NARSIS Workshop

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Severe Accident Phenomenology and Management

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Outline

- Introduction to severe accidents
- Phenomenology of severe accidents
- Severe accidents management guidelines

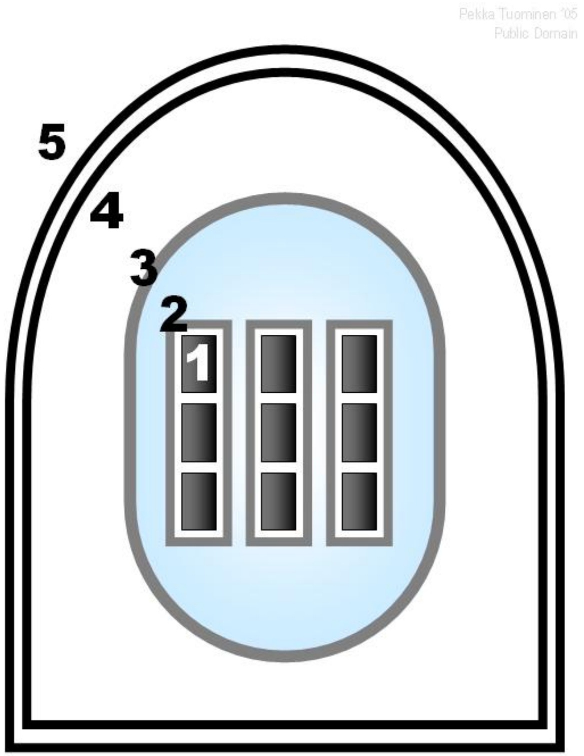
Introduction - accidents

- **Anticipated operational occurrences – AOO – (transients)**
  - Expected, no fuel damage
- **Design basis accidents - DBA**
  - Possible, no radiological impact
- **Design extension conditions A – DEC A – (Complex sequences)**
  - Unlikely, radiological consequences within limits
  - For which prevention of severe fuel damage in the core or in the spent fuel storage can be achieved
- **Design extension conditions B – DEC B – (Severe Accidents)**
  - Very unlikely, emergency response may be needed
  - With postulated severe fuel damage

WENRA Safety Reference Levels for Existing Reactors
IAEA SSG-2: Deterministic Safety Analysis for NPP, new revision 1, 2019

Introduction – protective barriers

- Fuel
- Fuel Cladding
- **Primary Circuit Pressure Boundary**
- **Containment**
- Emergency Measures



Introduction – What is severe accident?

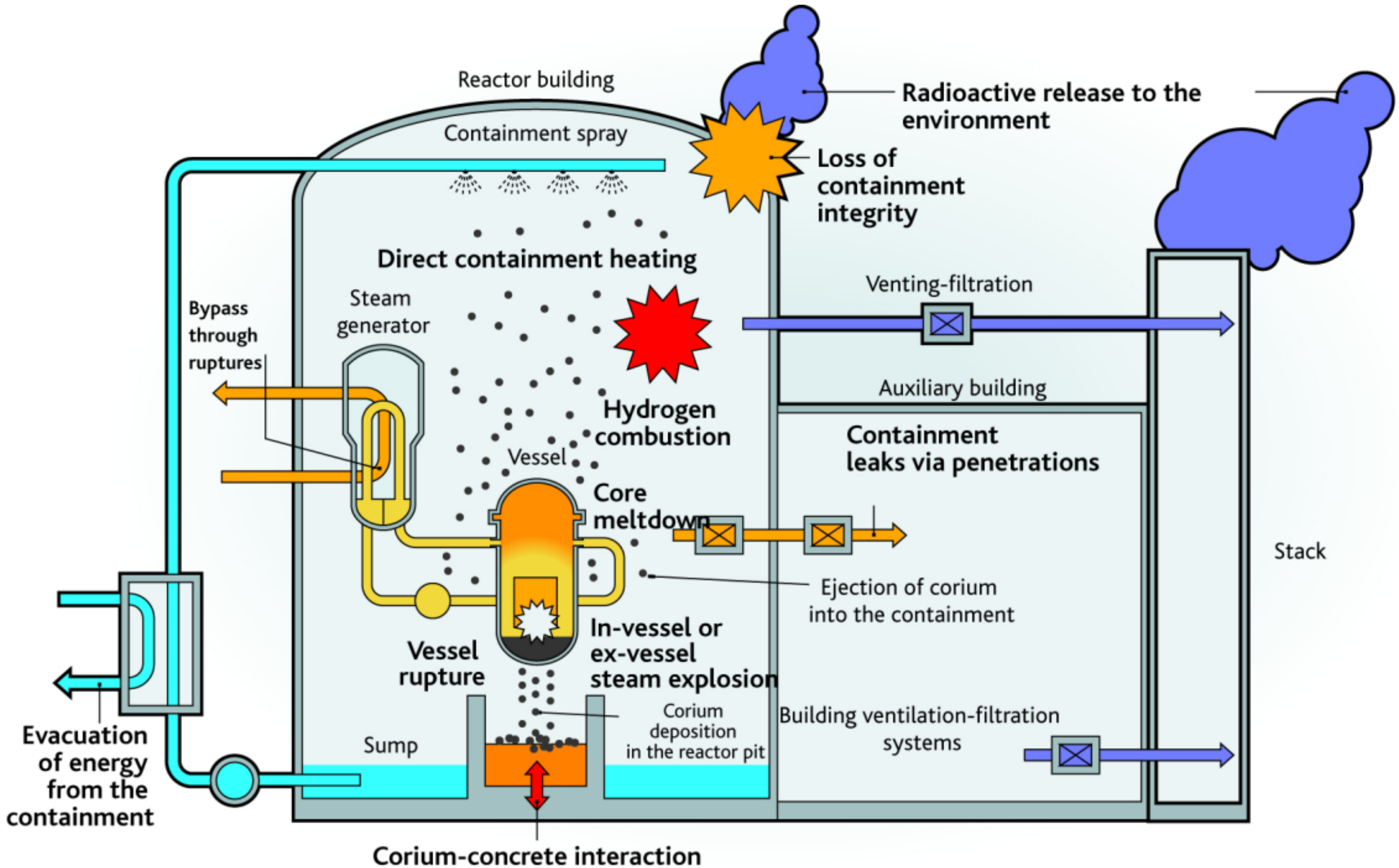
An event which is outside the design basis of the plant, and which leads to damage of the core. It may or may not progress further to core melt, vessel failure, containment failure, and radioactive releases.

a. PSA using conservative/traditional criteria
- Peak clad temperature (PCT) > 1204 °C, calculated using conservative models

b. PSA using more modern best estimate approach
- Hottest fuel/clad lumped node temperature, calculated using best estimate models,
- > 650 °C for > 30 minutes OR > 1075 °C

c. Plant operations, EOPs, SAMG
- Core exit thermocouples > 650 °C

Severe accident progression



Zircaloy – steam reaction

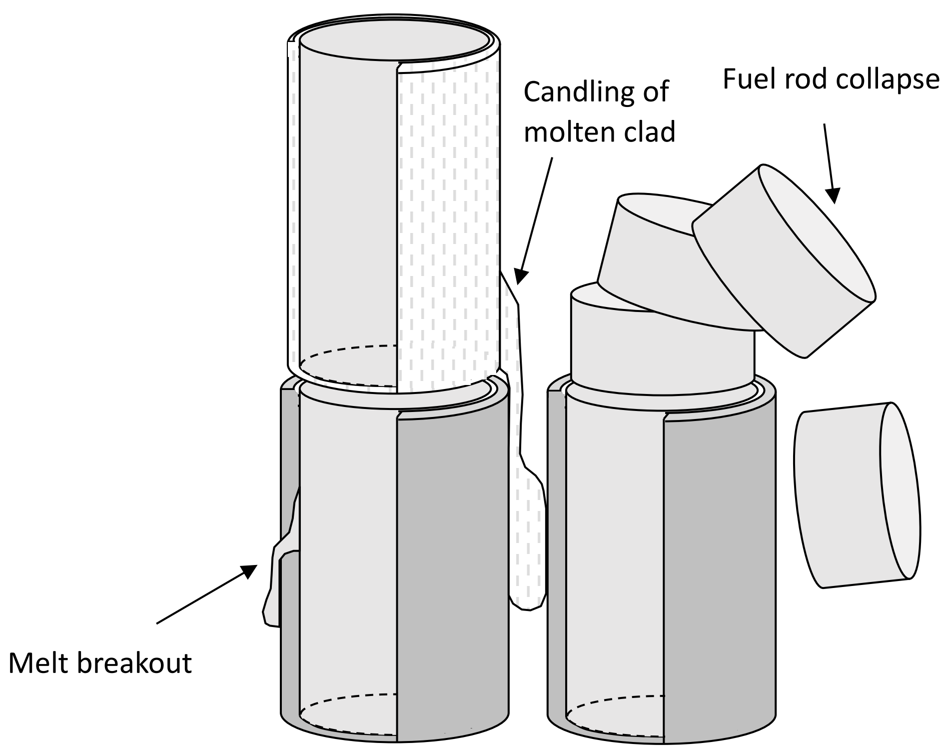
- **Major source of hydrogen to containment**

  $$Zr + 2H_2O \rightarrow 2H_2 + ZrO_2 + 6400\ \mathrm{kJ/kg\ Zr}$$

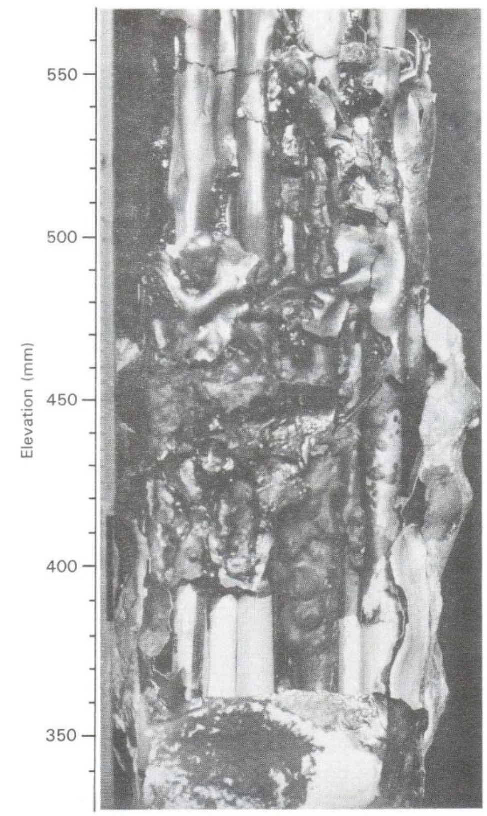
- **Heat of reaction causes significant increase in fuel assembly heat up rate**
- **Potential melting and downward "candling" of molten control rod & clad material**
  - Refreezes at lower elevation, reducing coolant flow area
- **Zr inventory 12 000 kg (2000 MWt reactor)**
- **Production of**
  - 525 kg H_2 (100% oxidation)
  - 315 kg H_2 (60% oxidation)
  - 184 kg H_2 (35% oxidation)

Zircaloy – steam reaction

Candling



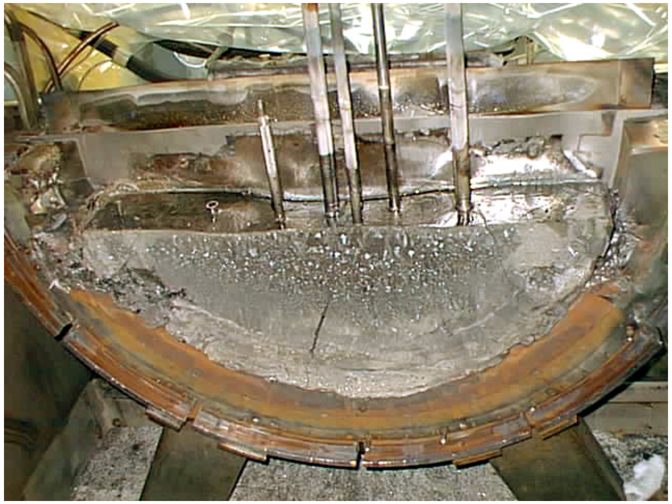
Fuel degradation



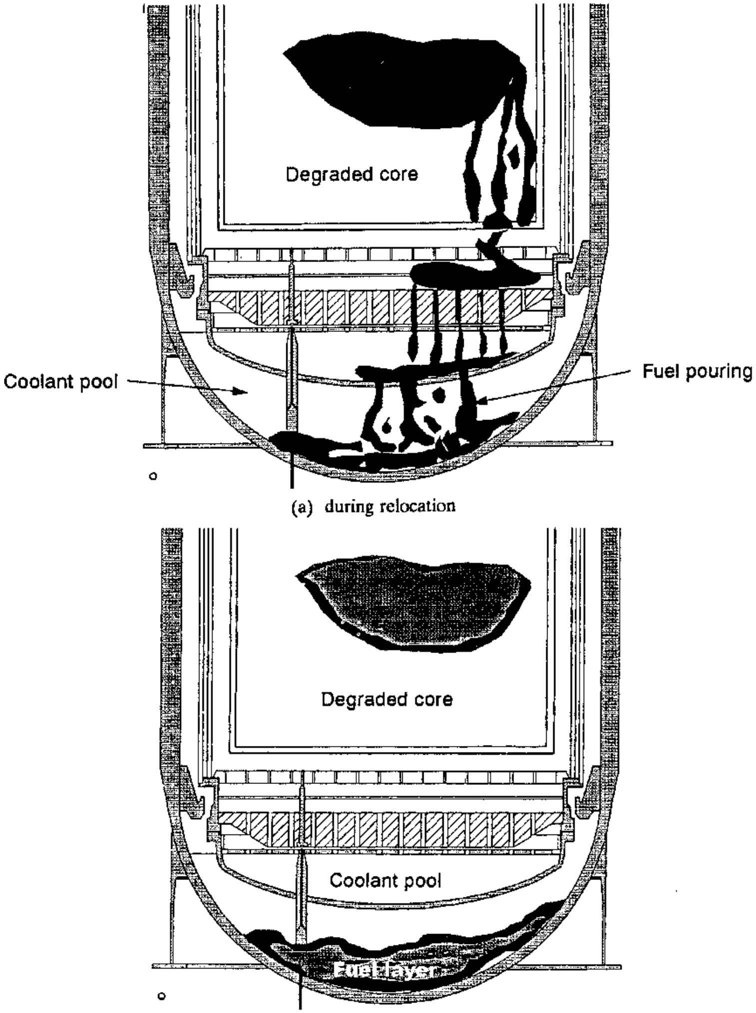
Hobbins, et al., Nucl. Tech., 95, Sept. 1991.
Hofmann, J. Nucl Mat, 270, 1999.

Corium relocation

Corium=mixture of melted nuclear fuel, fission products, control rods and structural materials



V. Strizhov, Eurocourse 2003



(a) during relocation

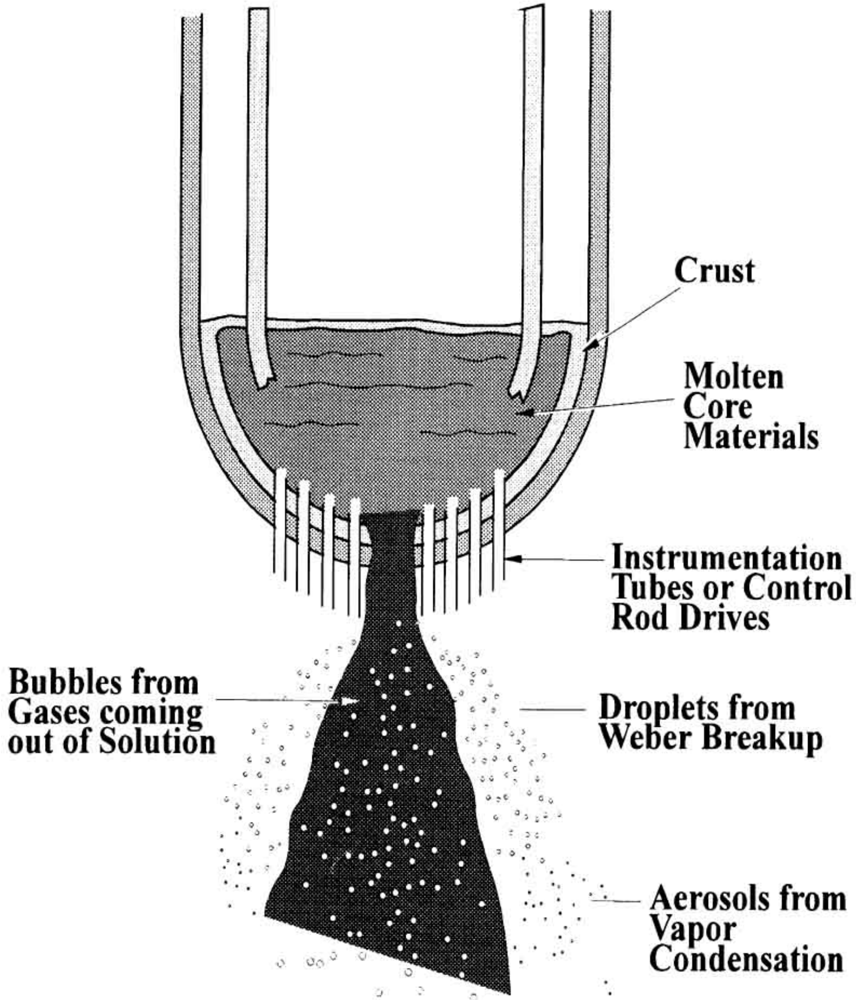
(b) after relocation

Ex-vessel phase

- **Major features: Core debris relocation into containment**
  - **If vessel failure occurs at high-pressure**
    - Possibility of melt dispersal and thermal interactions with containment atmosphere ("High-Pressure Melt Ejection" and "Direct Containment Heating": HPME / DCH)
  - **Vessel failure at low pressure results in gradual "pour" of debris onto containment floor**
- **After vessel failure, thermo-chemical interactions between molten core debris and concrete can dominate containment response.**

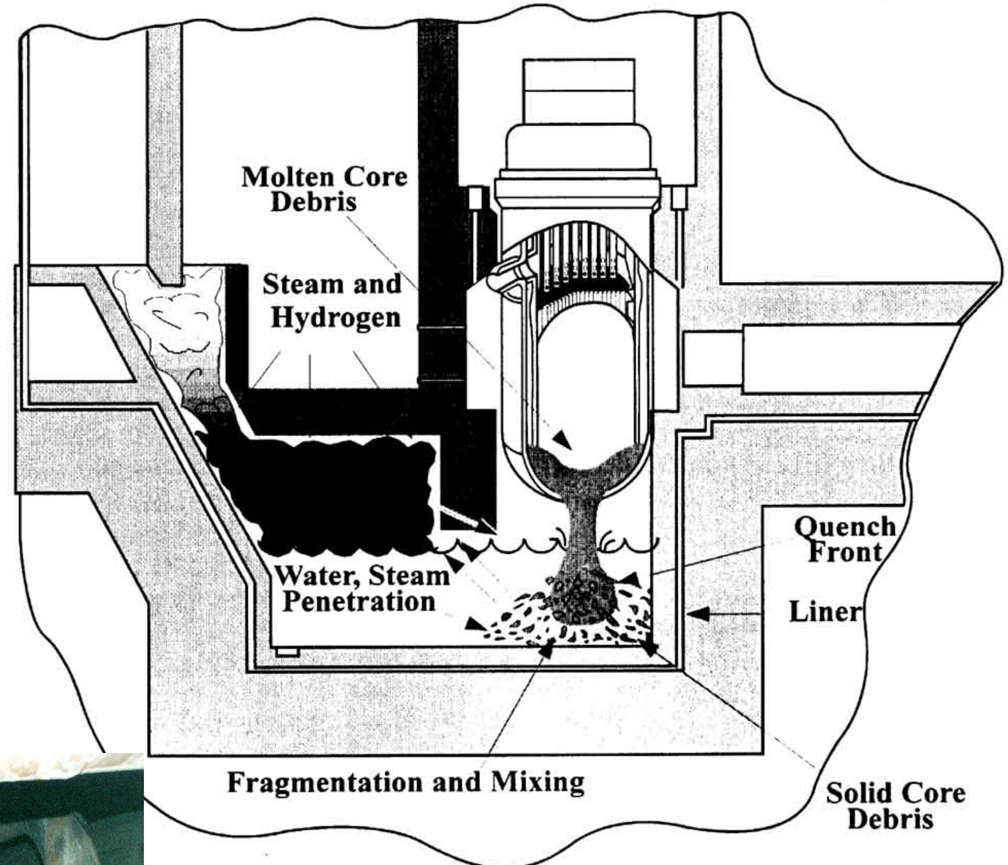
High Pressure Melt Ejection

- **Can be the cause of largest pressure increase in a PWR containment**
- **Combines:**
  - **RV blowdown from high pressure**
  - **Steam and H2 generation from melt-coolant interactions**
  - **Airborne debris particles directly heat containment atmosphere**



Low Pressure Melt Release

- Debris is "pour" out of RV lower head onto containment floor (cavity)
- May interact with water (if present) and quench
- Beginning of core-concrete interactions



Chernobyl - S.Bogatov, S. Gavrilov, V. Strizhov, Eurocourse 2003

Steam explosion

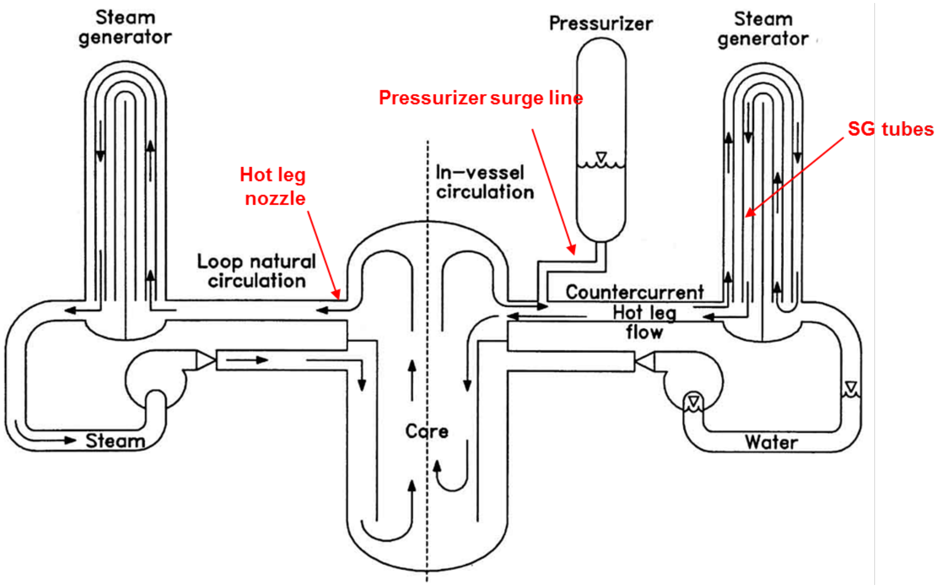
- **A dynamic process that can occur when a large quantity of molten core debris relocates into a pool of water**
  - In-vessel: Pour of molten material into RV lower head containing water (Phase 2)
  - Ex-vessel: Low-pressure pour of melt into wet reactor cavity (Phase 3)
- **A steam explosion requires four sequential phases of melt-coolant interaction to occur:**
  - Course mixing of melt and water
  - Collapse of vapor film at heat transfer interface causing an accelerated energy release ("trigger")
  - Propagation of the pressure pulse through the mixture to form a shock wave
  - Outward expansion of the shock wave (damage mechanism)

Molten Core-Concrete Interactions (MCCI)

- **Exothermic chemical reactions between core debris and concrete**
  - **Large quantities of gas is generated by concrete decomposition**
  - **$Zr + 2\ CO2 \rightarrow ZrO2 + 2\ CO$**
  - **Physical and chemical interactions between concrete decomposition gases and core debris release non-volatile fission products**
  - **Vertical and horizontal erosion of concrete basement can destroy containment foundation**
- **High local atmosphere temperatures**
  - **Potential for local heating of containment pressure boundary**
- **Non-condensable gas generations**
  - **Significant contributor to containment pressure**
- **Containment Structure Penetration**

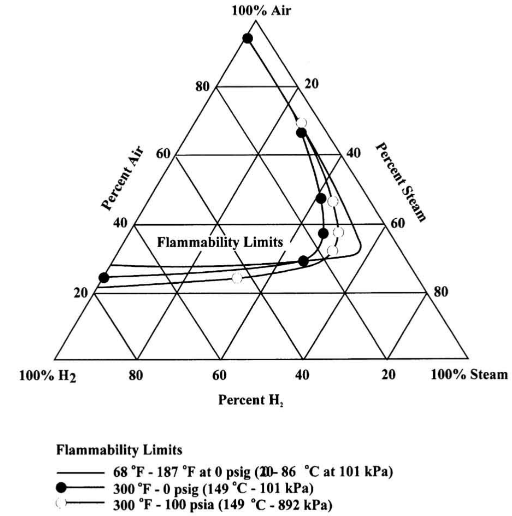
Creep failure

- Hot gases released from top of core during early phases of fuel damage
- Natural circulation flow patterns created
  - Hot gases cooled by transferring heat to colder surfaces
- Excess heating of pressure boundary can lead to creep rupture
  - Locations of concern: hot leg nozzles, pressurizer surge line, steam generator tubes
  - Leads to loss of coolant in RCS or Steam generator tube rupture - SGTR

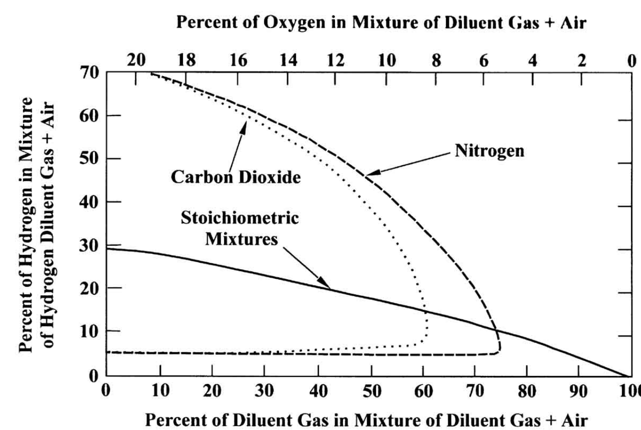


Hydrogen combustion

- Hydrogen is released to containment from RCS
  - Pressurizer PORV
  - LOCA: pipe break
- Hydrogen mixes with containment atmosphere
  - Distribution and local concentrations depend on flow field in containment
    - Pressure-drive flow among neighboring compartments
    - Natural convection
    - Ventilation system
- Combustion possible when local conditions exceed flammability criteria



Shapiro diagram
4% limit



High RCS pressure sequence (e.g. SBO)

- The High RCS pressure sequence starts with initiating event like station black out (total loss of internal and external electricity power), or loss of ultimate heat sink, where decay heat removal is lost in certain time window and the depressurization of reactor coolant system fails.
- The core is uncovered, fuel and its cladding temperature starts to rise and hydrogen production starts as a consequence of the contact of hot water and cladding.
- RCS pressure is stacked at pressurizer (PRZ) PORVs or safety valves setpoint pressure.
- The core lost coolable geometry and finally starts to melt.
- RPV can fail due to the different failure mechanisms but without RCS depressurization molten corium can be ejected to the containment at high pressure.
- High pressure molten ejection (HPME) can introduce direct containment heating (DCH) phenomena when fragmented corium can suddenly dissipate huge energy to containment atmosphere and produce pressure peak above design value.

High RCS pressure sequence (e.g. SBO)

- Containment pressure boundary can be jeopardized also by ejected corium fragments to the containment wall.
- If reasonable amount of corium is collected on RPV cavity floor the molten corium interaction with concrete (MCCI) can start to produce even more hydrogen and carbon monoxide, which either can form explosive mixture or increase containment pressure.
- After initial dynamic peak pressure at the time of RPV failure, the containment pressure starts to increase.
- Containment pressure boundary can fail either by initial peak pressure at RPV failure (HPME and DCH), hydrogen burn, long term pressurization by non-condensable gases (MCCI without containment heat removal) or melt through by not quenched and cooled corium on cavity floor due to MCCI.

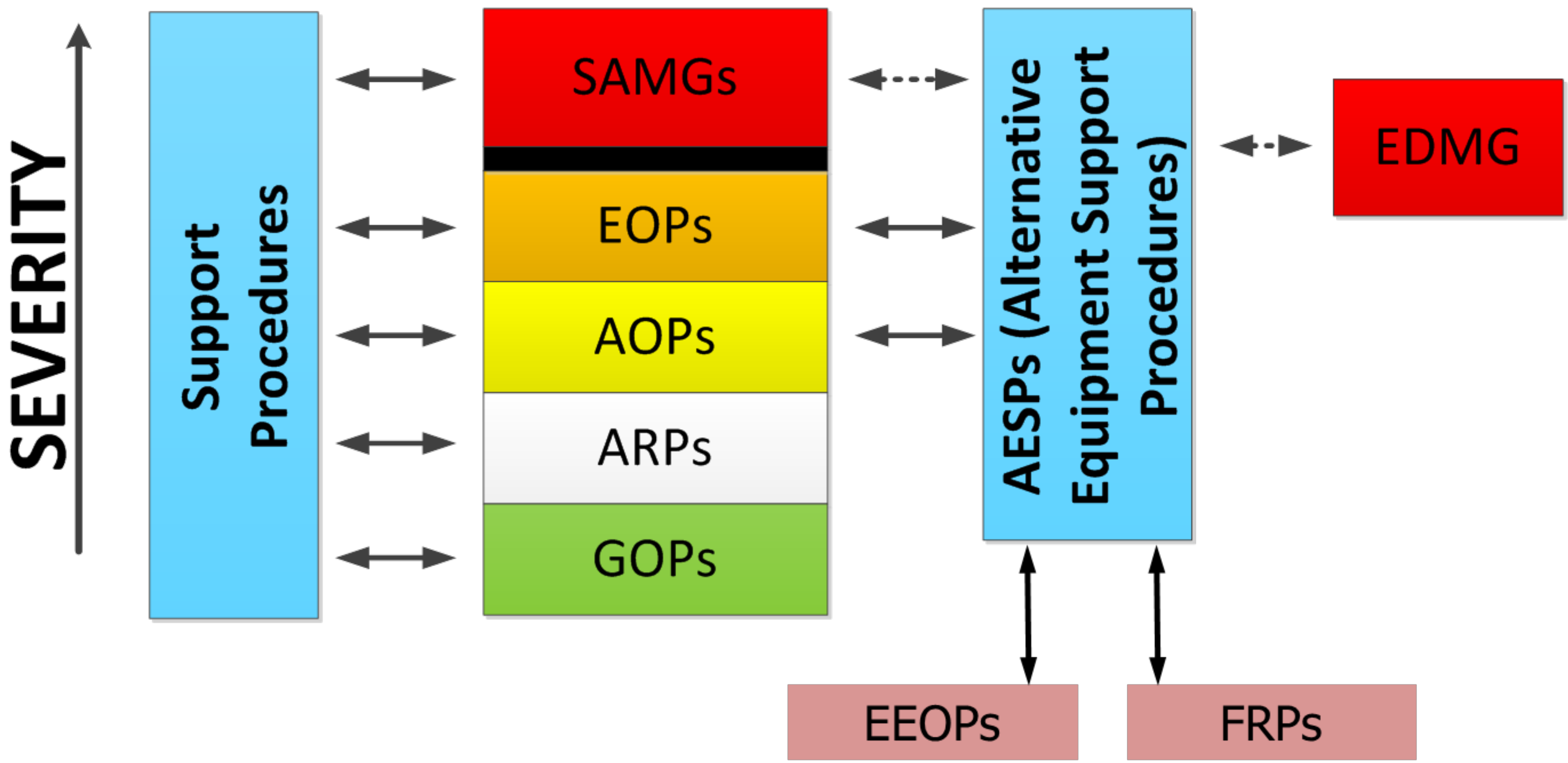
Low RCS pressure sequence (LB LOCA)

- The low pressure sequence starts with initiating event like loss of coolant accident, (LOCA) where the water in reactor coolant system is loss and there is no available means to remove decay heat.
- High RCS pressure seqence with deppresurization can be changed to low pressure sequence
- The core is uncovered, fuel and its cladding temperature starts to rise.
- Hydrogen is produced by cladding oxidation with hot steam till water present in RPV.
- The core temperature starts to rise. The core starts to melt and RPV fails at the bottom due to corium melt through its vessel.
- The reactor cavity bellow the reactor pressure vessel can be flooded with water or not.

Low RCS pressure sequence (LB LOCA)

- Hot corium in contact with water can initiate steam explosions, which can threaten containment integrity.
- The corium collected on RPV cavity floor can evaporate existing water (if there is no containment injection) in cavity or immediate starts the molten corium interaction with concrete (MCCI) if cavity is dry and it starts to produce even more hydrogen and carbon monoxide, which either can form explosive mixture or increase containment pressure.
- Containment pressure boundary can fail either by initial peak pressure at RPV failure (or steam explosion if some water exists in RPV cavity), hydrogen burn, long term pressurization of non-condensables (MCCI without containment heat removal) or melt through by not quenched and cooled corium on cavity floor due to MCCI.

Procedures and guidelines in NPP



Severe Accident Management Guidelines - SAMG

Entrance to SAMG

This SAMG is entered when core exit thermo-couples are greater than 650 °C and EOP actions from function restoration guidelines to cool the core are not successful.

Severe Accident Management Guidelines - SAMG

- Determine that **information is timely and accurate** / Determine that **information is sufficient for decision**
- Determine that **strategy was effective**
- Determine that the **plant status is as expected**
- Determine that the **challenge was mitigated**

Severe Accident Management Guidelines - SAMG

- **Severe Accident Control Room Guidelines**
- **DFC – Diagnostic Flow Chart**
- **Severe Challenge Status Tree**
- **Severe Accident TSC Guidelines**
  - **Inject into the Steam Generators (SAG-1)**
  - **Depressurize the RCS (SAG-2)**
  - **Inject into the RCS (SAG-3)**
  - Inject into Containment (SAG-4)
  - Reduce Fission Product Releases (SAG-5)
  - Control Containment Conditions (SAG-6)
  - Flood Containment (SAG-7)
  - Refill the Spent Fuel Pool (SAG-8)

Main control room actions

Check, Isolate, Restore

1. Check entry conditions
2. Evacuate Containment
3. Restore Containment Integrity
4. Isolate RHR system from RCS
5. Check Containment penetration isolation
6. Depressurize RCS if RHR is NOT isolated from RCS.
7. Check Main if Control Room Charcoal Cleanup System is Actuated
8. Place Control Switches for any of the Non-Operating Equipment in PULL-OUT (e.g.: Charging Pumps, SI Pumps, RH Pumps, Containment Spray Pumps, Containment Fan Coolers, AFW Pumps, SW Pumps…)
9. Turn on Containment Hydrogen Monitors
10. Check Containment Recirculation Sump Level - GREATER THAN 3.9 m
11. Check TSC Status
12. Reset SI
13. Reset Containment Isolation Phase "A" and Phase "B"
14. Establish Instrument Air to Containment

Main control room actions

Check, Isolate, Restore

15. Check If Any RCPs Should Be Stopped
16. Check If RCS Should Be Depressurized
17. Verify that associated SW and CC train are in operation
18. Establish RCS Injection Flow:
19. Check if Containment Fan Coolers should be stopped:
20. Check Containment Recirculation Sump Level - GREATER THAN 3.9 m
21. Determine Containment Spray Requirements (Suction from RWST):
22. Check if Containment Spray should be running in recirculation:
23. Initiate actions to isolate idle flow paths that penetrate the containment boundary
24. Check SG levels:
25. Initiate actions to isolate idle secondary release flow paths:
26. Initiate sampling / monitoring
27. Evaluate plant status:
28. Return to Step 11. OBSERVE NOTE PRIOR TO STEP 11.

Diagnostic flow chart - DFC

Purpose

- Provides a method for the TSC to diagnose the plant conditions during a severe accident and to select the appropriate Severe Accident Guidelines (SAGs) for implementation. Specifically, the information contained in DFC relates to:
  - Plant conditions that indicate a controlled stable state has been reached,
  - Plant conditions that represent a challenge to a containment fission product boundary,
  - Insufficient SFP cooling
  - Instrumentation that can be used to provide an indication of the plant status for the parameters on the DFC.

Purpose of DFC parameters

- **SG Water Level**
  - To determine if there is an RCS heat sink available.
  - To determine if creep rupture of the SG tubes is a concern.
  - To mitigate fission product releases from faulty or leaking SG tubes.
- **RCS Pressure**
  - To determine the ability to inject into the RCS.
  - To determine if HPME is a concern.
  - To determine if there is an uncontrolled opening in the RCS.
  - To determine if creep rupture of the SG tubes is a concern

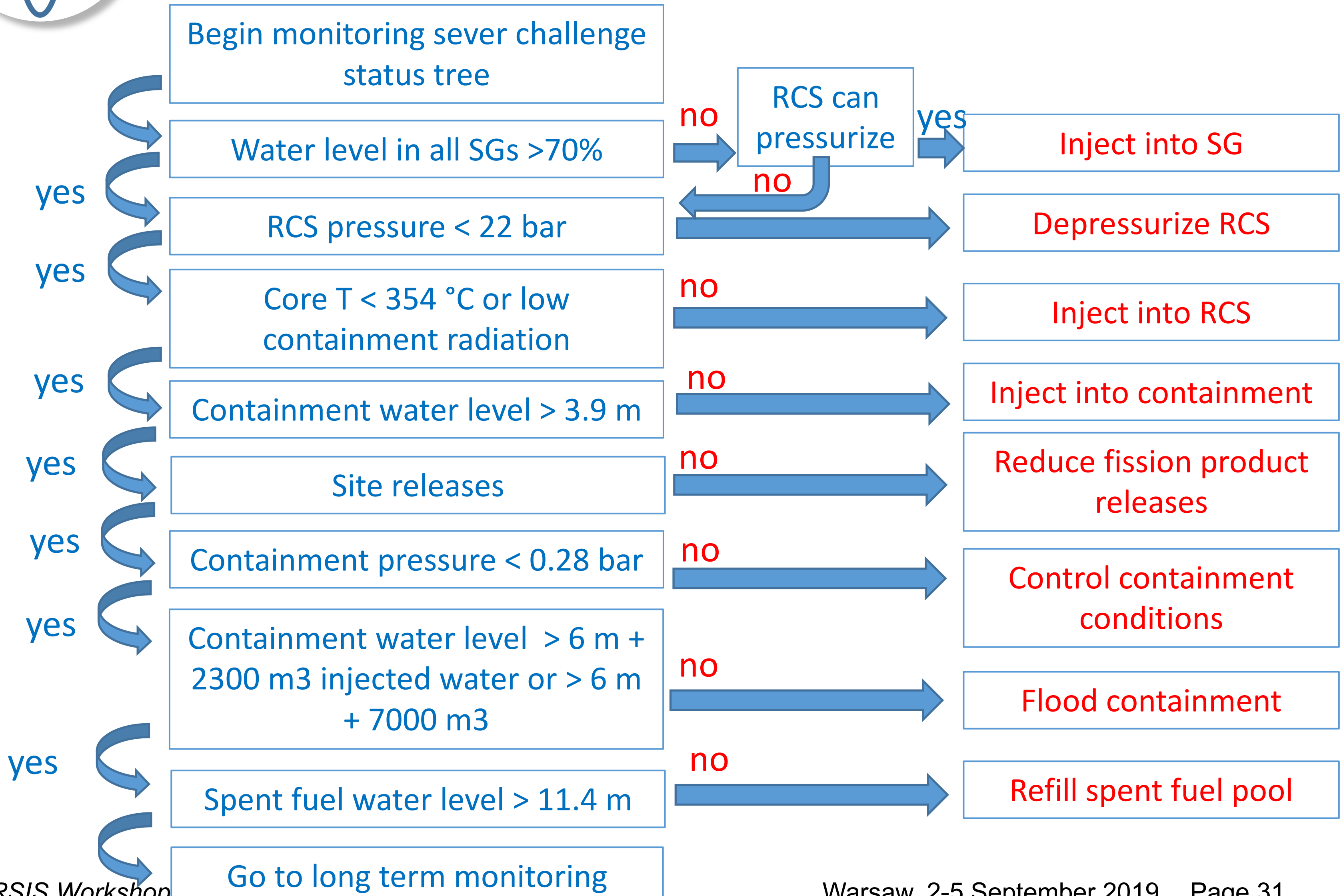
Purpose of DFC parameters

- **Core Temperature (RCS Temperature)**
  - To determine if the core is covered with water.
- **Containment Water Level**
  - To determine if equipment and instruments are flooded.
  - To determine if ECCS and/or containment spray recirculation is possible.
  - To determine if the core is coolable if RPV failure occurs
- **Site Release**
  - To determine if release mitigation is desired

Purpose of DFC parameters

- **Containment Pressure**
  - To determine if there is a challenge to the containment due to overpressurization or due to subatmospheric condition.
  - To determine if the containment atmosphere is steam inert.
- **Containment Hydrogen Concentration**
  - To determine if there is a long term challenge to the containment due to hydrogen flammability.
- **SFP level**
  - To determine if the spent fuel pool has sufficient water inventory
  - To mitigate fission product releases from the fuel handling building

Severe Challenge Status Tree



Injection into SG

- **Entry conditions:**
  - water level in all SGs <70% NR and RCS is pressurized (no large opening)
- **The purposes of injecting into the steam generators are:**
  - to protect the steam generator tubes form creep rupture,
  - to scrub fission products that enter the steam generators via tube leakage,
  - to provide a heat sink for the RCS.

Injection into SG

What? When? How to avoid?

NEGATIVE IMPACT	APPLICABILITY	MITIGATING ACTIONS
Thermal shock of SG	**Feeding a hot, dry SG** • If steam generator wide range level is less than 4%	• Limit flow to SG to 22 m3 /hr to the first 10 minutes of injection • Feed only one dry SG at a time to minimize consequences of SG tube failure until minimum wide range SG level is indicated. • Feed only isolatable SGs to minimize consequences of SG tube failure.
Fission product release from leaking SG tubes	**Feeding a ruptured or leaking SG**	• Feed/steam only intact SGs. • Depressurize the RCS to minimize primary to secondary leakage (refer to SAG-2, DEPRESSURIZE THE RCS). • Depressurize SG by dumping steam to the condenser.
Creep rupture of SG tubes	**Depressurizing a SG with low water level** • If steam generator wide range level in SG being depressurized is less than 12% AND if RCS pressure is greater than SG pressure.	• Depressurize only one hot, dry SG at a time to minimize consequences of SG tube failure. • Establish feed flow as soon as possible once SG pressure is below the shutoff head of the feed source. If SG WR level is less than 4%, then limit flow to SG to 22 m3/hr for the first 10 minutes of injection. • Depressurize the RCS (refer to SAG-2, DEPRESSURIZE THE RCS).
Degraded heat transfer	All means of SG injection with raw water sources	• Limit use of raw water to prevent build-up of precipitated materials on metallic surfaces
Component corrosion	All means of SG injection with raw water sources	• Limit use of raw water to prevent corrosion of metallic surfaces.

Depressurize the RCS

- **Entry conditions:**
  - RCS pressure > 22 bar
- **The purposes of depressurizing the RCS are:**
  - to prevent a high pressure melt ejection,
  - to prevent creep rupture of the steam generator tubes when the SGs are dry,
  - to allow RCS makeup from low pressure injection sources,
  - to maximize RCS makeup from any centrifugal pump injection source,
  - to prevent RHR system overpressure if still aligned for service.

Depressurize the RCS

NEGATIVE IMPACT	APPLICABILITY	MITIGATING ACTIONS
Containment severe challenge from overpressure	**All RCS vent paths that release to containment** • IF containment pressure is greater than 3.48 bar	• Use SGs or aux pressurizer spray • Start containment heat sinks (refer to SAG-6, CONTROL CONTAINMENT CONDITIONS). • Use one pressurizer PORV to reduce rate of containment pressurization.
SG fission product releases	**Depressurizing a ruptured or leaking SG**	• Use intact SGs that are isolated from ruptured SGs. • Use pressurizer PORVs or aux pressurizer spray • Use the steam dumps instead of the SG PORVs to provide additional fission product scrubbing. • Maintain SG NR water level above 70%
Loss of SG inventory	**Depressurizing a SG with low feed flow** • IF the SG feed rate is low	• Maintain SG NR water level above 70% • Use pressurizer PORVs or aux pressurizer spray.
Containment fission product releases	**All RCS vent paths that release to containment** • IF containment integrity is impaired	• Establish containment integrity • Use SG or aux pressurizer spray to depressurize the RCS • Maximize containment spray and fan coolers.

Inject into the RCS

- **Entry conditions:**
  - **RCS temperature > 354 °C or containment radiation high**
- **The purposes of injection into the RCS are:**
  - **to remove stored energy from the core when it has been uncovered,**
  - **to provide an ongoing decay heat removal mechanism, by:**
    - continuous injection and steaming of the water through an opening in the RCS, or
    - short-term injection into an intact RCS to establish a heat transfer pathway with the steam generators,
  - **to prevent or delay vessel failure,**
  - **to provide a water cover to scrub fission products released from the core debris,**
  - **to provide water to cool fuel in the refueling cavity.**

Inject into the RCS

NEGATIVE IMPACT	APPLICABILITY	MITIGATING ACTIONS
Creep rupture of SG tubes	**All means of RCS injection** • If steam generator wide range level in any steam generator is less than 12%, AND if RCS pressure is greater than SG pressure	• Maximize injection flow to SGs. • Open RCS vent paths. • Control the initial RCS injection flow so pressure across the SG tubes remains less than 34.32 bar • Close SG PORVs and steam dump valves.
	Bumping RCPs • If steam generator wide range level in any steam generator is less than 12%	• Establish SG water wide range level greater than 12% BEFORE Bumping RCPs in that loop • Open RCS vent paths
Containment flooding	All means of RCS injection with external water sources • If a large inventory of water will be injected, AND if there is an uncontrolled opening in the RCS. • determine vital equipment and monitoring capabilities that may be lost.	• Use pumps in ECCS recirculation mode to prevent containment water level increase. • Limit RCS injection flow to value determined by, to limit rate of containment water level increase.
Containment overpressure Severe challenge	**All means of RCS injection** • If MCCI is occurring • Containment pressure greater than 4.02 bar	• Stop injection to the RCS to limit containment pressure increase
Aux Building Habitability	**All Recirculation Pathways**	• Position portable shielding. • Evaluate impact on critical local actions. • Notify local work crews.
RCP Seal Degradation	**Bumping RCPs**	• None
Component corrosion	**All means of RCS injection with non reactor grade sources**	• Limit RCS injection flow • Switch RCS injection to a reactor grade water source, when sufficient inventory available
Fission product releases	**Using RWST gravity drain to RCS**	• Monitor RWST level and containment pressure, RWST gravity drain to RCS, to ensure no backflow. • Identify potential containment heat sinks