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MELCOR Applications to SOARCA and Fukushima

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Topics for discussion

- Background
- Overview of Fukushima Accidents
- Comparisons of SOARCA Study with Fukushima accidents
- Equipment functioning in real-world accidents
- Conclusions

SNL Fukushima MELCOR Reactor Models

U.S.NRC

State-of-the-Art Reactor Consequence Analyses Project

Volume 1: Peach Bottom Integrated Analysis

- BWR Mk-I model from the NRC's State-of-the-Art Consequence Analysis (SOARCA) project used as a template
  - 20+ years of BWR model R&D
  - Current state-of-the-art/best practices
- Incorporated reactor-specific information into the template to create Fukushima reactor models
- Developed surrogate information for unavailable Fukushima information
- Analyses performed using MELCOR 2.1

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The Accidents

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Earthquake Led to Loss of Offsite Power

- Seismic events disrupted roads and power lines
- Regional blackout isolated Fukushima station from power grid
- Reactors shut down
- Site operated by onsite diesel generators

Circuit Breaker damaged

Used by permission from TEPCO
Kenji Tetawa

Collapsed tower

Daiichi Site was Inundated

Used by permission from TEPCO

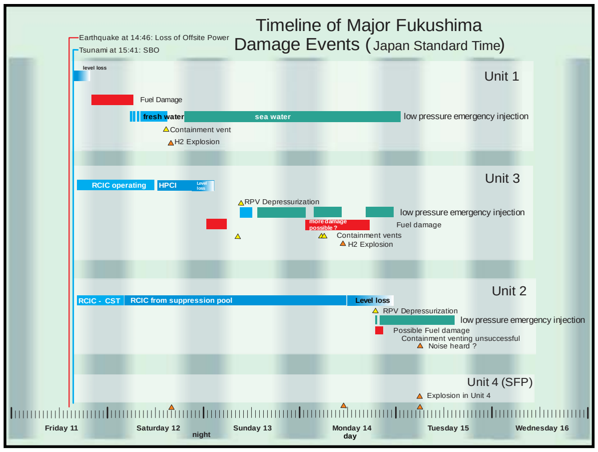
- Site flooding initiated “Station Blackout”
  - Diesel generators flooded
- Unit 1 lost all power (AC/DC) and had no ECCS available
- Unit 2 lost all power, but RCIC ran uncontrolled
- Unit 3 maintained some DC and ran RCIC and HPCI systems
- All reactors isolated from ultimate heat sink (Ocean)

Mark-I Containment

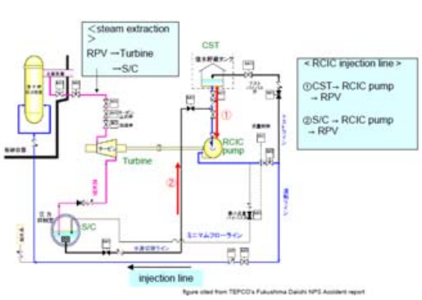
NRC Training Manual

Browns Ferry from Wikipedia

Timeline of Major Fukushima Damage Events (Japan Standard Time)



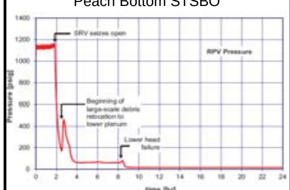
Unit 2 and 3 Has RCIC and HPCI

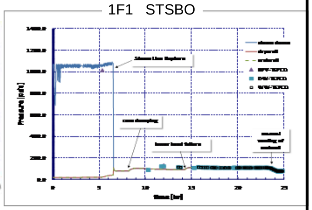


- RCIC is turbine driven pump
- Steam drawn from RPV and exhausted to suppression pool
- Water drawn from CST or suppression pool

SOARCA PEACH BOTTOM VERSUS FUKUSHIMA ACCIDENTS

Comparison of SOARCA PB-STSBO with 1F1

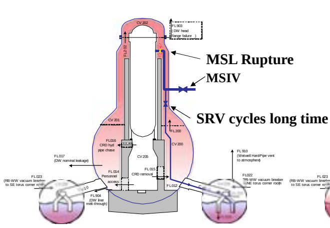




- SBO at start of accident
- Core damage by 1 hour
- SRV seizure just before 2 hours
- Core slumping by ~2.5 hours
- Lower head failure ~8.5 hours
- MCCI and Dry well liner failure ~8.5 hours+

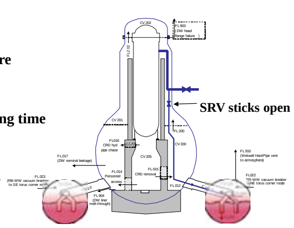
- SBO at ~1 hour due to tsunami
- Core damage at ~4 hours
- MSL rupture at ~ 6.5 hours
- Core slumping by ~8 hours
- Lower head failure ~12.5 hours
- MCCI and DW head flange leak ~12.5 hours+
- No liner failure evidence in DW pressure trend

SRV Seizure Versus MSL Rupture



Main Steam Line Rupture vents
Fission products to drywell

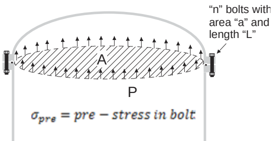
Release to environment via head
Flange failure or drywell liner melt through



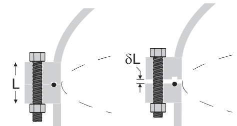
SRV Seizure vents fission products
Into wetwell

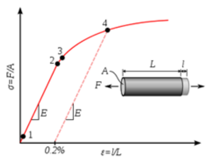
Wetwell scrubbing prevents release
To the environment

Drywell Head Pressure Response



$\sigma_{pre} = pre - stress\ in\ bolt$





$$\sigma_{bolt} = \frac{P \cdot A}{n \cdot a} \qquad \varepsilon = \frac{\sigma}{E} = \frac{\delta L}{L} \qquad \delta L = \frac{\sigma \cdot L}{E}$$

$$\delta L(P) = \frac{[\sigma(P) - \sigma_{pre}] \cdot L}{E}$$

$$A_{leak} = \pi D \cdot \delta L(P)$$

Drywell Pressure

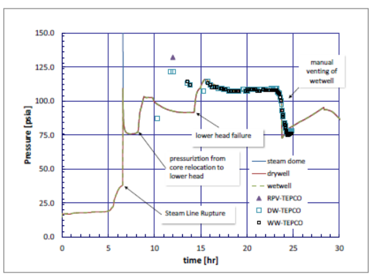
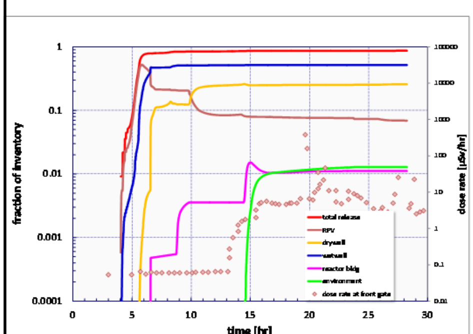


Figure 44 MELCOR-predicted containment pressure during the MCCI gas generation phase up to the point of manual containment venting.

Cs Release 1F1

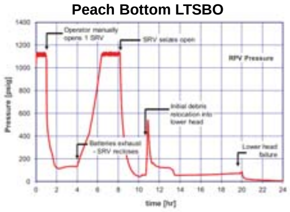


Radiation monitors at front gate jump at ~13 hr

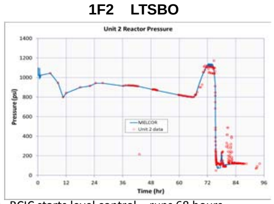
Cs Env calculated release about 400,000 Ci

SOARCA PB LTSBO vs 1F2

Peach Bottom LTSBO



1F2 LTSBO

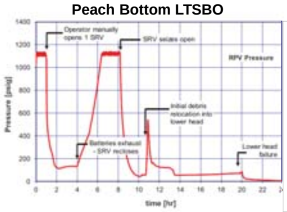


- RCIC starts level control
- Operator SRV control on pressure
  - RCIC controlling level
- Battery depletion @4 hours
  - SRV closes and RCIC runs full on
  - MSL floods and RCIC assumed to fail
- Water level loss and core damage
- Time to core slump – 7 hrs after RCIC fails

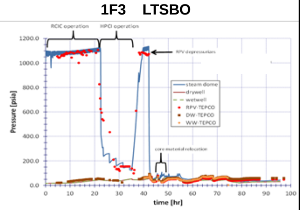
- RCIC starts level control – runs 68 hours (uncontrolled due to SBO after 1 hour)
- RPV overfilling passes 2-phase water to turbine
  - Enthalpy removal set to match RPV pressure
  - Cyclic turbine response proposed
- RPV re-pressurizes following RCIC failure
- Water level loss, manual SRV open, reflood
- Time to core slump – ~5 hrs after RCIC fails

SOARCA PB LTSBO vs 1F3

Peach Bottom LTSBO



1F3 LTSBO



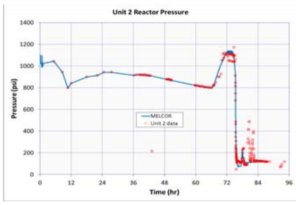
- RCIC starts level control
- Operator SRV control on pressure
  - RCIC controlling level
- Battery depletion @4 hours
  - SRV closes and RCIC runs full on
  - MSL floods and RCIC fails
- Water level loss and core damage
- Time to core slump – 7 hrs after RCIC fails

- RCIC starts level control – runs 21 hours
- Operators keep RPV pressure high
  - RCIC controlling level
- HPCI run continuously using bypass mode until failure @ ~35 hours
- Water level loss, manual SRV open
- Time to core slump – 10 hrs after HPCI fails

Summary of SOARCA-Fukushima Comparisons

- SOARCA BWR analyses included STSBO and LTSBO and were performed *before* Fukushima accidents
  - Both sequence types were observed in Fukushima accidents
  - These accidents are classic and among the collection of "usual suspects"
- While variants of STSBO and LTSBO are observed
  - Striking similar trends and operator responses
- More information to come from post-accident decommissioning activities
  - MSL creep rupture, SRV seizure, Liner failure
- Equipment performance brings new insights into realistic operation as seen in following slides

Long Term RCIC Operation

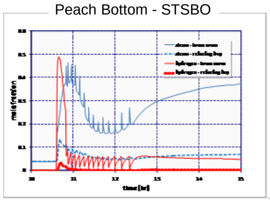


- RCIC pump is driven by "Terry Turbine"
- Robust design tolerates wet steam (i.e. water/steam)
- Prior assumptions held that steam line flooding would kill RCIC
- 1F2 experience shows otherwise
- Should this be modeled in safety analyses ?

RPV pressure drop caused by large 2-phase enthalpy flow through robust Terry turbine

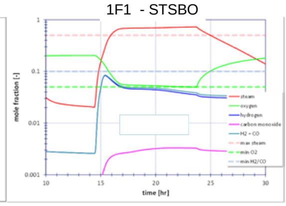
Hydrogen Behavior

Peach Bottom - STSBO



- Source to reactor building via liner failure – torus room
- H_2 burns in torus room
- Blowout panels are calculated to "blown out"
- True building damage not assessed

1F1 - STSBO



- Source to reactor building via DW head flange leak
- H_2 explodes in refueling bay after flammable conditions are attained
- Building damage evident

Damage from Explosions

Used by permission from TEPCO
Kenji Tetawa

Conclusions on Hydrogen Comparison

- Containment failure mode affects hydrogen behavior and has implications on hydrogen control
  - Liner failure releases hydrogen low in building
    - Uncontrolled release
  - DW head flange releases hydrogen to refueling bay
    - Release can be controlled by venting via hardened/reliable vent path
- Flammability or detonability affected by steam content and condensation
- MCCI progression is very important
  - Produced liner failure in PB but probably not in 1F1
  - MCCI calculated to sustain containment over-pressure in 1F1

Conclusions

- SOARCA STSBO and LTSBO were analyzed prior to Fukushima accidents
  - Real-world Fukushima accidents appear to be slight variants on SOARCA studies
  - While more data is forthcoming, comparisons are very encouraging
- RCIC and HPCI operation at Fukushima showed differences in idealized (modeled) performance
  - Equipment proved more robust than thought
- Potential bifurcation points in accident progression
  - MSL rupture versus SRV seizure
  - Containment liner failure versus DW head flange leak
- Hydrogen threat to reactor buildings is clear from Fukushima accidents
  - Burns/explosions could be either low in building or high in building
  - DW head flange leak can be controlled by venting via hardened pathway
  - Liner failure leak path is uncontrolled
- SOARCA is a methodology
  - Safety can be further increased by using computer codes (MELCOR/MAAP) to characterize accidents and potential mitigative actions