Insights from Development and Application of an EPR MELCOR Model

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Content

Model development actions

Model application

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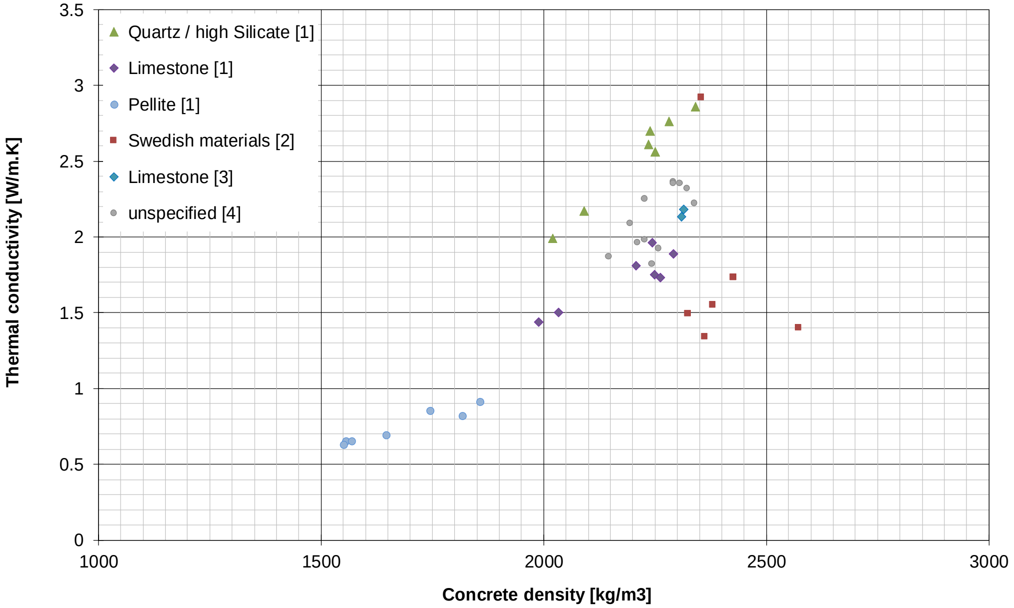
1. Containment Pressure & Concrete Thermal Conductivity

Containment Pressure & Concrete Thermal Conductivity (1of3)

- **Heat absorption by concrete walls is the dominant heat sink in the containment**
  - In case of accident, concrete properties have a significant impact on containment pressure
- **MELCOR standard concrete values**
  - $\rho = 2306.7\ kg/m^3$
  - $\lambda = 0.9344\ W/m.K$
- **Density ρ measurement for EPR-reactors**
  - $\rho = \sim 2500\ kg/m^3$ with low uncertainty
- **Thermal conductivity λ**
  - Depends on aggregate, density, measurement method, sample preparation, ...
  - Typically with higher density and the more silicate aggregate, the higher λ
  - Rebar increases conductivity further



[1] Modeling the Thermal Conductivity of Concrete Based on Its Measured Density and Porosity
https://web.ornl.gov/sci/buildings/conf-archive/1992%20B5%20papers/013.pdf
[2] Thermal properties of concrete with different Swedish aggregate materials
https://lup.lub.lu.se/luur/download?func=downloadFile&recordOId=4358448&fileOId=4358449
[3] Study on The Thermal Properties of Concrete Containing Ground Granulated Blast Furnace Slag, Fly Ash and Steel Reinforcement (wvu.edu)
https://researchrepository.wvu.edu/cgi/viewcontent.cgi?article=8540&context=etd
[4] Effects of Aggregate Types on Thermal Properties of Concrete [link]

Containment Pressure & Concrete Thermal Conductivity (2of3)

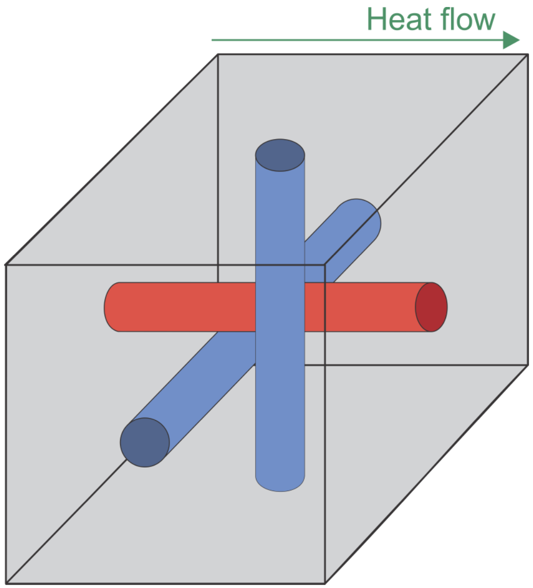
- **Impact of axial rebar on thermal conductance**
  - $\lambda_{\text{RebarConcrete}} \cdot \frac{A_{\text{Steel}}+A_{\text{Concrete}}}{Distance} = \lambda_{\text{Steel}} \cdot \frac{A_{\text{Steel}}}{Distance} + \lambda_{\text{Concrete}} \cdot \frac{A_{\text{Concrete}}}{Distance}$
  - $\lambda_{\text{RebarConcrete}}/\lambda_{\text{Concrete}} \sim 1 + 0.06 \cdot [\text{axial steel mass fraction in \%}]$

- **Impact of transverse rebar**
  - Measurement in Reference [3]
  - $\lambda_{\text{RebarConcrete}}/\lambda_{\text{Concrete}} \sim 1 + 0.01 \cdot [\text{tranverse steel mass fraction in \%}]$

- **Typical reinforcements**
  - ~5 mass% for unloaded in-containment structures
  - Up to 15 mass% for RPV support shield

- **Framatome choice of λ**
  - Low λ → conservative in p, optimistic in H_2
  - High λ → optimistic in p, conservative in H_2

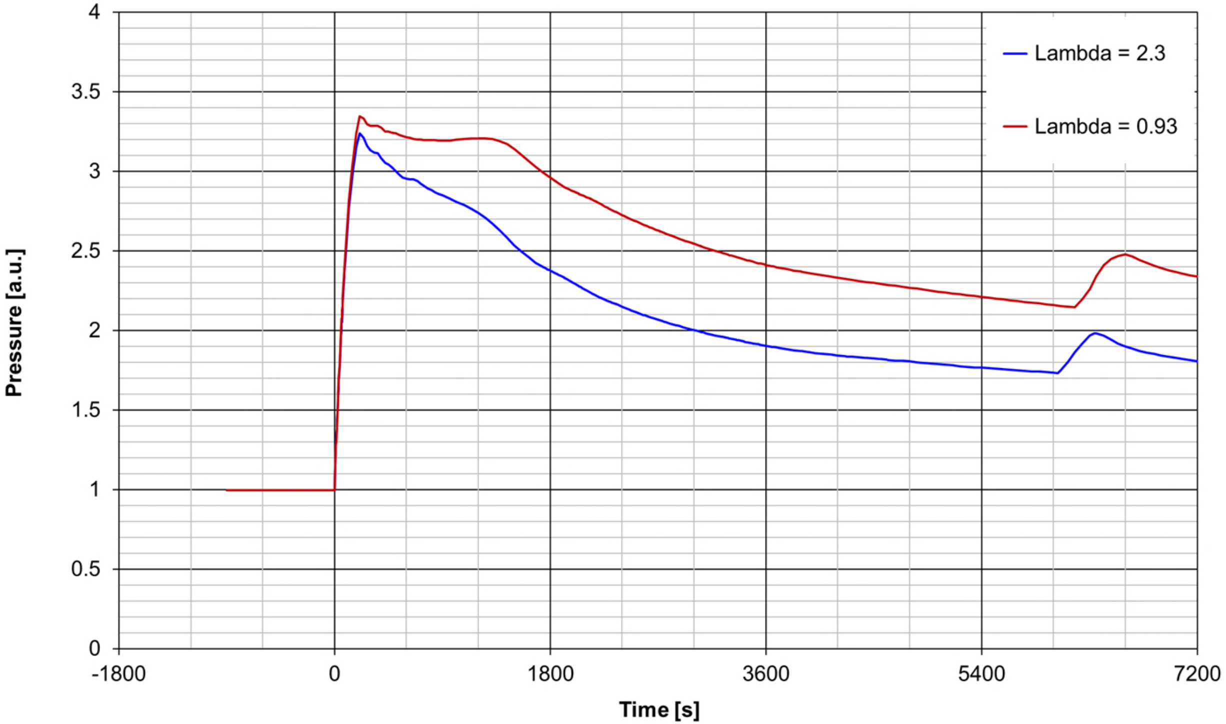
  → Balance between bounding and best-estimate thermal conductivity λ = 2.0 - 2.5 W/m.K



[3] Study on The Thermal Properties of Concrete Containing Ground Granulated Blast Furnace Slag, Fly Ash and Steel Reinforcement (wvu.edu)
https://researchrepository.wvu.edu/cgi/viewcontent.cgi?article=8540&context=etd

Containment Pressure & Concrete Thermal Conductivity (3of3)

- **Impact of concrete thermal conductance on containment pressure for a LB-LOCA**



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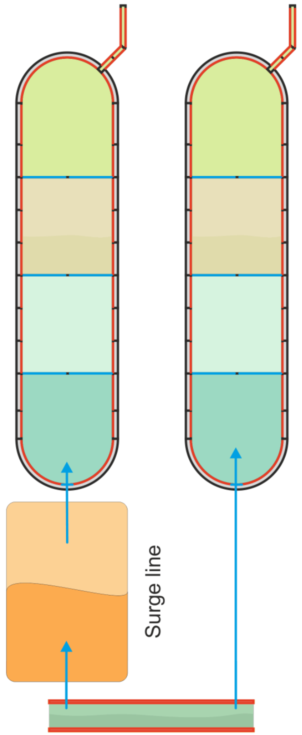
2. Surge Line Countercurrent Flow Limitation

Surge Line Countercurrent Flow (1of3)

- **During an accident like a LOCA at the pressurizer top, the pressurizer may or may not drain into the primary loop**
  - Steam wants to ascend upwards through the surge line
  - Water wants to drain downwards through the surge line
  - Gas-water countercurrent flow limitation

- **When surge line is represented as one flow path only**
  - FL_LME (Length for Pool/Atmosphere Momentum Exchange) can act as fit parameter
  - Simulation **runs stable**
  - Default FL_LME should not be blindly trusted, but seen as a starting point

- **When the surge line is itself a CV**
  - Representing the surge line as CV is beneficial when wanting to examine a possible creep rupture failure
  - The existence of the CV, and thus the phase separation within already couples the flows of steam and water
  - Often becomes **numerically instable** (it is expected to be a physically unstable situation)

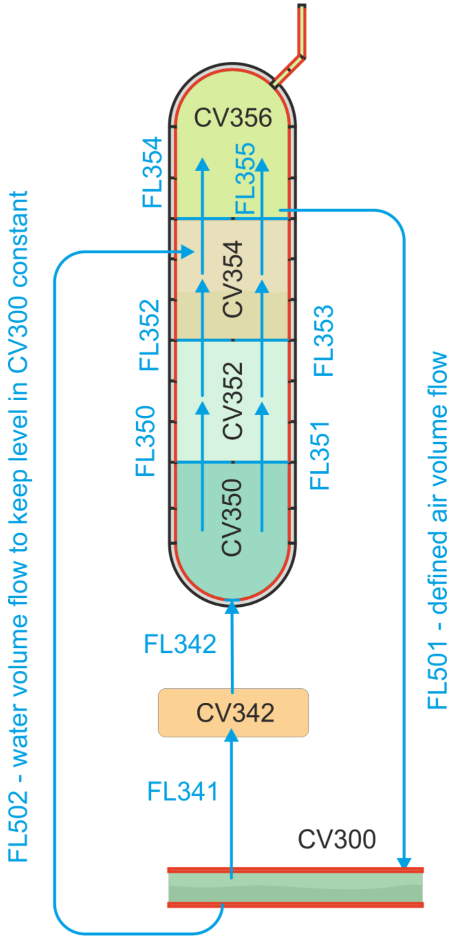


Surge Line Countercurrent Flow (2of3)

- **Cut-out the pressurizer into a MELCOR-test-model to find a modelling that**
  - Is numerical stable
  - Shows similar flow limitation as in experiments

- **Relevant scale experiments [217] show, the flow limitation occurs mostly at the pipe → pressurizer exit**

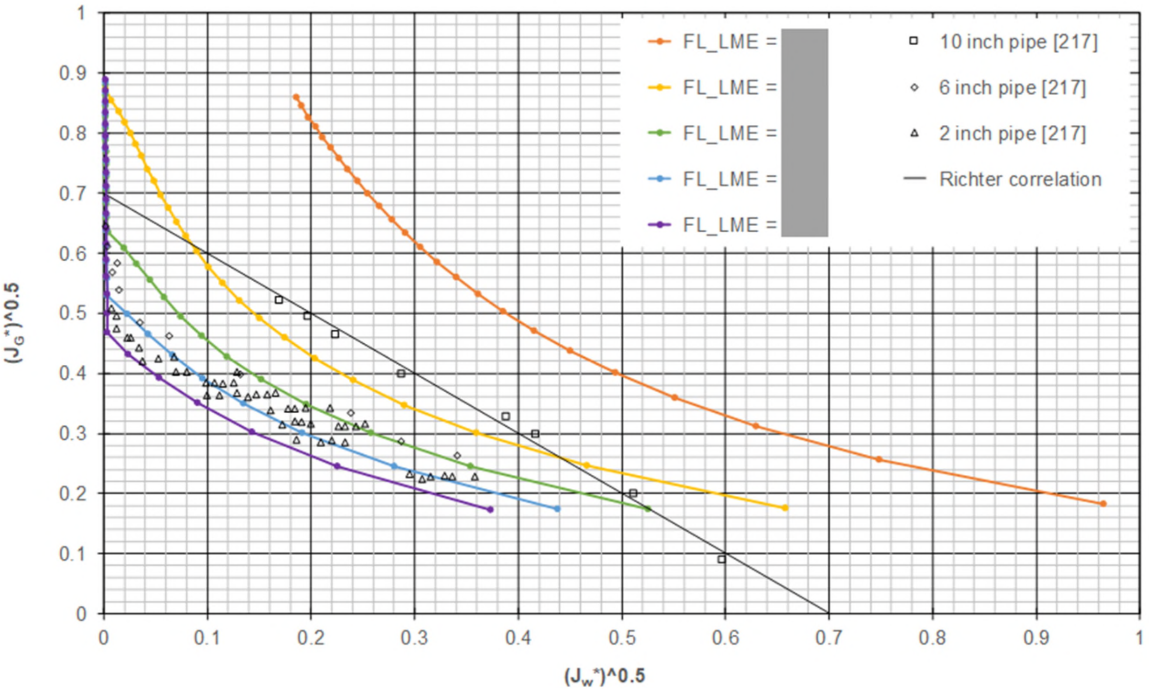
- **Framatome modeling**
  - FL341 has a to opening height **FL_JLT** over the entire surge line volume CV342
  - FL342 has a from opening height **FL_JLF** over the entire surge line volume CV342
  - The CC flow limitation thus occurs only at the entry to the pressurizer
  - The momentum exchange length **FL_LME** of both FL is set equal and used as a fit parameter

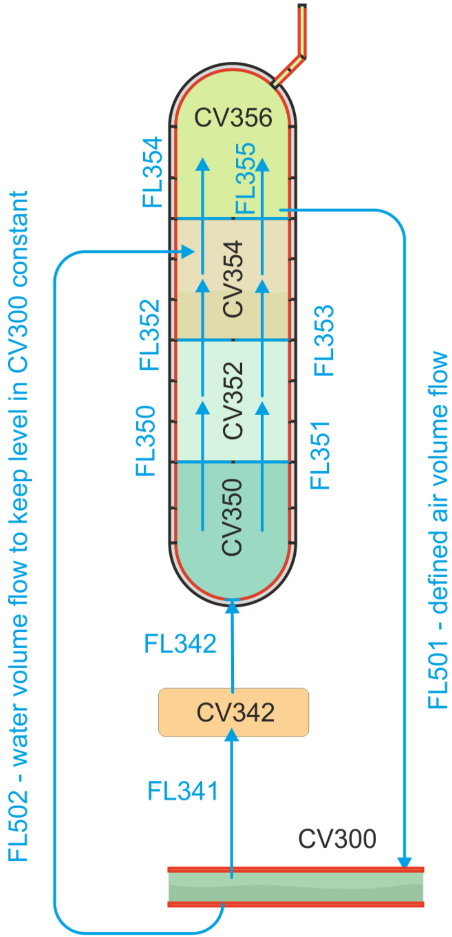


[217] Countercurrent Flow Limitation Experiments and Modeling for Improved Reactor Safety, https://www.osti.gov/servlets/purl/938628

Surge Line Countercurrent Flow (3of3)

- **Simulation results in comparison to the data obtained by Richter [217] for different FL_LME**





[217] Countercurrent Flow Limitation Experiments and Modeling for Improved Reactor Safety, https://www.osti.gov/servlets/purl/938628

3. MCCI-related Code-to-Code Comparison

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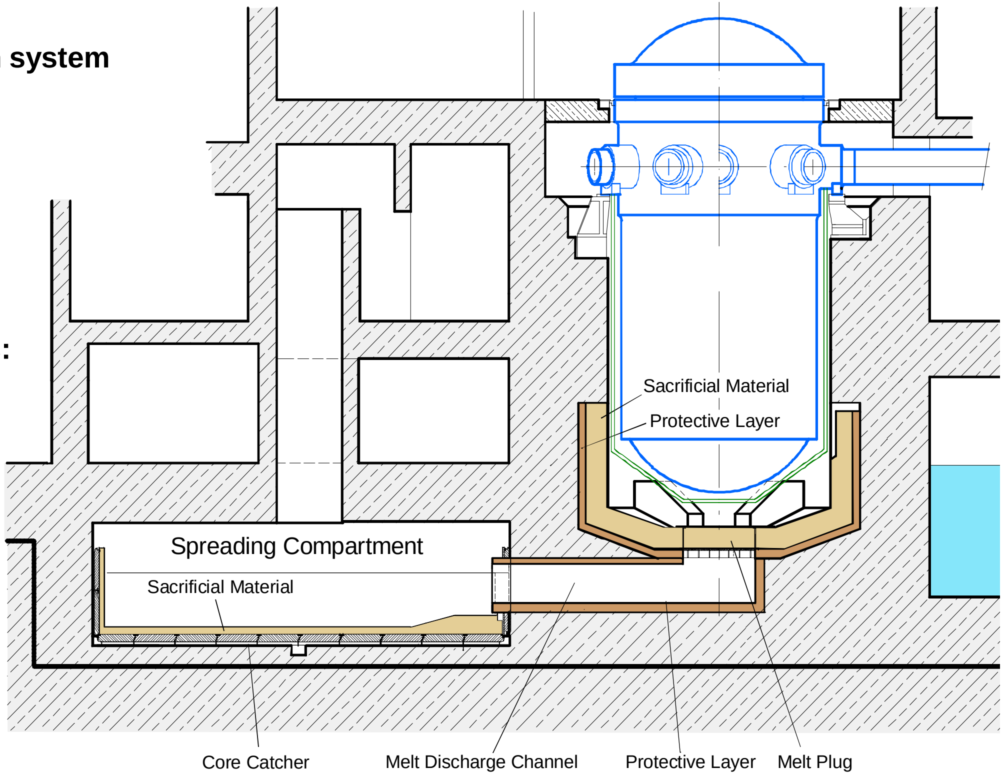
MCCI-related Code-to-Code Comparison (1of5)

- **EPR is equipped with dedicated core melt stabilization system**
  - Core melt conditioning in the reactor pit by MCCI with sacrificial concrete
  - After certain axial erosion → Melt plug breach
  - Spreading of conditioned melt in core catcher
  - Flooding & quenching of the core melt

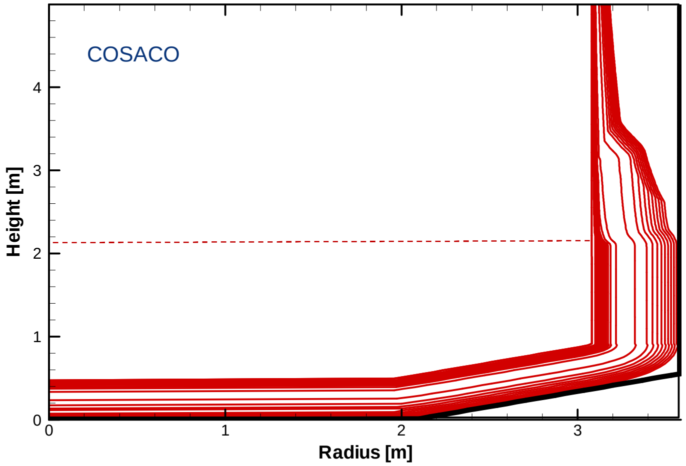
- **System design is based on simulations with the codes:**
  - In-vessel & RPV failure with **MAAP**
  - MCCI-phase in the pit with **COSACO**
  - Spreading, quenching & cooling in the core catcher by others

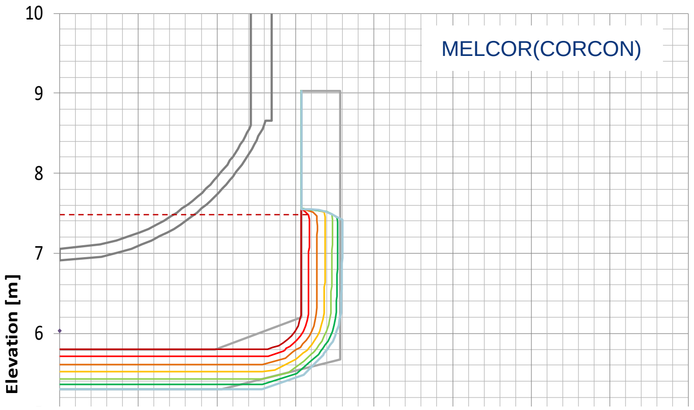


MCCI-related Code-to-Code Comparison (2of5)

- **Code-to-code comparison COSACO with MELCOR in the frame of simulation consolidation**
  - COSACO delays onset of MCCI as long as the core melt viscosity is too low for convective heat transport out of the melt
  - MELCOR does not consider a convective limitation of heat transport

  - COSACO predicts concrete erosion above the collapsed core melt liquid level by void formation & thermal radiation
  - MELCOR only considers heat transfer at direct contact surface of concrete and melt (without void)





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MCCI-related Code-to-Code Comparison (3of5)

- **CCI-experiments [12] show concrete erosion above collapsed (solidified) melt → supporting the COSACO point of view**
- **For the EPR - MELCOR likely under-predicts ...**
  - the amount of sacrificial concrete eroded until melt-plug breach and spreading of melt in core catcher (due to cavity shape)
  - the time until spreading (by onset criteria for MCCI)

1.) Despite the identified differences, key quantities like melt viscosity (→ spreading) correspond well between codes

2.) EPR core melt stabilization system is sufficiently robust to comply with either simulation results

3.) Overall, in-vessel uncertainties (MELCOR-MAAP) dominate over the ex-vessel simulation differences

[12] OECD MCCI Project 2-D Core Concrete Interaction (CCI) Tests: Final Report
tps://www.tepco.co.jp/en/hd/decommission/information/newsrelease/reference/pdf/2022/reference_20220210_01-e.pdf

MCCI-related Code-to-Code Comparison (4of5)

Insights from Fukushima

- **Exploration of FKS Daiichi Unit 1 primary containment vessel 02.2022 [9]**
  - Pedestal opening - entrance to the CRD drive room
  - ~0.5m thick debris (melt) layer on floor
  - Complete concrete destruction with exposed wall rebar for another ~0.5m above debris layer

- **Hypothesis 1: MCCI – but why does the rebar remain standing**

- **Hypothesis 2: Steam explosion (appears unlikely)**

- **Hypothesis 3: Fire spalling**
  - Concrete temperatures significantly above saturation condition
  - Free water vaporizes in closed pores → internal pressure buildup
  - Fracturing the concrete
  - Frequently observed in fires in rebar-concrete buildings [11]
  - low permeability → high-density promotes spalling

[9] Implementation Status of the Unit 1 PCV Internal Investigation (As of February 10) at the FKS1 NPP
tps://www.tepco.co.jp/en/hd/decommission/information/newsrelease/reference/pdf/2022/reference_20220210_01-e.pdf
[11] Spalling of Concrete in a Fire
https://www.youtube.com/watch?time_continue=3&v=xbFzMnSBp1o&feature=emb_logo&ab_channel=TylerLey

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MCCI-related Code-to-Code Comparison (5of5)

Why does fire spalling not occur in MCCI experiments?

- **Experiments**
  - Performed on time scale of minutes to few hours
  - Very high heat fluxes (thermite reaction / inductive heating)
  - Very steep thermal gradient in the concrete
  - → Dominant surface erosion / melting of concrete & rebar

- **FKS Unit 1 accident**
  - Occurred in time scale of many hours / days
  - Likely with moderate heat fluxes (melt spreading, temporary water injections)
  - Deeper reaching / shallow temperature gradient in the concrete
  - → Mechanical destruction of concrete by spalling, rebar remains intact

Fukushima Unit 1 [9]

CCI experiments [10]

[9] Implementation Status of the Unit 1 PCV Internal Investigation (As of February 10) at the FKS1 NPP
tps://www.tepco.co.jp/en/hd/decommission/information/newsrelease/reference/pdf/2022/reference_20220210_01-e.pdf
[10] The Most Dangerous (Man-Made) Lava Flow
https://www.wired.com/2013/04/the-most-dangerous-manmade-lava-flow/

4. Framatome Emergency Response Team Support

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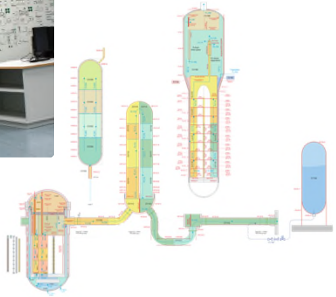
Framatome Emergency Response Team Support (1of5)

Emergency Response Team Support - Consulting Services and Engineering Solutions [link]

- **Off-site support for the plant Emergency Response Team (ERT)**
  - Framatome OEM plants
  - Centers in Paris & Erlangen
  - 24-7 readiness

- **Regular internal and external drills**
  - Test alarm chain
  - Improve knowledge (system-related and accident-related)
  - Training of remote communication / information sharing

- **Drill preparation**
  - When focus of drill lies in already evaluated accidents
    → full-scope plant simulator
  - When focus lies in complex design-extension conditions or radiological questions
    → engineering simulator (MELCOR)

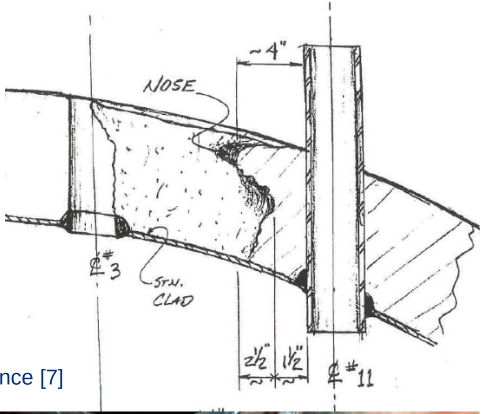


Framatome Emergency Response Team Support (2of5)

Drill: LOCA at RPV Head – “Davis Besse”-like Scenario

- **Assumed accident situation**
  - Control rod ejection from RPV head → DN100 hole
  - No positive core reactivity change as in normal operation, rods are retracted
  - Loss of coolant from RPV head to reactor cavity room above the RPV
  - Assumed secondary damage leads to partial loss of core instrumentation
  - → Not directly a design-base accident in the sense of the FSAR

- **Tasks for the ERT Support**
  - Identification of accident situation based on available measurements (pressure, temperature, ...)
  - Does RPV head leakage affect LOCA procedures in the manual?
  - How far will water level in cavity rise and IRWST drop?
  - Does IRWST water level drop endanger safety injection pumps by cavitation?
  - Why did the reactor cavity suddenly drain?
  - What are recommendations for normalizing the plant conditions?



See Reference [7]

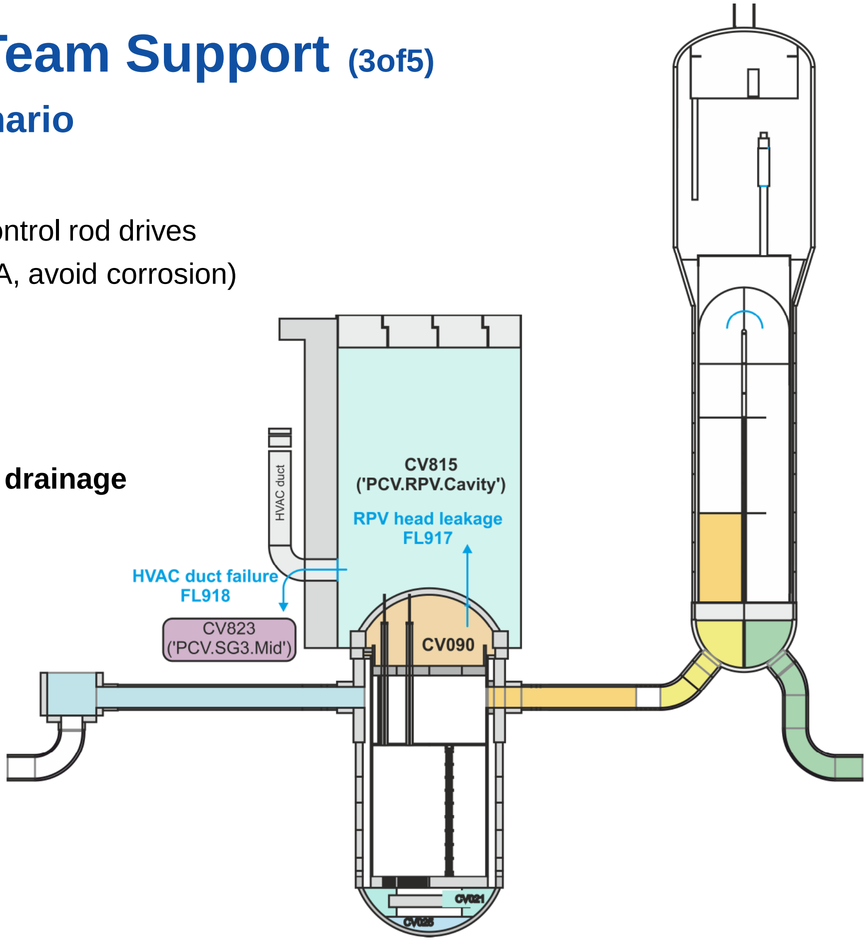
[7] Davis-Besse Reactor Vessel Head Degradation
https://www.nrc.gov/reactors/operating/ops-experience/vessel-head-degradation.html

Framatome Emergency Response Team Support (3of5)

Drill: LOCA at RPV Head – “Davis Besse”-like Scenario

- **Reactor Cavity Ventilation**
  - Cavity must be ventilated in normal plant operation to cool the control rod drives
  - Cavity must be drained to avoid condensate accumulation (LOCA, avoid corrosion)
  - Cavity must be water-tight for fuel outage
  - Various ventilation ducts / drainage pipes are opened / closed by water-tight door in different plant states

- **For the EPR: In case the RPV head LOCA over-whelms the cavity drainage**
  - The reactor cavity can be completely filled without endangering the ECCS suction from the IRWST
  - Control rods fail passive-safely if at all (rods in)
  - Water likely will cause a failure of a HVAC duct (which is not designed to hold the water mass)



Not a design-base accident, even though plant always remains in a safe state – but challenging for the ERT support to gain a clear picture of the accident situations (reason this scenario was chosen)

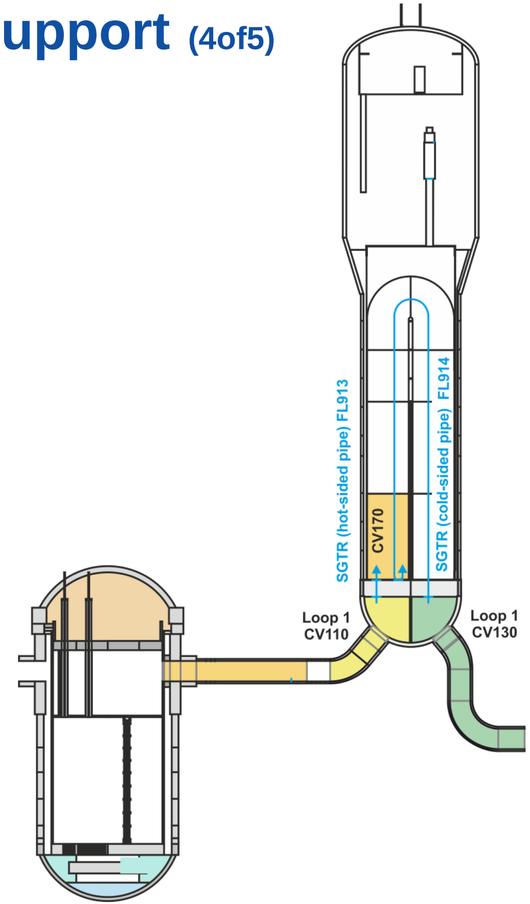
Framatome Emergency Response Team Support (4of5)

Drill: SGTR after Cladding Damage

- **Situation**
  - Cladding damage occurred during power operation
  - 10 fuel rods, dissolving 10% I_2 & Xe, and 1% Cs into primary coolant [8]
  - During plant shutdown, SGTR occurs, indirectly causing loss of offsite power
  - Stuck-open main steam relief valve causes release into environment

- **Tasks for the ERT Support**
  - Radiological estimates (Xe dominates as re-entrainment of aerosols is small)
  - Recommendations for normalizing the plant conditions

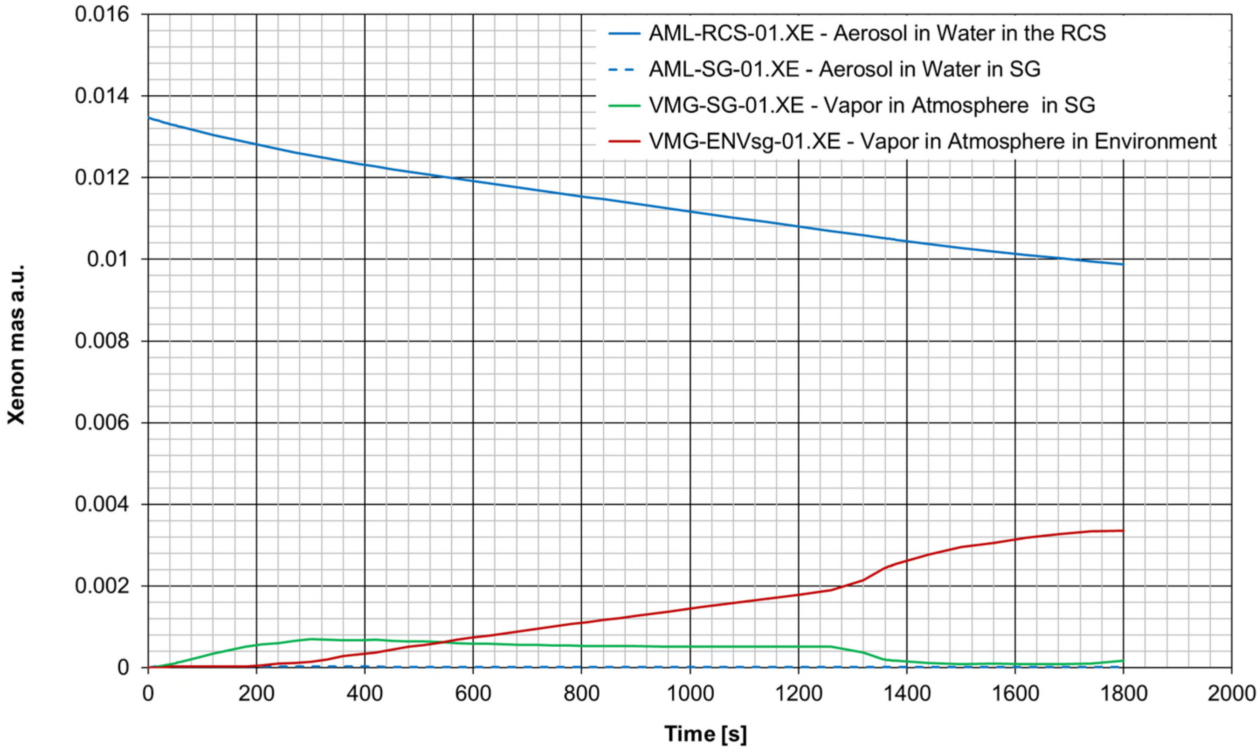
- **Challenge in MELCOR: water dissolved Xe cannot be simulated**
  - Gaseous FP gas-out of liquid within minutes
  - Solution: initially, add Xe as aerosol to RCS water (**RN1_AL**)
  - Xe-aerosols are transported by water loss into the SG
  - In SG, where boiling drives out dissolved gases,
    remove the aerosols (**RN1_AS**, can be assigned a negative rate)
    and add vapor (**RN1_VS**)



[8] Supplementary reading: Brennstoffdefekte und Gegenmassnahmen - Die Erfahrung des KKL
https://www.researchgate.net/publication/261992251_Brennstoffdefekte_und_Gegenmassnahmen_-_Die_Erfahrung_des_KKL

Framatome Emergency Response Team Support (5of5)

Drill: SGTR after Cladding Damage



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