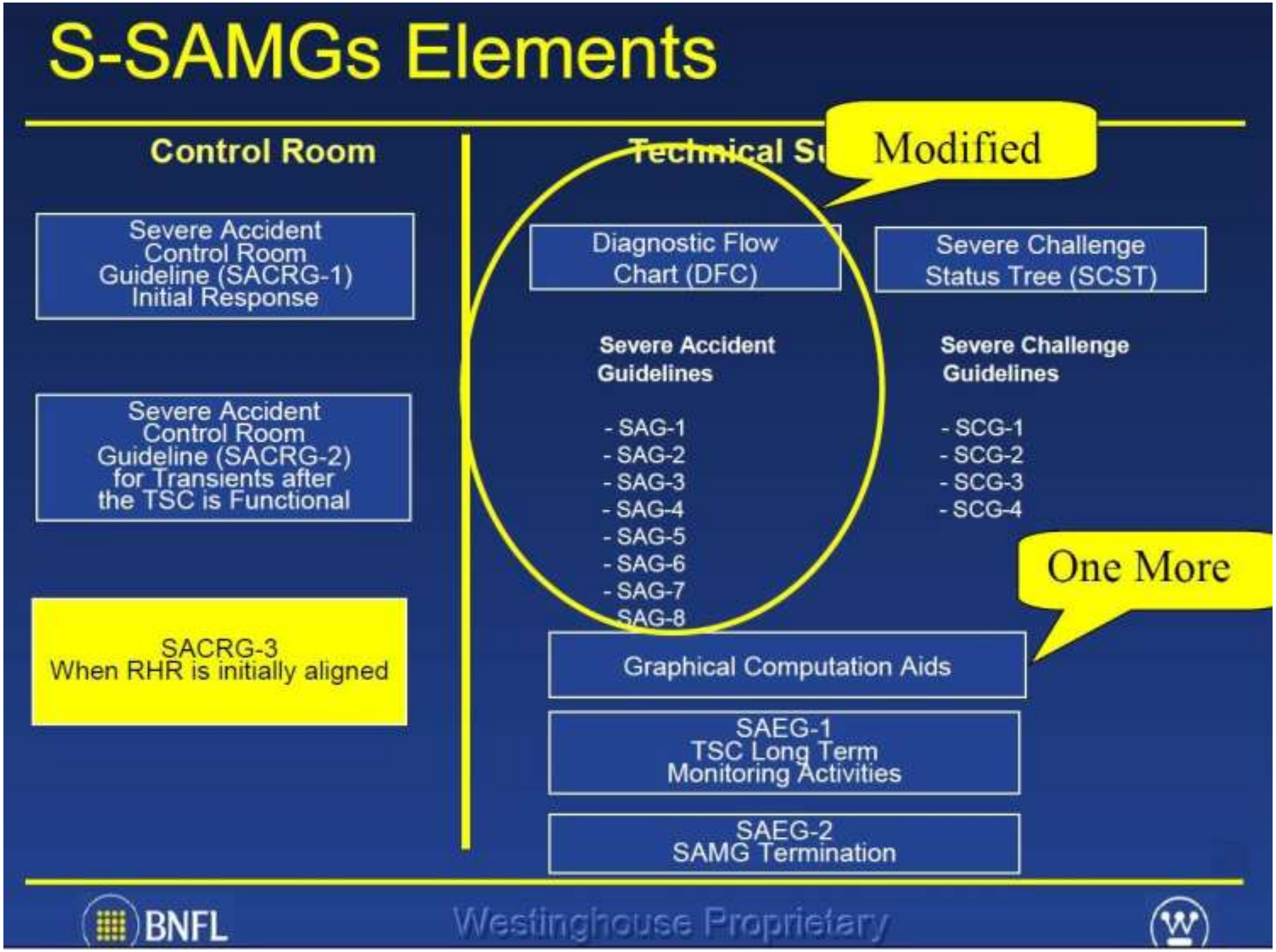


Westinghouse Approach

SAMG

- The Westinghouse SAMG package consists of symptom based guidelines that are originally designed to interface with the Westinghouse Emergency Operating Procedures (EOPs).
- Symptom-based ERGs
  - Event-structured
  - Function-structured
- SAMGs
- Symptom-based
- Valid for ‘at power conditions’
- Westinghouse Owners Group (WOG) material
  - Maintained by W for WOG

Westinghouse Approach



Westinghouse Approach

Main difference between SAG and SCG

- SAG
  - Evaluate benefit versus negative impact
- SCG
  - No choice anymore
  - Action is systematically taken
- Requires knowledge-based decisions based on severe accident plant conditions

SSAMGs Development

- Why be concerned about shutdown states? The first probabilistic safety assessments (PSAs) performed on nuclear power plants (NPPs) considered only accident sequences which could occur when the NPP is operating at full power, with the implicit assumption that during shutdown the risk is much lower.

- Nowadays we know that Shutdown Risk significant

- Shutdown SAMGs
  - Not WOG Material

- First Application
  - Koeberg

- List of other applications presented by B. Prior on IAEA TM in Beijing 2011

SSAMGs Development

- General approach: extending the existing SAMG (At-power) for use during low power or shutdown conditions.

- Therefore the current SAMG package has been reviewed and the necessary changes and additions were identified.
  - More sequences to consider
  - S-SAMGs are still Symptom-Based
  - RHR alignment is key
  - SFP issues are covered

SSAMGs Development

- Following ground rules were set and robustly maintained:
  - The Shutdown SAMG (SSAMG) is an **extension of the existing SAMG package**. Thus, the approach is to extend the range of applicability of the SAMG package;
  - The **WOG SAMG is symptom based**, primarily because in a severe accident it is difficult to identify which events caused the severe accident. For shutdown conditions, the number of possible plant configurations is larger, therefore it is even more important that the SSAMG is symptom based;
  - The SSAMG should as far as possible be applicable **to all Plant Operational States (POS).** Severe accidents could occur and may be more likely to occur during the transition from one POS to another.
  - The potential damage of spent fuel in the **spent fuel pool/storage** is considered in the SSAMG.
  - As large scale maintenance is frequently carried out during planned shutdown states, the first concern of SSAMG is the safety of the workforce.
  - Shutdown severe accident management covers also **external events**, such as fires, floods, seismic events and extreme weather conditions that could damage large parts of the plant as well as specific challenges posed by external events, such as higher probability of loss of the power supply, loss of the control room and reduced accessibility to systems and components.

SSAMGs Development

- The first step reviews the Plant Operating Technical Specifications (OTS) and shutdown Level 1 and Level 2 PRAs with the objective of defining the characteristics of different Plant Operational States.
  - the different plant thermal-hydraulic states,
  - different instrumentation and control configurations,
  - the status of containment isolation,
  - the location of the fuel,
  - the level and volume of water in the primary system,
  - availability of vent paths in the primary system,
  - available safety and other systems,
  - whether the vessel head is in place or not, and
  - the conditions during changes from one state to another.

POS? Examples

- Define the systems which support each shutdown safety function in each POS

- Example from plant's administrative procedure:

  Safety Function: Shutdown Cooling (DHR)

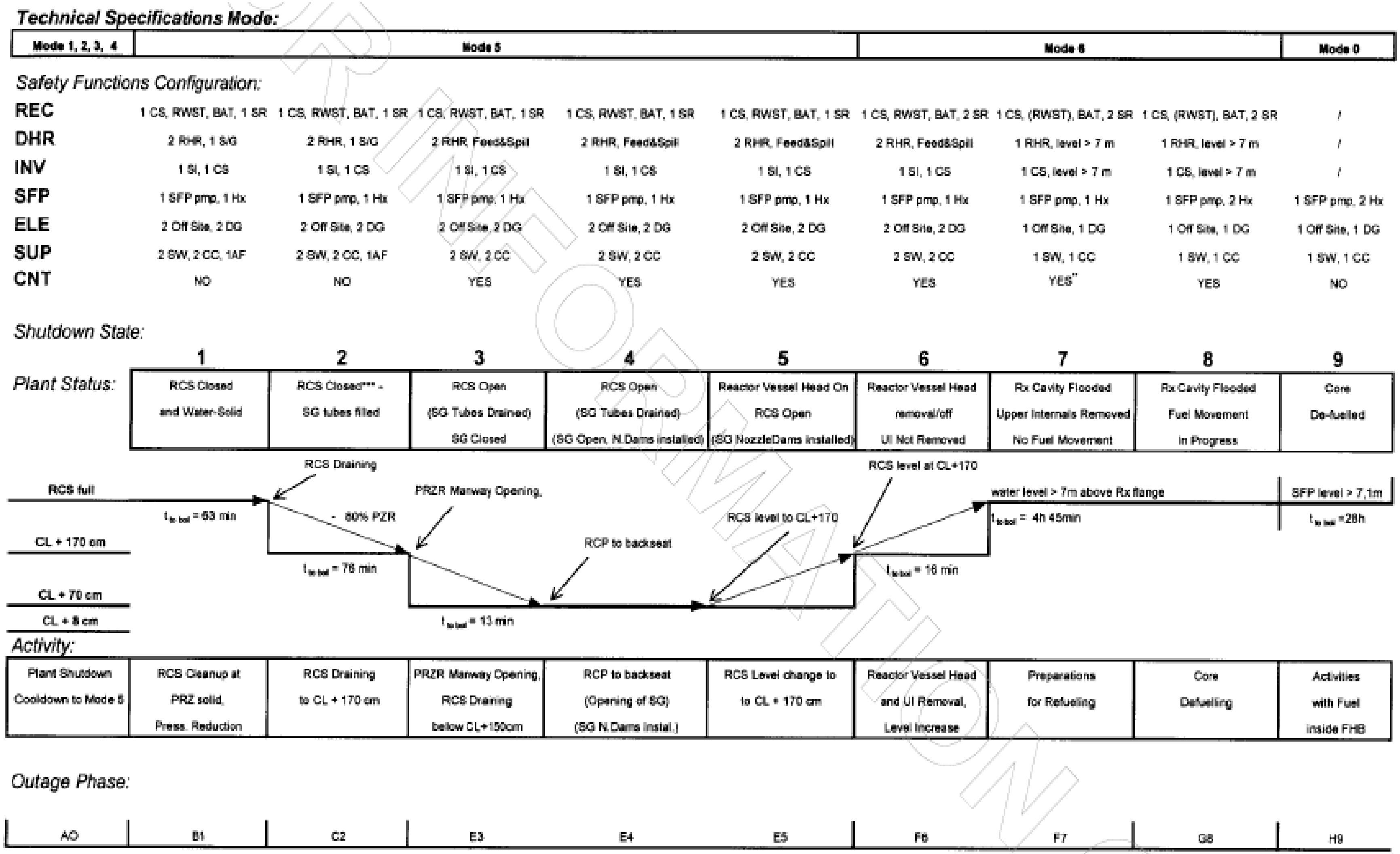
  – Define requirements for RHR system as normal means for DHR
  – Define the operability of RHR system (e.g. supporting systems)
  – Define applicable alternative ways for DHR in the case of Loss of RHR
    - Secondary Heat Sink
    - Feed and Spill
    - Refueling Cavity

POS?

Shutdown State	TS Mode	REC	DHR	INV	SFP	ELE	SUP	CNT	ACTIVITY	PLANT STATUS
1	5	1 CS RWST BAT 1 SR	2 RHR 1 SG	1 SI 1 CS 1 MW	1 Pmp 1 Hx	2 OFF SITE 2 DG	2 CC 2 SW 1 AF	NO	RCS cleanup, press reduction	RCS closed and RCS water-solid
2	5	1 CS RWST BAT 1 SR	2 RHR 1 SG	1 SI 1 CS 1 MW	1 Pmp 1 Hx	2 OFF SITE 2 DG	2 CC 2 SW 1 AF	NO	RCS draining to CL+170cm	RCS closed, SG tubes filled
2*	5	1 CS RWST BAT 1 SR	2 RHR feed & spill	1 SI 1 CS 1 MW	1 Pmp 1 Hx	2 OFF SITE 2 DG	2 CC 2 SW 1 AF	YES	RCS degassification and filling	RCS closed, SG tubes empty
3	5	1 CS RWST BAT 1 SR	2 RHR feed & spill	1 SI 1 CS 1 MW	1 Pmp 1 Hx	2 OFF SITE 2 DG	2 CC 2 SW	YES	PRZR opening / closure, RCS draining to CL+20cm	RCS open, (SG tubes drained), SG closed
4	5	1 CS RWST BAT 1 SR	2 RHR feed & spill	1 SI 1 CS 1 MW	1 Pmp 1 Hx	2 OFF SITE 2 DG	2 CC 2 SW	YES	RCP to/from backseat Open/closing of SG, N.Dams inst./deinst.	RCS open, (SG tubes drained, SG open, N.Dams installed)
5	5	1 CS RWST BAT 1 SR	2 RHR feed & spill	1 SI 1 CS 1 MW	1 Pmp 1 Hx	2 OFF SITE 2 DG	2 CC 2 SW	YES	RCS level change betw. CL+170cm and CL+20cm	Reactor vessel head on, RCS open, (Nozzle dams installed)
6	6	1 CS RWST BAT 2 SR	RHR eed & pill avity fill	1 SI 1 CS 1 MW	1 Pmp 1 Hx	2 OFF SITE 2 DG	2 CC 2 SW	YES	Rx Vessel Head and UI removal/instal.	Rx vessel head removal/off, Upper internals not removed
7	6	1 CS BAT RWST 2 SR	RHR 7m level	1 CS >7m lvl 1 MW	1 Pmp 1 Hx	1 OFF SITE 1 DG	1 CC 1 SW	YES	Preparations for defuelling, Activit. after refuelling	Cavity flooded, Internals removed, No fuel movement
8	6	1 CS BAT RWST 2 SR	RHR 7m level	1 CS >7m lvl 1 MW	1 Pmp 2 Hx	1 OFF SITE 1 DG	1 CC 1 SW	YES	Core defuelling and refuelling.	Cavity flooded, Fuel movement in progress
9	0	N/A	/A	N/A	1 Pmp 2 Hx	1 OFF SITE 1 DG	1 CC 1 SW	NO	Activities with fuel inside SFP	Core de-fuelled

Example: System operability requirements for different POSs

POS?



Example:
TS Modes of Operation Plant Shutdown States (POS) System/function requirements Time to boiling

RCS status?

- RCS pressure boundary conditions considered in TH analyses (example):
  - RCS pressure boundary open and boiling occurs at atmospheric pressure
  - RCS pressure boundary closed and boiling occurs at the valve setpoint at letdown orifice outlet to PRT
  - RCS pressure boundary is opened through the Pressurizer manway and RV head is on
  - RCS refuelling cavity flooded and reactor vessel head is off

Time to RCS Boiling

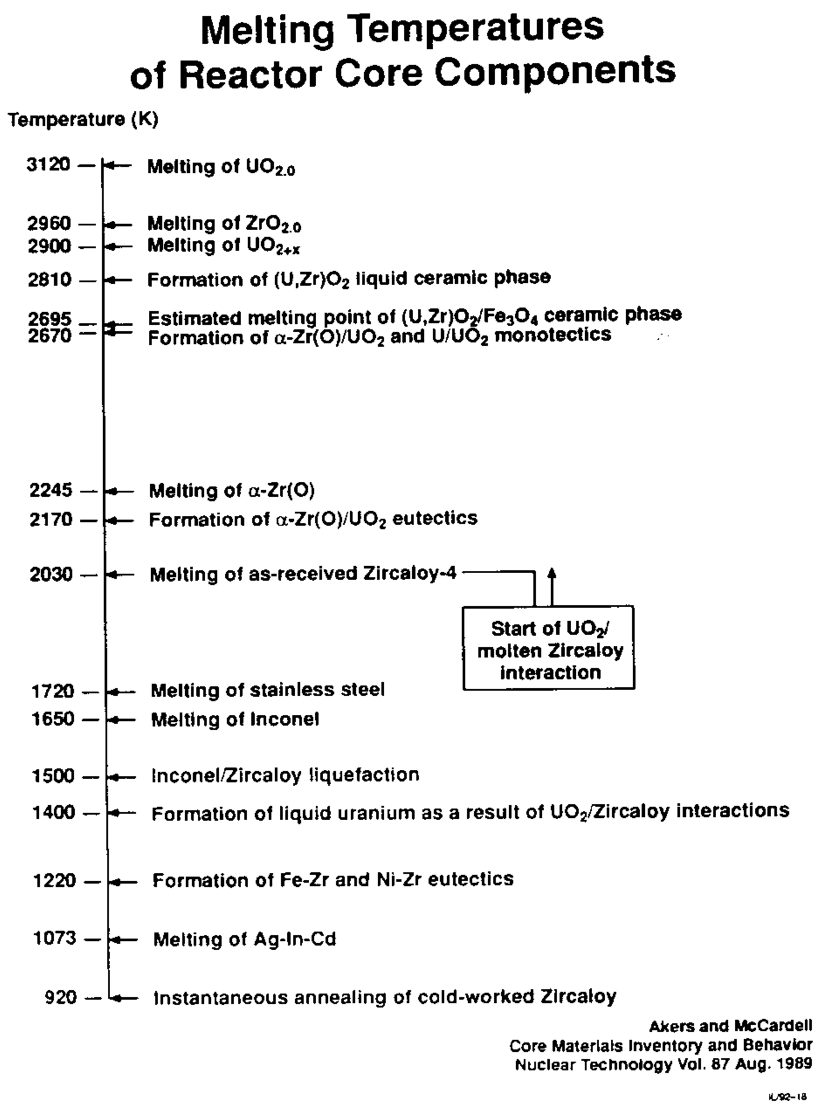
- A factor in determining the time to the start of boiling of the coolant is the status of the RCS pressure boundary.
- If the boundary is open:
  - Boiling will occur at atmospheric pressure
- If the boundary is closed:
  - Boiling will occur at valve setpoint at letdown orifice outlet to PRT
  - This will delay the onset of boiling since the reactor vessel volume must be heated to a higher temperature

Time to Core Uncovery (Damage)

- Option 1:
- In shutdown safety analyses (very conservative), core damage can be assumed to occur when the RCS level drops below the level of the top of active fuel (TAF).
- Therefore, a case needs to be evaluated where we boil and vaporize all the water above the TAF.
- With respect to the RCS Pressure Boundary status (open / close), the same cases apply as for the time to boiling analyses

Time to Core Uncovery (Damage)

- Option 2:
  - Option 2: MELCOR/MAAP model and calculation:
    - PSA conservative/traditional criteria (PCT > 1204 °C, calculated using conservative models) OR
    - using more modern best estimate approach with hottest fuel/clad lumped node temperature, calculated using best estimate models,TCRHOT> 650 °C for > 30 minutes OR > 1075 °C



Other Analyses

- Small Break LOCA / draindown Inventory Loss Factor
- General steps:
  - Postulate small LOCA
  - Determine flow rate out of the RCS/RHR combined system
    - Select break location to produce maximum head
  - Evaluate the effect of the inventory loss on time to boiling calculation
  - Consider various RCS Pressure Boundary conditions

Other Analyses

- TH analyses of SFP
  - Time to boiling
  - Time to fuel uncovery
- RCS gravity feed from the RWST
  - RWST water level vs. RCS water level
    - RWST level decreases with time
  - Pressure in containment
    - CTMT pressurization analysis
    - Availability of Containment Fan Coolers

SSAMGs Development

- The second step involves the review of the existing shutdown PRAs to gain insights with regard to:
  - dominant accident sequences and initiators,
  - vulnerable plant states,
  - time to boiling, time to core damage, and time to containment failure,
  - consequences of core damage, and
  - the symptoms of severe accident phenomena.

SSAMGs Development

- The third step involves reviewing the existing emergency operating procedures. The objective of this review is to identify:
  - changes required to OTS and the Shutdown Emergency Operating Procedures (Shutdown EOPs) to accommodate SSAMG,
  - identify conditions for entry into SSAMG for accident sequences not covered by Shutdown EOPs, and
  - identify appropriate kick-outs from Shutdown EOPs to the SSAMG.

SSAMGs Development

- In step 4 the SAMG DFC and SCST are evaluated for shutdown conditions. The following issues are investigated for each of the POSs defined in Step 1:
  - identify relevant phenomena and available or relevant diagnostic parameters (e.g. induced SGTR cannot occur when the vessel head is removed),
  - identify the available instrumentation to measure the diagnostic parameters (e.g. are the core exit thermocouples available),
  - determine the priority of diagnostics for each POS,
  - define structure of DFC and SCST applicable to all POSs,
  - verify the parameters and measurement for the definition of a controlled stable containment and core state.

SSAMGs Development

- Step 5: This step involves an assessment of the existing SACRGs, SAEGs, SAGs and SCGs for shutdown conditions:
  - identify applicable SAGs and SCGs,
  - for each of these identify additional systems, negative impacts, limitations and long term concerns,
  - define any new guidelines that may be required.

SSAMGs Development

- Step 6: In this Step, the applicability of computational aids (CA) is assessed:
  - check which computational aids are applicable,
  - identify any required modifications (such as the extension of duration for decay heat estimation),
  - identify any new computational aids.
- Step 7: In a concise way identify the essential changes to the SAMG and document the elements of the complete package.

SSAMGs Development

- Validity
  - RHR Initially aligned

- New issues
  - RHR
  - Status of RCS
  - CTMT Isolation Status
  - Fuel location
  - Instrumentation status
  - Spent Fuel Pit procedure

- Shift in priorities compared to SAMGs

S-SAMGs

- Elements
  - NEW SACRG-3
  - Modified DFC/SAG
  - NEW Computational Aid
  - NEW Entry Diagnostic Table (EDT)
  - NEW SA Fuel Building Guideline

SSAMGs Development

S-SAMGs

- Shutdown Risk Significant
  - Many studies such as the shutdown PRA for Beznau, Koeberg, EdF 900/1300, and VVER plants in Central Europe (Hungary, Slovak and Czech Republic) as well as latest industry events, such as Paks NPP shutdown fuel damage accident, demonstrated that the core damage frequency from an accident occurring when at shutdown or low power operation modes was of the same order of magnitude (up to 80% of CDF for some plants) than the one at power.
  - SSAMG for consistency

- Shutdown SAMGs
  - Not a new package
  - Complementing SAMGs
  - Some new elements

- Implemented at PWR plants (Koeberg, Beznau) and VVER-440 plants (Paks and Mochovce 3&4 NPPs).

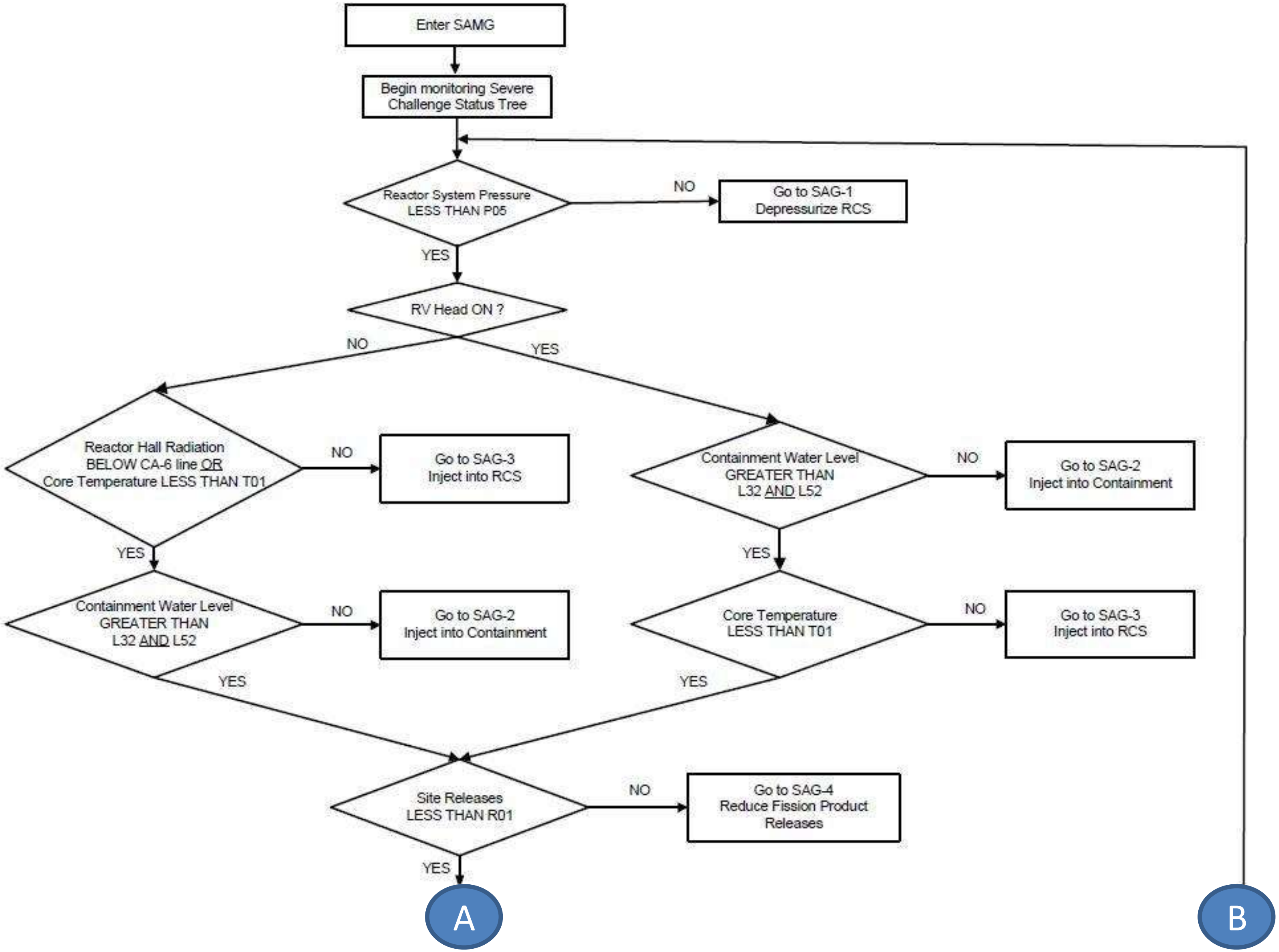
Transition criterion from EOP to SAM

- One significant challenge for Shutdown States
- The most suitable criterion for transition from EOP to SAM is the "onset of core damage". A suitable, unambiguous and easily used symptom which indicates that core damage is imminent or occurring is therefore required.
- Over the years, different plant parameters and conditions have been considered for performing this function of recognizing the onset of core damage:
  - core (fuel assembly) coolant outlet temperature (referred to here as core exit temperature or CET),
  - containment radiation levels,
  - containment hydrogen concentration
  - and/or reactor vessel level.

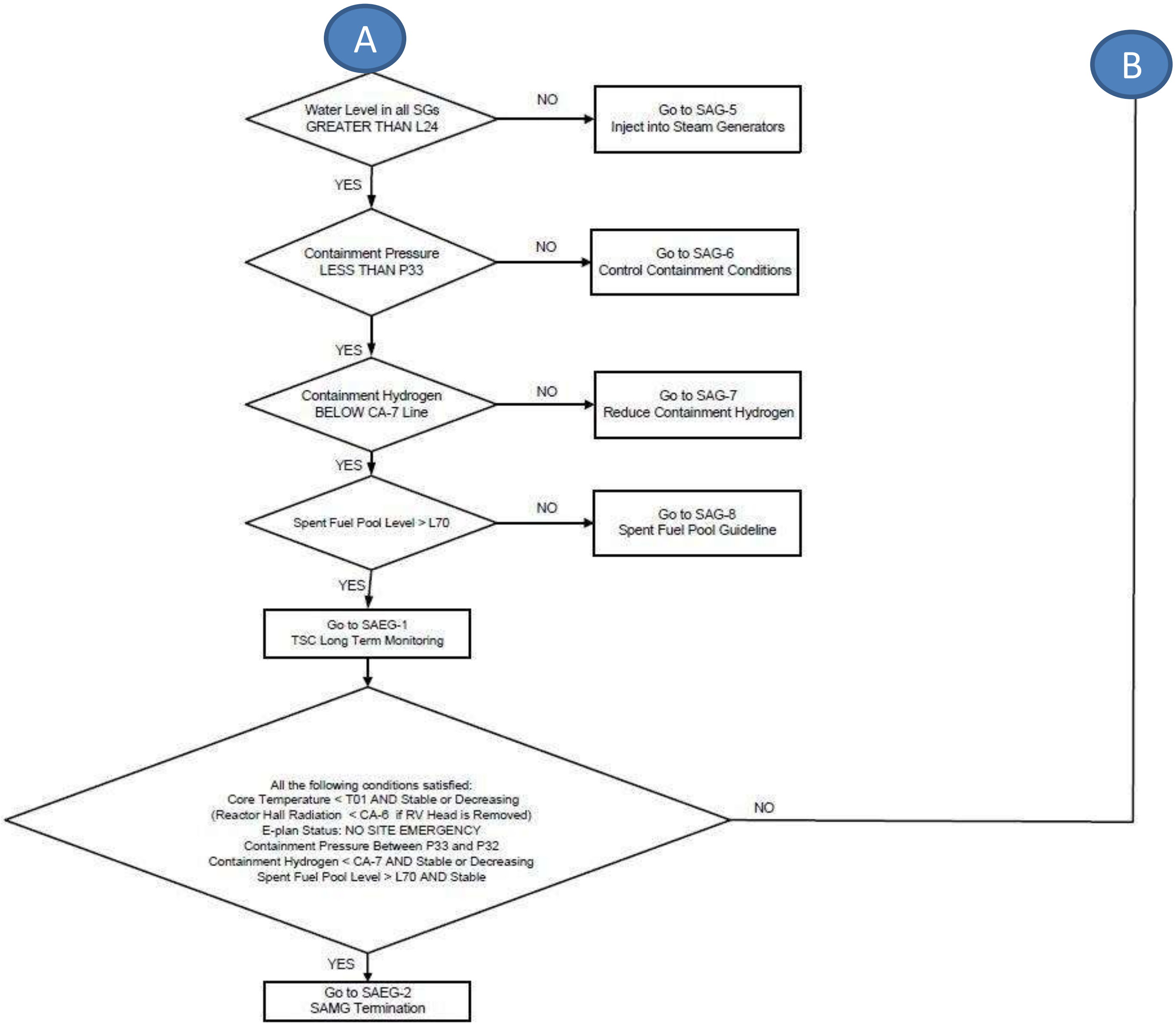
Transition criterion from EOP to SAM

- Some of these (especially those using containment parameters) are very sensitive to the specific accident scenario (i.e., the value at the onset of core damage for one scenario may vary significantly from that for another, for example due to the influence of sprays and fission product deposition phenomena).
  - some range of uncertainty that must somehow be considered
  - for application in emergency response, clear, easy to use tools and symptoms are preferred as they do not require lengthy and complex evaluations to be performed as a pre-requisite to decision making
  - assessments should not involve undue conservatisms (for example, it is inappropriate to transition from EOP to SAMG either too early or too late by including conservatism in the evaluation and definition of a symptom's setpoint).

Westinghouse Approach



Westinghouse Approach



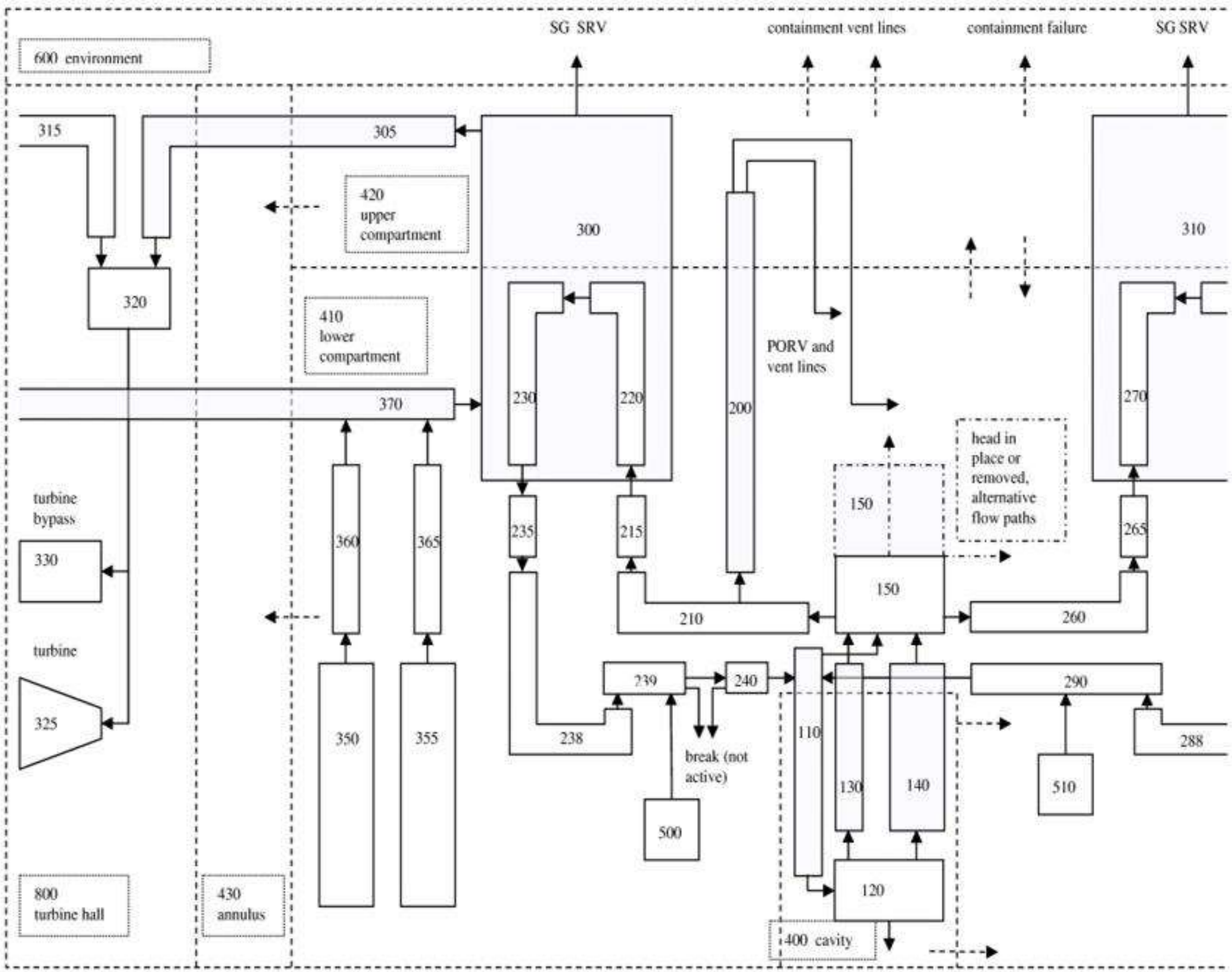
Verification of SAM Actions by SA Code

- Introduction to recent MELCOR applications at PSI
- Loss of RHR accidents during mid-loop operation
- LOCAs during hot shutdown operation

Verification of SAM Actions by SA Code

- Beznau power plant:
  - Two loop Westinghouse PWR
  - 1130MW core thermal power
  - Safety injection pumps: JSI 1-A, B,C,D
- Loss of RHR during mid-loop operation (22h after reactor trip)
  - Initial conditions with core power at 0.57%FP, low primary pressure
- LOCAs during hot shutdown operation (4h after reactor trip)
  - Initial conditions with core power at 0.92%FP, intermediate primary pressure
- This talk focuses on effect of safety injection time, injection rate and steam generator reflux condensation on core recovery

Verification of SAM Actions by SA Code



Verification of SAM Actions by SA Code

Loss of RHR during mid-loop operation

- Objective
  - Determine latest injection time to recover the core without damage
- Assumptions
  - Upper head in place and bolts detensioned
  - No accumulator available
  - One injection pump available for recovery
    - with limited flow rate (3.5kg/s for base case, 3.0kg/s for sensitivity study)
    - delayed some time after core uncovery (2840s for the reference case, 2640s and 3040s for sensitivity studies)

Verification of SAM Actions by SA Code

Comparison of event sequences

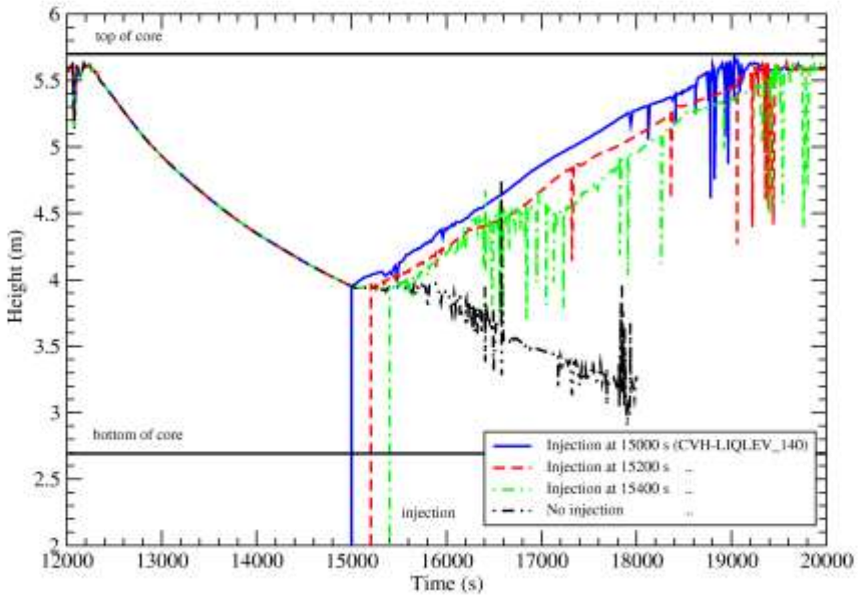
Parameter (unit)	Injection time (s)		
	15000	**15200**	**15400**
Start of core uncovery (s)	12360	12360	12360
Start of injection, t_i (s)	+ 2640	+ 2840	+ 3040
Level in core at t_i (m)	1.26	1.25	1.25
Max. core temperature at t_i (K)	992	1100	1185
Start of oxidation (s)	++ 35	-- 165	-- 365
Peak core temperature (K)	1185	1240	2369
Time to final quench (s)	++ 3920	++ 4010	++ 3040*
Mass of H_2 generated (kg)	2	3	20

+ relative to start of core uncovery

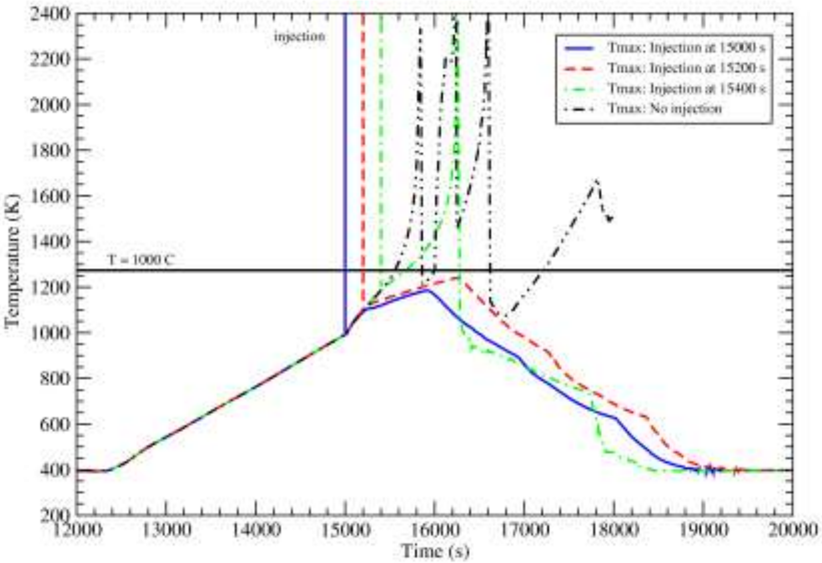
* for intact rods

-- / ++ relative to start of injection

Verification of SAM Actions by SA Code



Comparison of core liquid levels

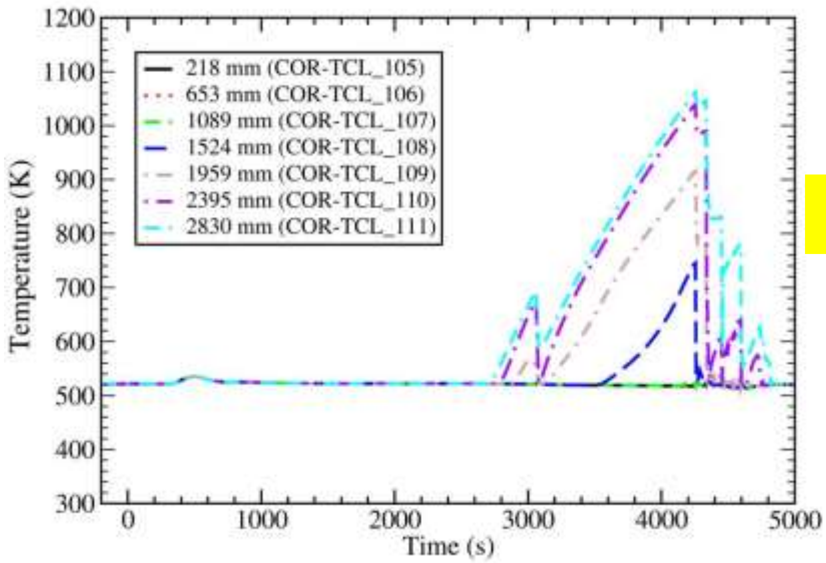


Comparison of maximum fuel rod temperatures

Verification of SAM Actions by SA Code

LOCAs during shutdown operation

- Small break LOCA (3cm)
  - No accumulator available
  - Full injection of only one pump (JSI 1-D) at 1500s after core uncovery
  - Secondary side at constant pressure (37bar)



Cladding temperatures in central ring

Spent Fuel Pool Vulerability

Example: SFP States for Risk Significance Evaluation, Time Window to Recover SFP cooling

State	Description	SFP Decay Heat (MW)	SFP Water Inventory	Time to Boil (hr) [1]	Time to Evaporate to FA+1m (hr) [2]	Duration (days)	Duration (%)
SFP1	Complete core from the previous cycle in the SFP [3]	6.40 – 4.39	C1	11.0 – 20.0	111.3 – 162.6	15.2	2.8%
SFP2	Partially burnt FAs from previous cycle returned to the core. Decay heat level higher than 1.5 MW.	2.37 – 1.50	C1	44.8 – 74.9	303.3 – 474.7	71.2	13.0%
			C2 (C3)	32.0 – 53.5 (32.0 – 53.5)	224.7 – 351.7 (174.1 – 272.6)		
SFP3	Decay heat level lower than 1.5 MW.	< 1.50	C2 (C3)	> 53.5 (> 53.5)	> 351.7 (> 272.6)	461.5	84.2%
					Total:	547.9	100%

Fukushima accident – SANDIA Evaluation

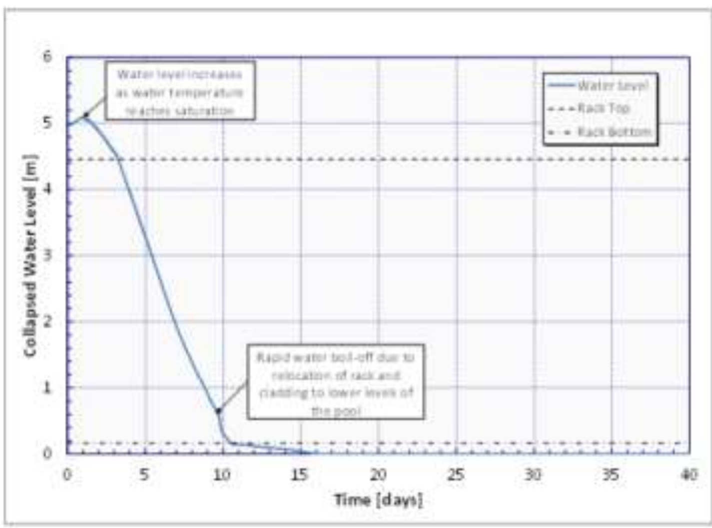


Figure 122. MELCOR Predicted Spent Fuel Pool Collapsed Water Level (0.5 m above Top of Racks Case).

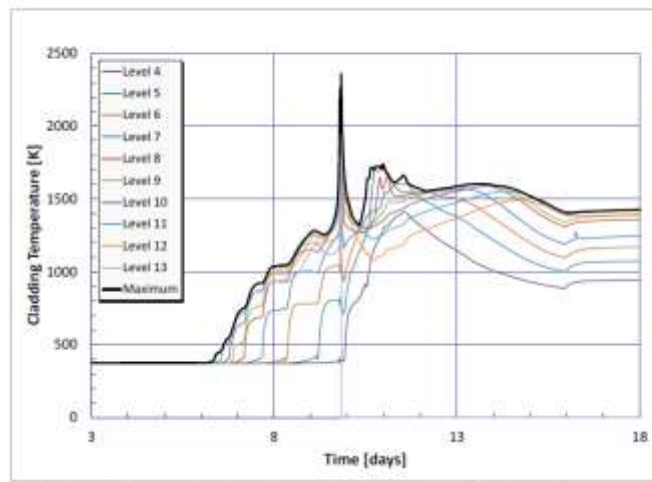


Figure 124. MELCOR Predicted Spent Fuel Pool Maximum Cladding Temperatures (0.5 m above Top of Racks Case, Detailed View).

Insights

- Due to flexibility and high adaptability of Westinghouse At-power SAMG, package could be modified and extended to effectively cover ALL plant operating states for different PWR (Westinghouse, Areva, and Siemens) and VVER plant designs.

- Procedures for Accident Management during shutdown (EOPs, SAMGs for shutdown modes) improve shutdown safety. After implementation of a shutdown Accident Management program, the shutdown core damage frequency is expected to be lower than the CDF from power modes and is mainly dominated by human error rates.

- During shutdown modes, several conditions are favourable with respect to restoration of core cooling by alternate Accident Management measures such as mobile equipment. These conditions are the long time windows and the fact that core degradations starts considerably after fuel uncovery.

Insights

- Shutdown risk with respect to large early releases is mainly dominated by scenarios with failure or impossibility to reclose the containment equipment hatches or airlocks.

- There are specific challenges to thermal-hydraulic codes for Low Power and Shutdown plant states; verification of codes, model modifications and improvements required for:
  - small system pressure,
  - small pressure differences,
  - influence of non-condensable gases,
  - low velocity boron transport,
  - large volume mixing,
  - Spent Fuel Pools (High Density Racks) accidents.

Regulator Review Role

Regulator Options

- Development of specivic Regulatory Review Guide (RRG) based on IAEA guides (NS-G-2.15, SRS32(SAMG), SRS48(SEOP), Services Series No.9, etc.)
  - Review the SAMG development and maintenance process, documentation, update, implementation of findings after drills and excercise,...
- Organizing the IAEA RAMP mission or other kind of independent review
- Participate in execution of drills and excercise

- Do not forget: Responsibility of safety during DBA and SA is in NPPs, Regulatory Body approval of SAMG is not recommended due to sharing responsibility if something is wrong

References

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Questions?

Comments?

Thanks for your attention!