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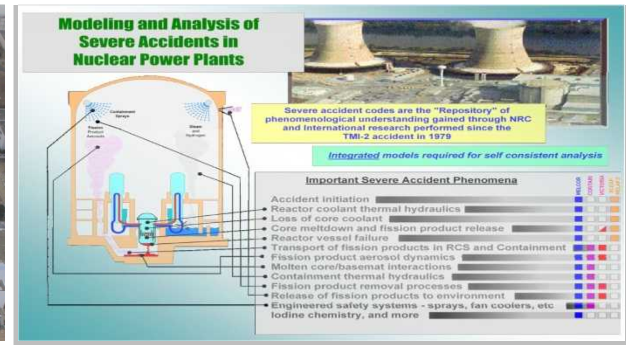
Source: Tokyo Electric Power Company



MELCOR Applications to SOARCA and Fukushima

Presented at the USNRC Regulatory Information Conference – RIC2014

March 13, 2014

Randall O. Gauntt – Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7110, Vol. 1

State-of-the-Art Reactor Consequence Analyses Project

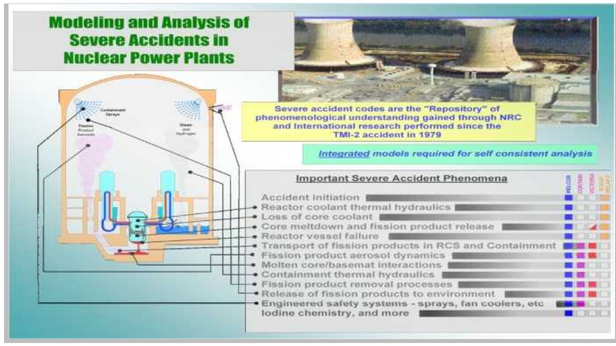
Volume 1: Peach Bottom Integrated Analysis

Manuscript Completed: January 2012
Date Published: January 2012

Prepared by:
Sandia National Laboratories
Albuquerque, New Mexico 87185
Operated for the U.S. Department of Energy

- 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

Source: Tokyo Electric Power Company



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

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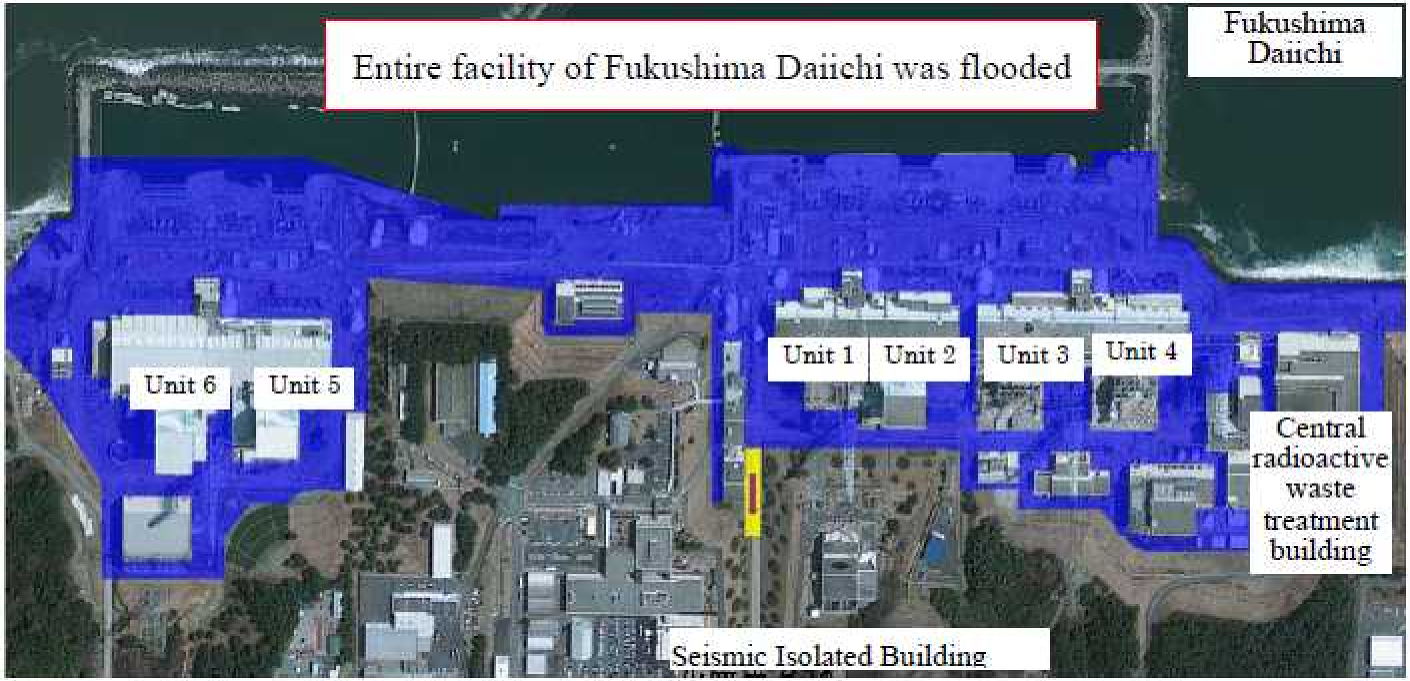
Kenji Tetawa

Collapsed tower

Daiichi Site was Inundated



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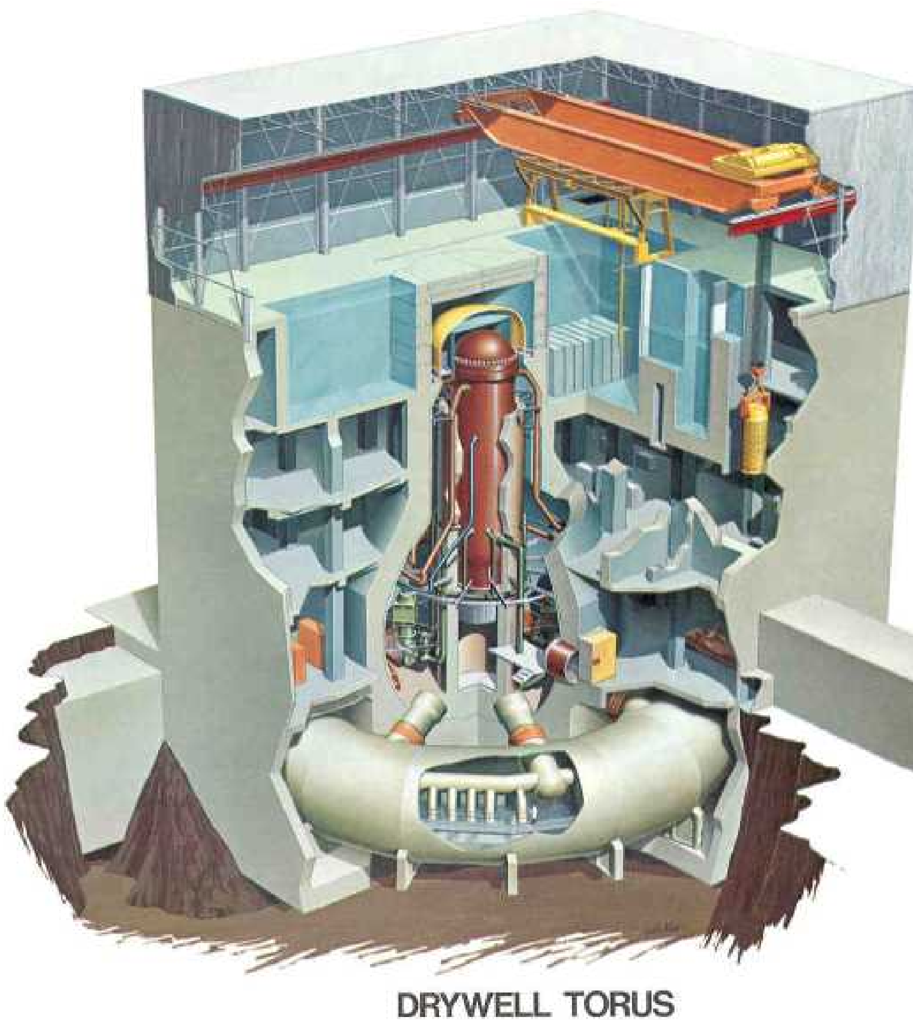
- Site flooding initiated “Station Blackout”
  - Diesel generators flooded
- Unit 1 lost all power (AC/DC) and had no ECCS available
- Unit 2 lost all power, but RCIC ran uncontrolled
- Unit 3 maintained some DC and ran RCIC and HPCI systems
- All reactors isolated from ultimate heat sink (Ocean)

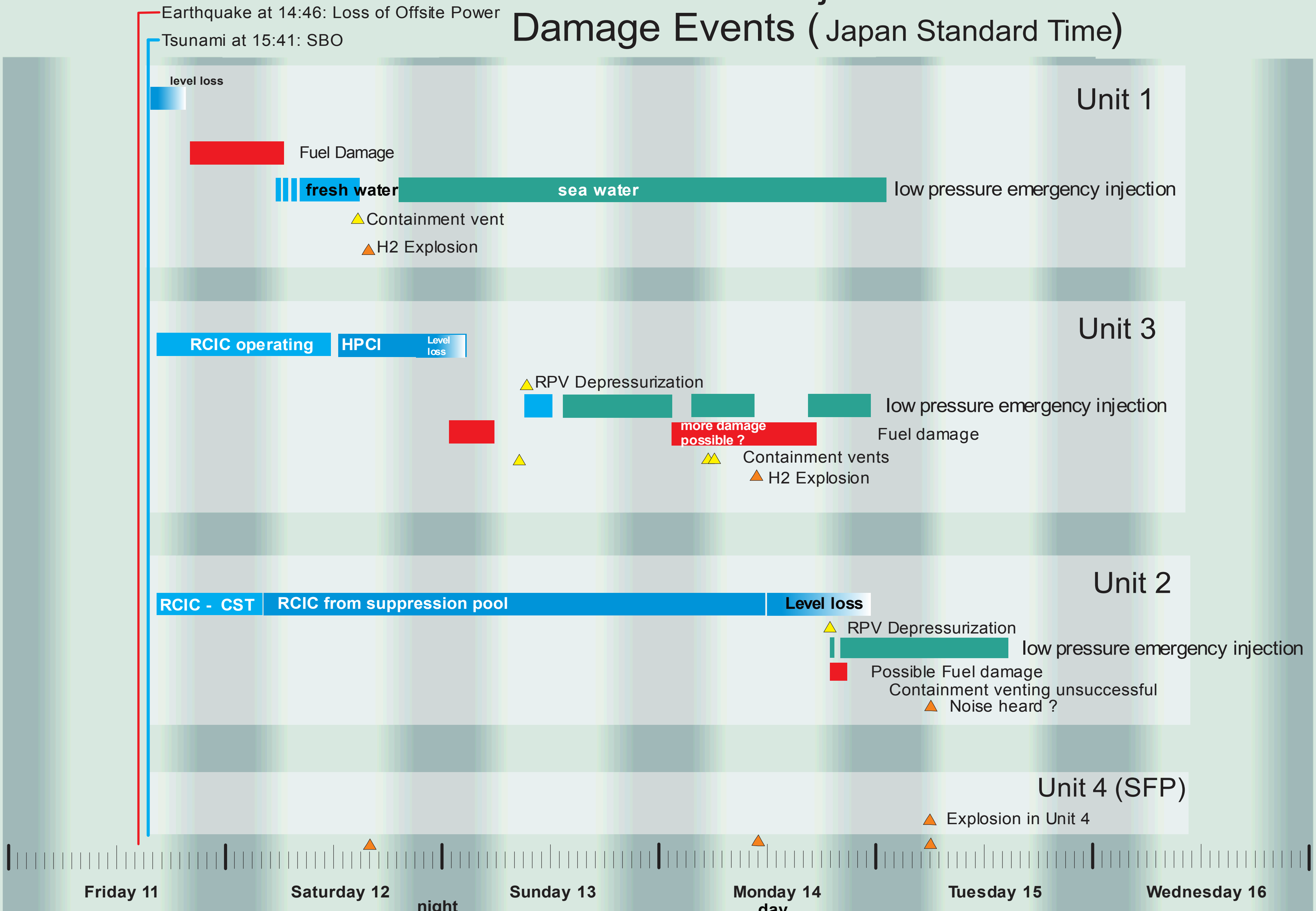
Mark-I Containment



NRC Training Manual

Browns Ferry from Wikipedia

Timeline of Major Fukushima Damage Events (Japan Standard Time)



Unit 1 Isolation Condenser

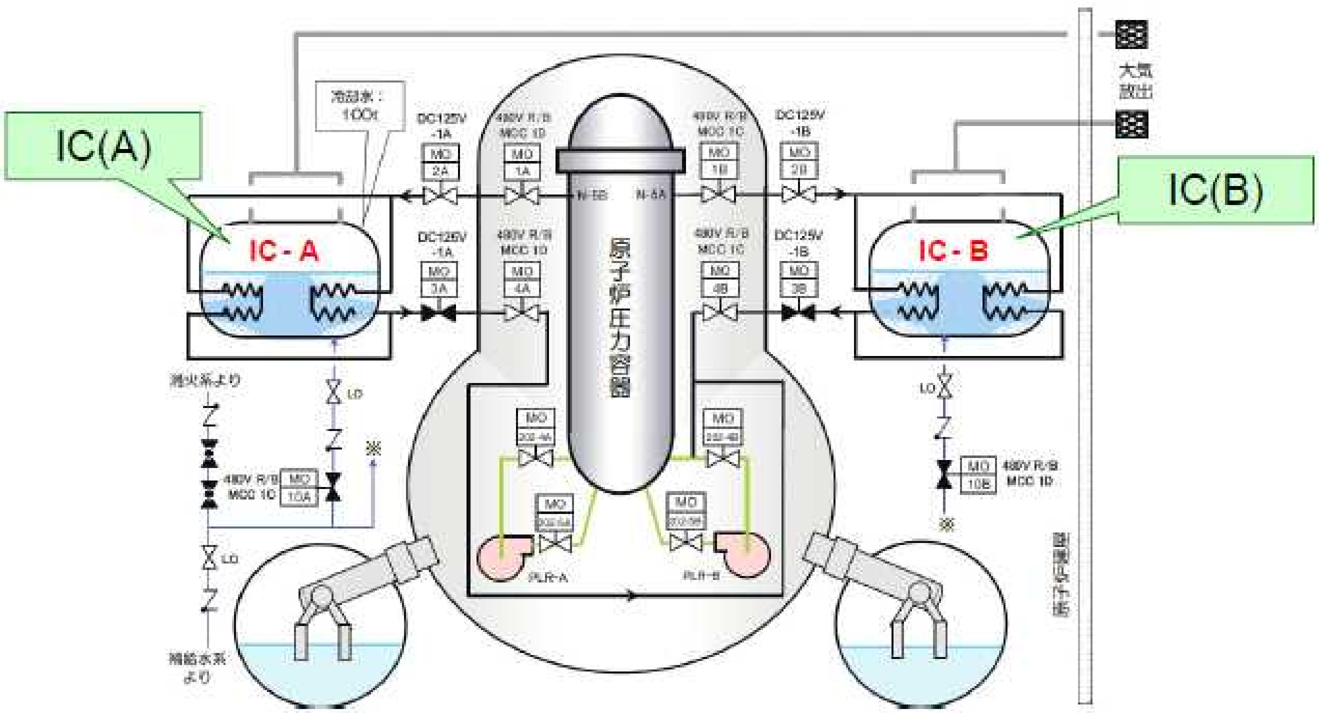


figure cited from TEPCO's Fukushima Daiichi NPS Accident report

- In older BWR models
- Steam from RPV condensed in IC
- Returned to RPV
- Capable of rejecting decay heat
- Operated by opening return valve

Unit 2 and 3 Has RCIC and HPCI

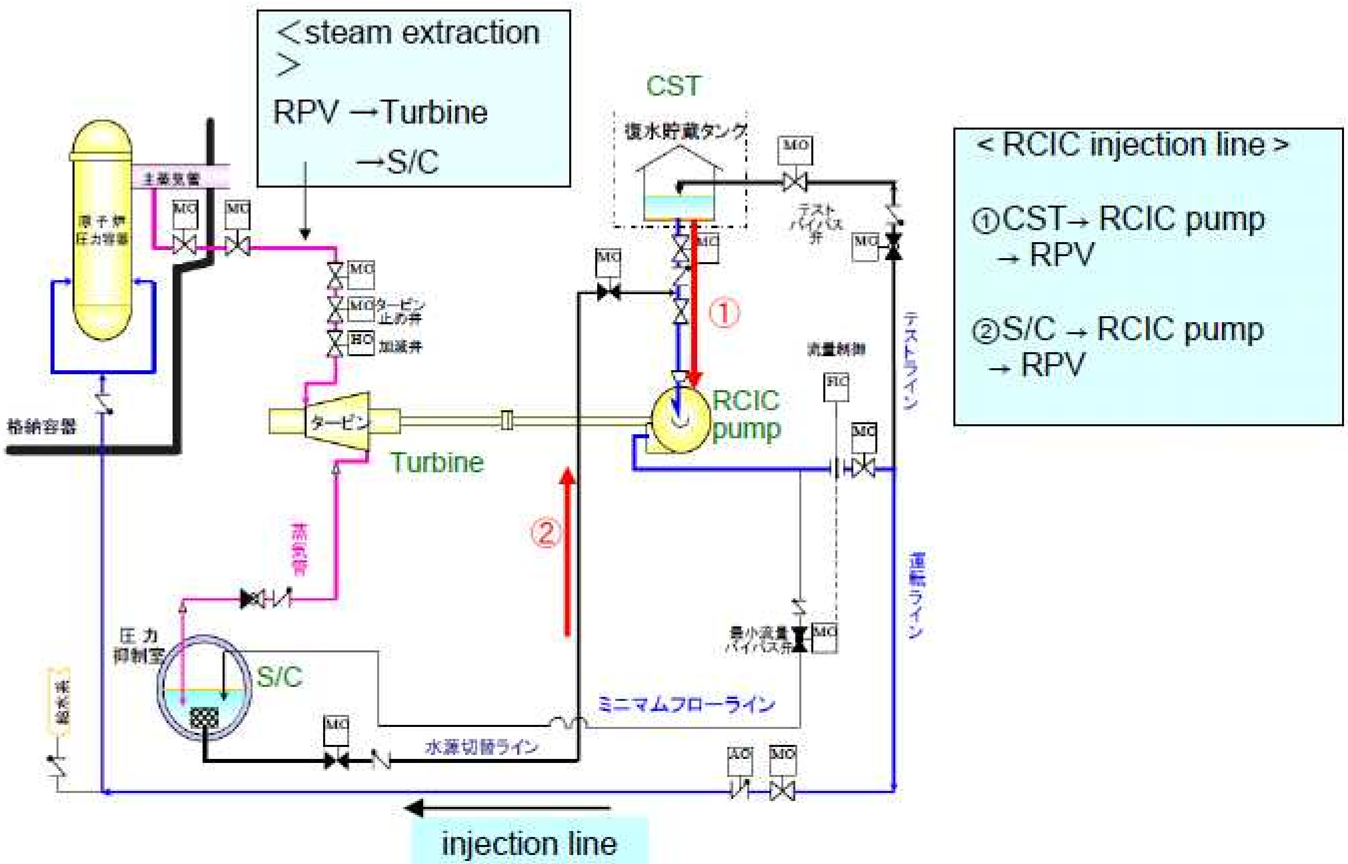


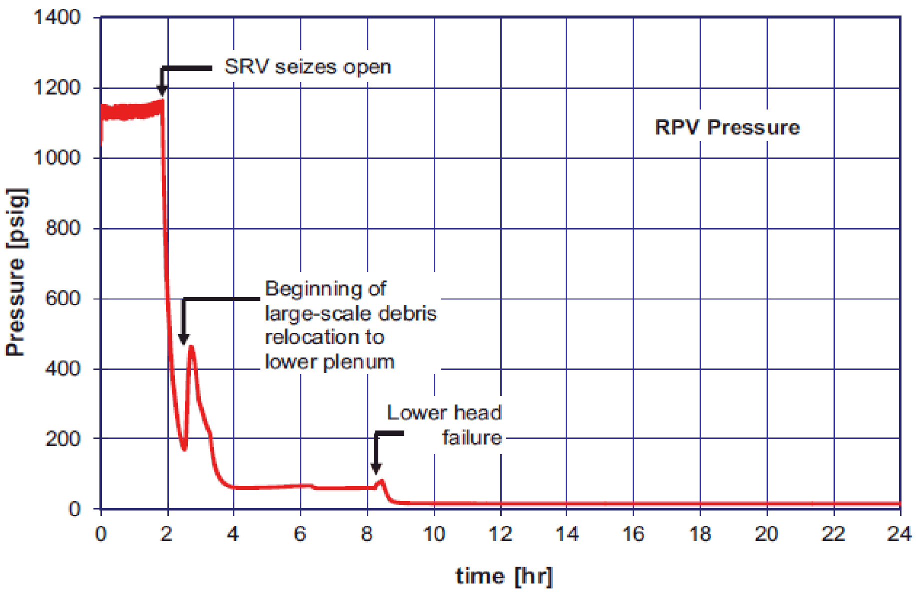
figure cited from TEPCO's Fukushima Daiichi NPS Accident report

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

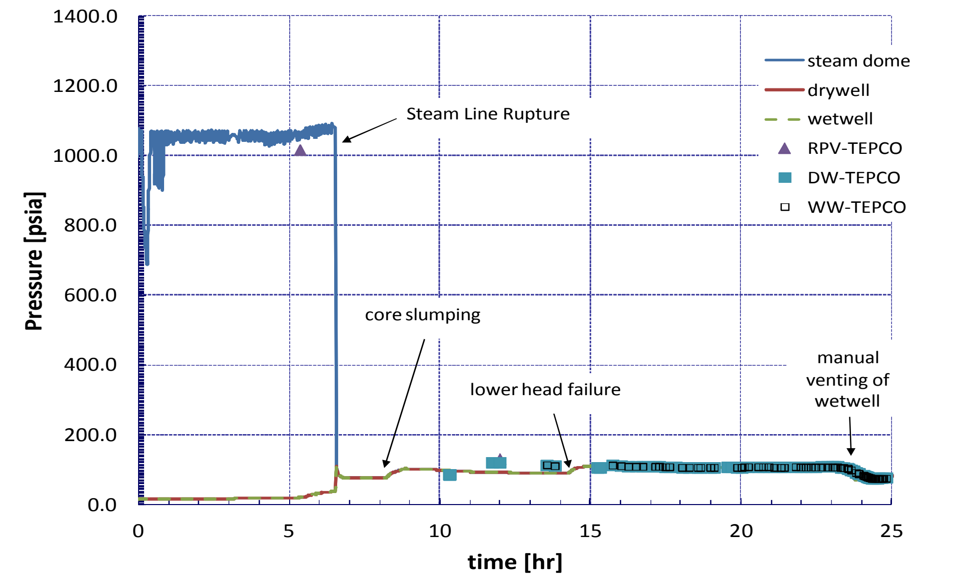
SOARCA PEACH BOTTOM VERSUS FUKUSHIMA ACCIDENTS

Comparison of SOARCA PB-STSBO with 1F1

Peach Bottom STSBO



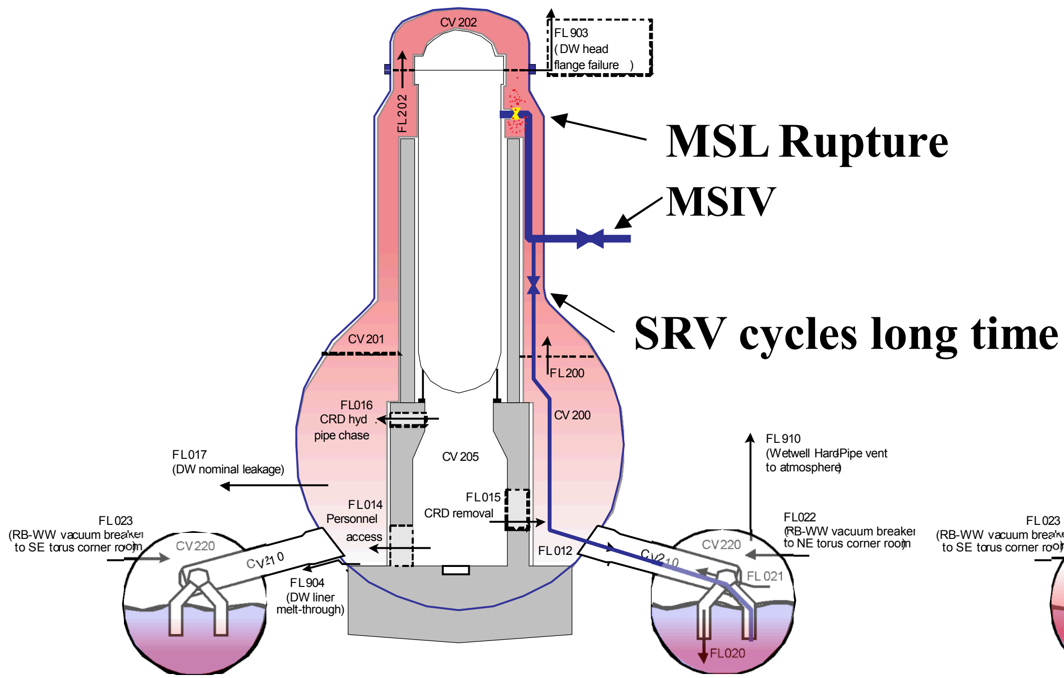
1F1 STSBO

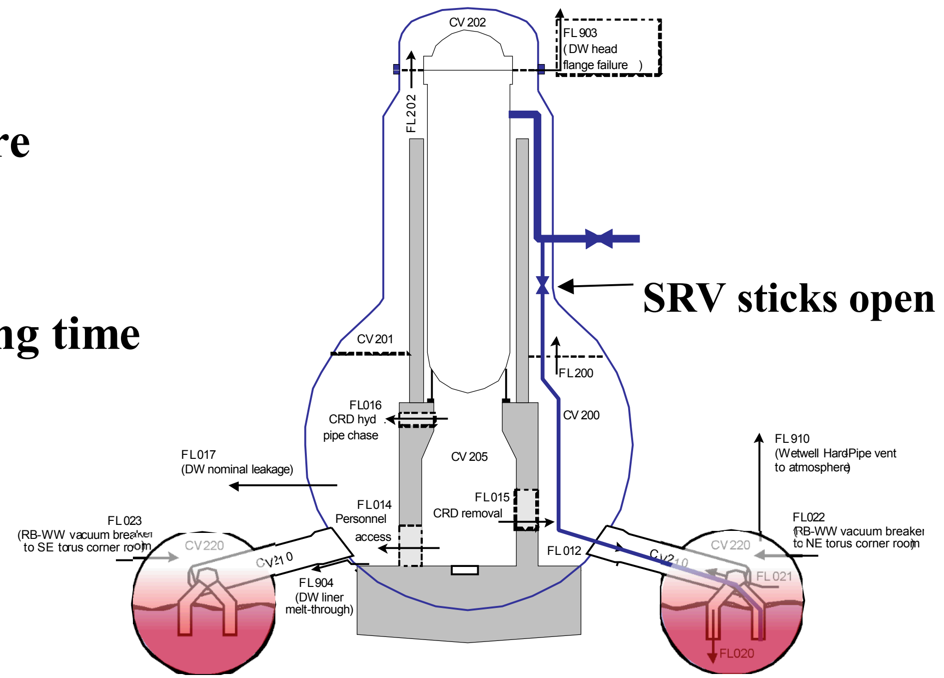


- SBO at start of accident
- Core damage by 1 hour
- SRV seizure just before 2 hours
- Core slumping by ~2.5 hours
- Lower head failure ~8.5 hours
- MCCI and Dry well liner failure ~8.5 hours+

- 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





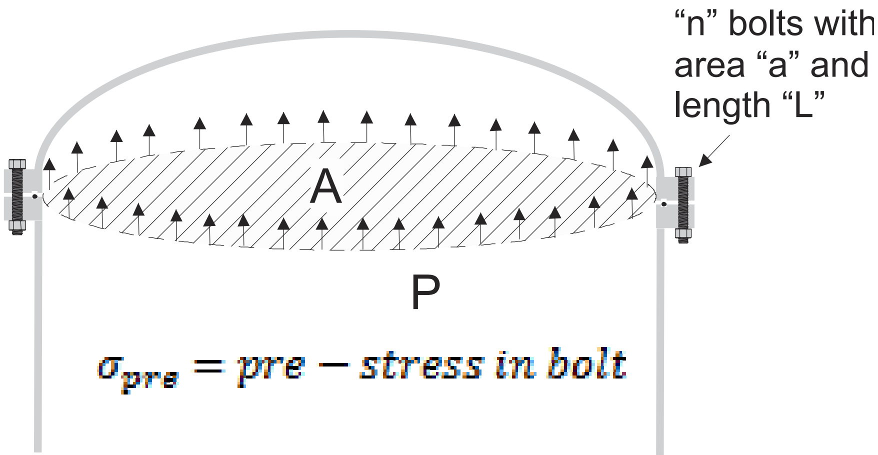
Main Steam Line Rupture vents
Fission products to drywell

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

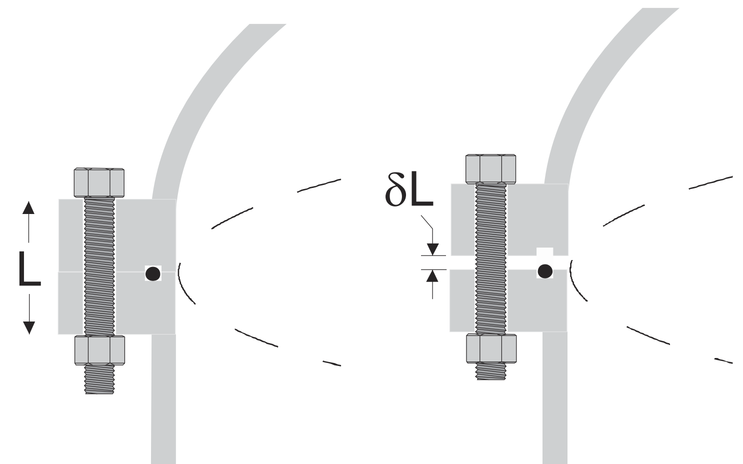
SRV Seizure vents fission products
Into wetwell

Wetwell scrubbing prevents release
To the environment

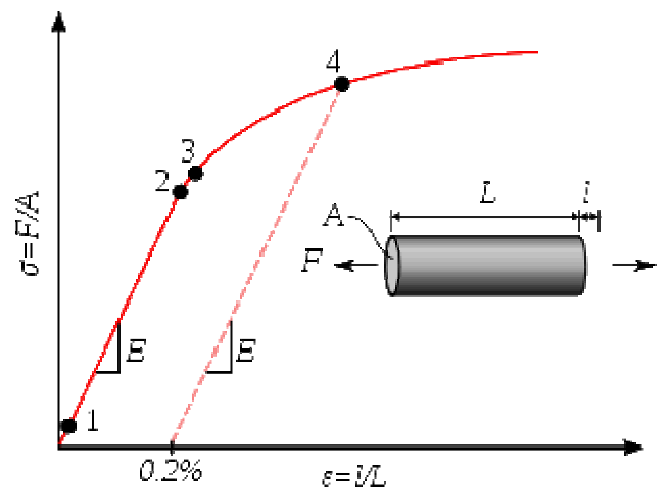
Drywell Head Pressure Response



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



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



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

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

Drywell Pressure

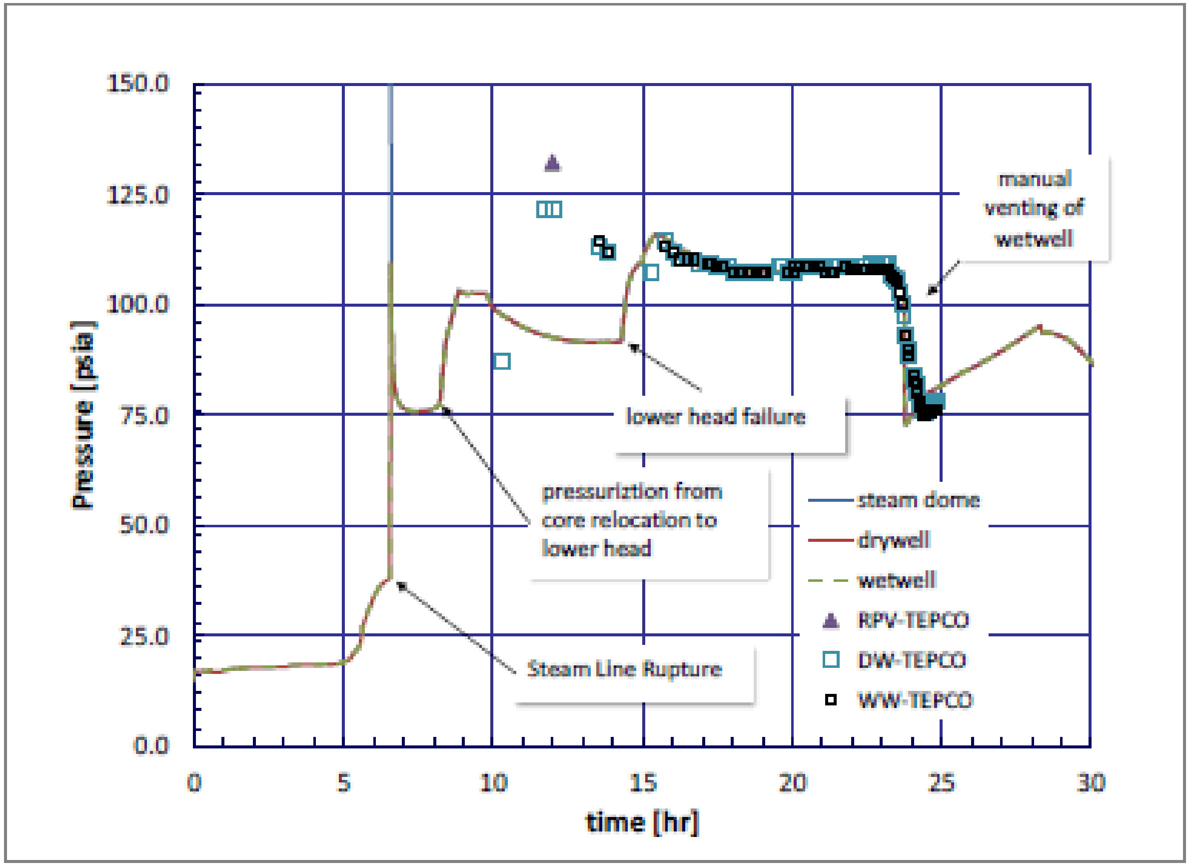
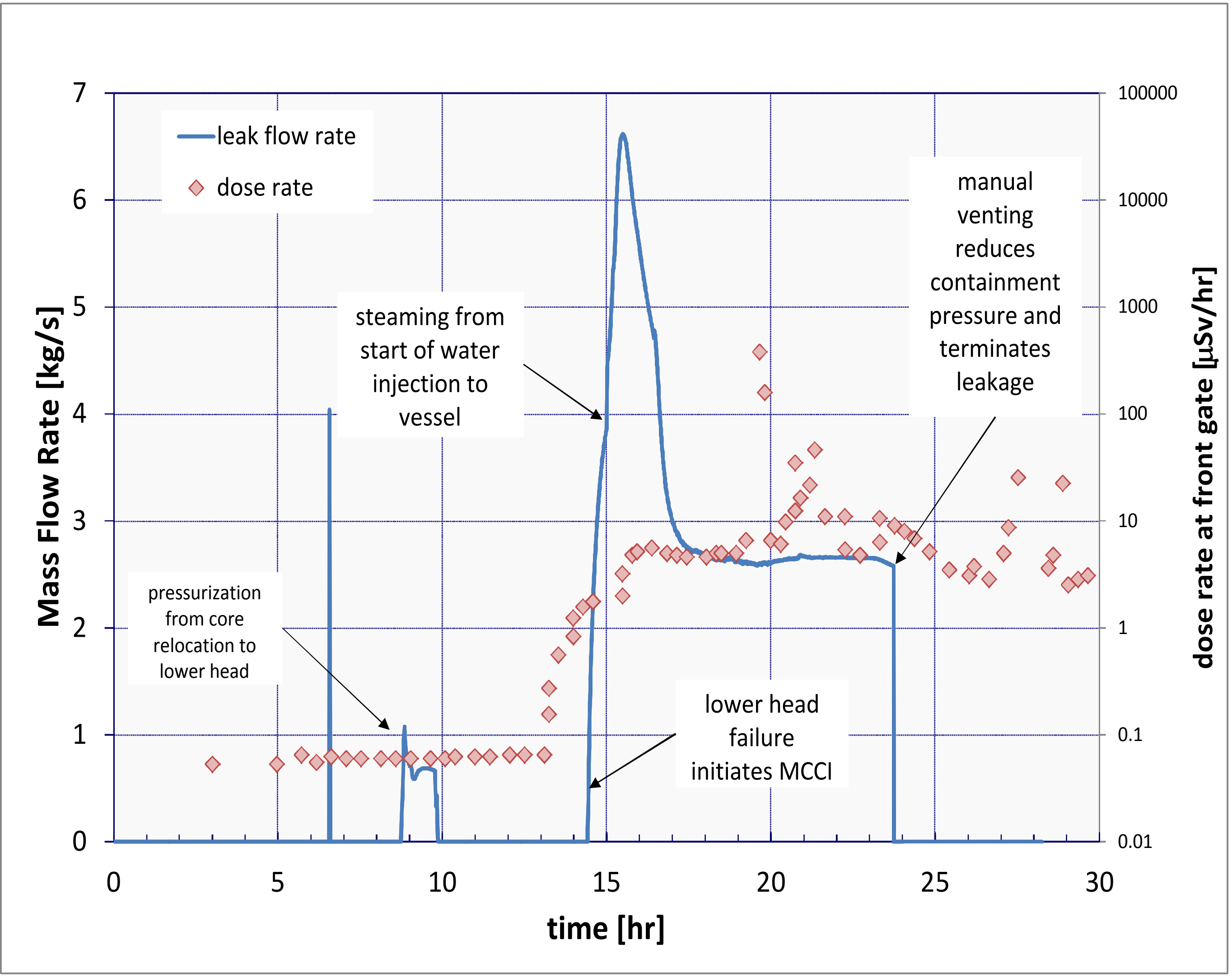


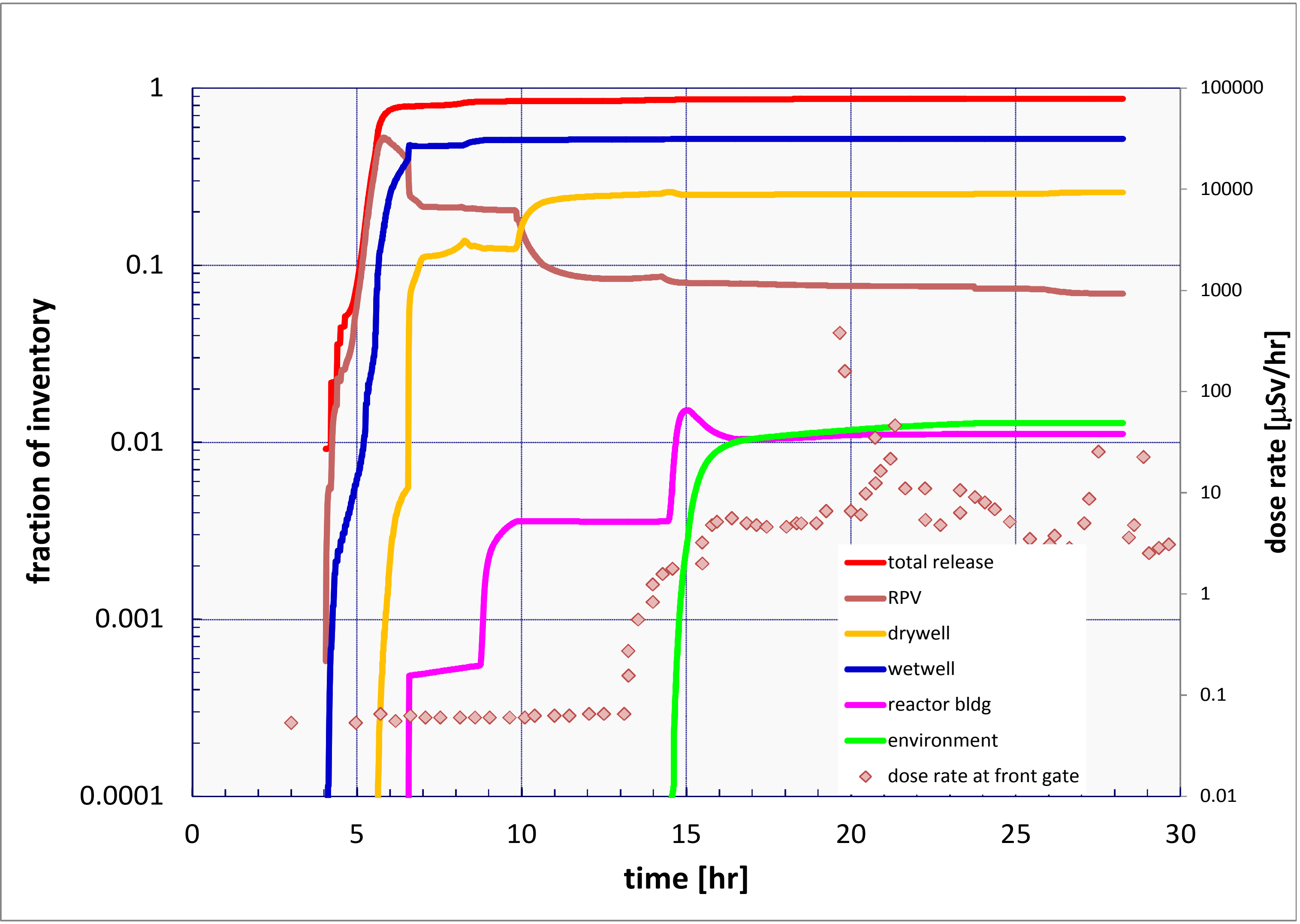
Figure 44 MELCOR-predicted containment pressure during the MCCI gas generation phase up to the point of manual containment venting.

Dry Well Head Flange Leakage



- Flange leakage driven by MCCI gas generation and by steam from water injection
- Idealized flange leakage model closes leak path when manual venting lowers PCV pressure
- Also, water injection is suspended just prior to venting
- Stops (or slows) steam/gas leak to refueling bay

Cs Release 1F1

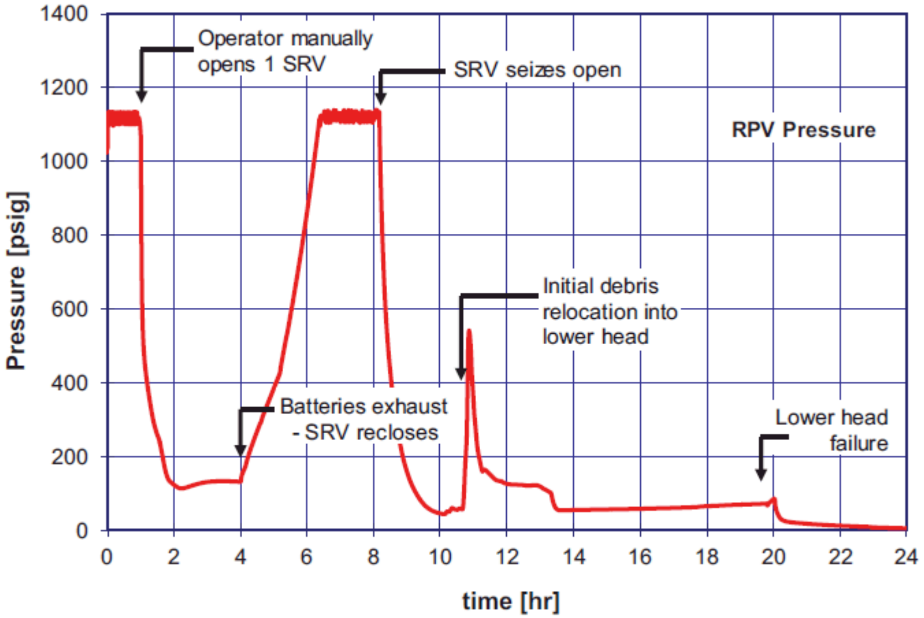


Radiation monitors at front gate jump at ~13 hr

Cs Env release about 400,000 Ci

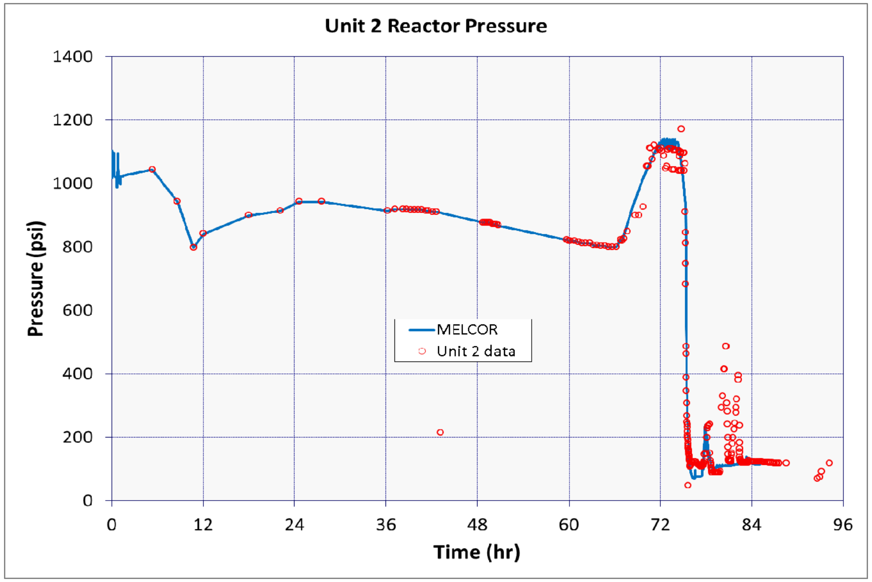
SOARCA PB LTSBO vs 1F2

Peach Bottom 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

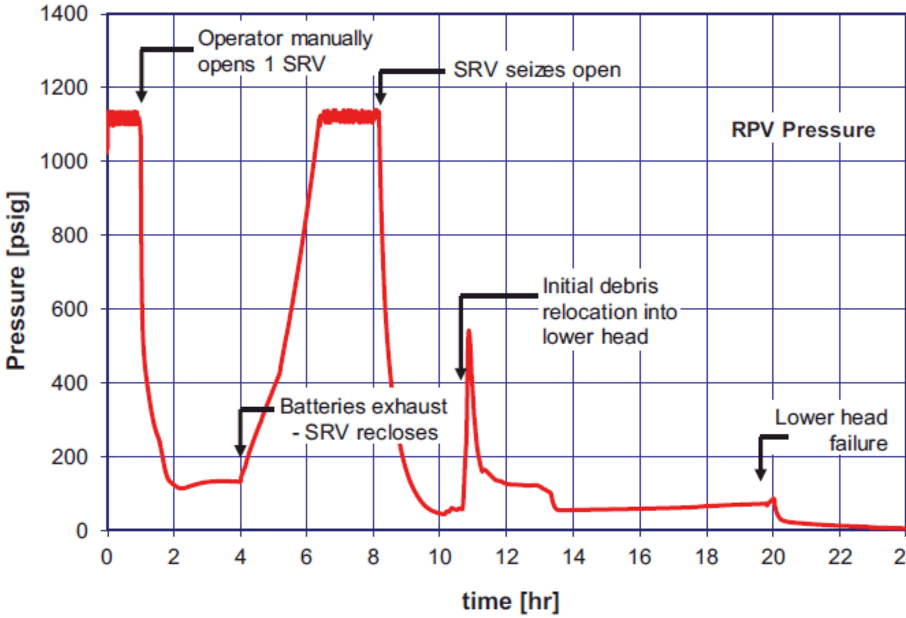
1F2 LTSBO



- 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

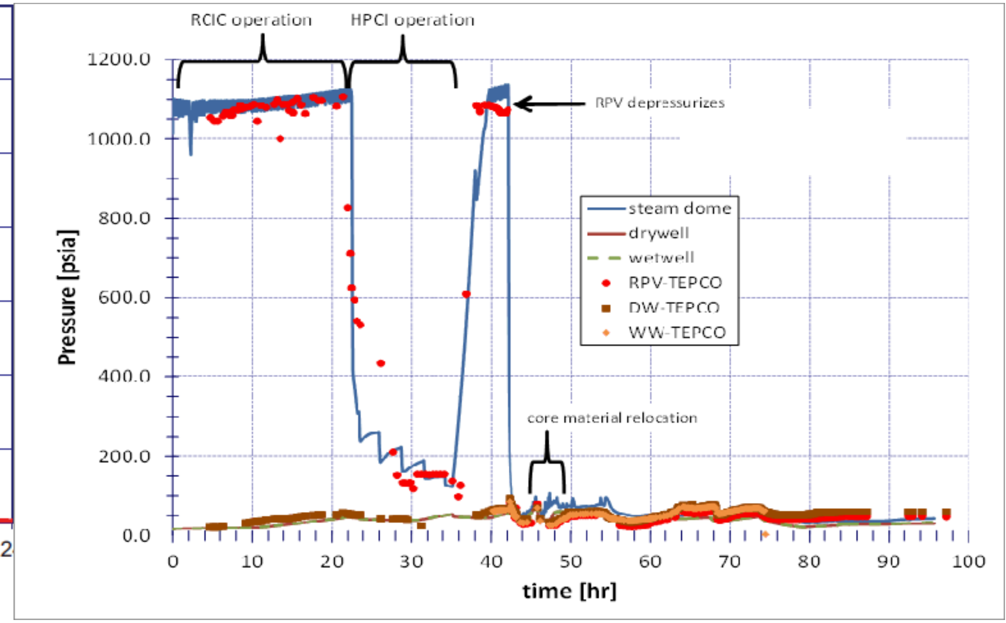
SOARCA PB LTSBO vs 1F3

Peach Bottom LTSBO



- 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

1F3 LTSBO

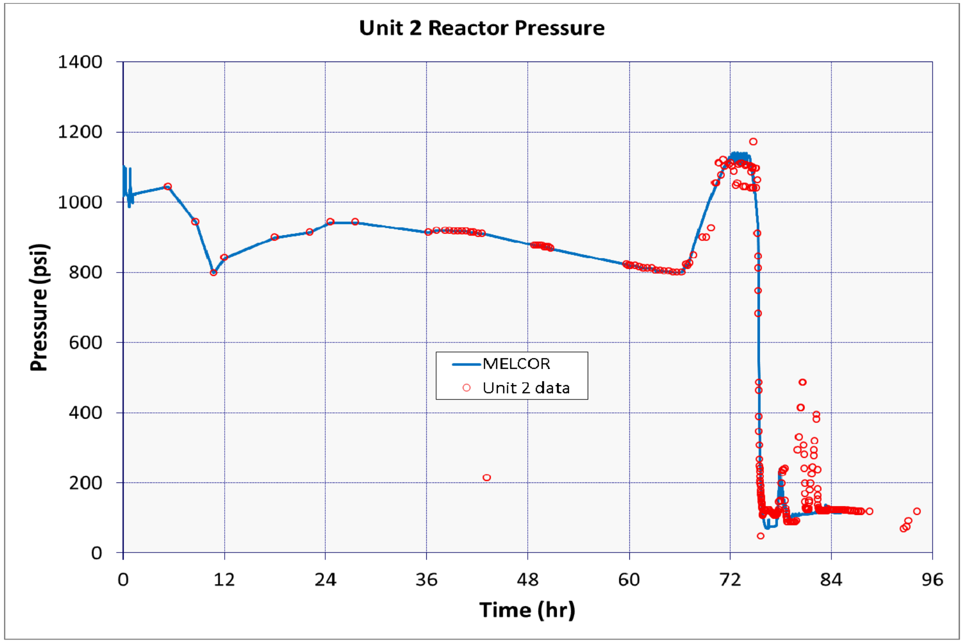


- RCIC starts level control – runs 21 hours
- Operators keep RPV pressure high
  - RCIC controlling level
- HPCI run continuously using bypass mode until failure @ ~35 hours
- Water level loss, manual SRV open
- Time to core slump – 10 hrs after HPCI fails

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

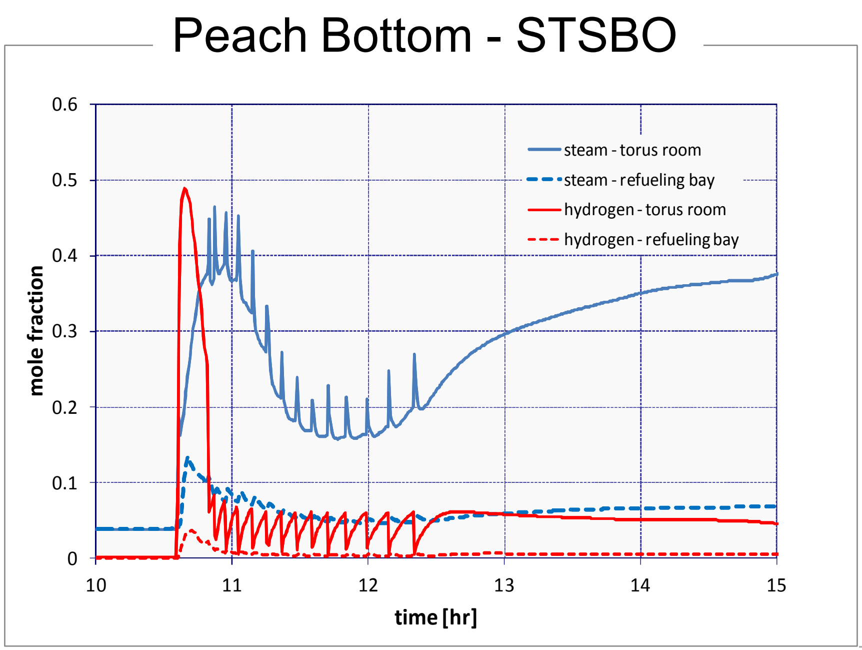
Long Term RCIC Operation

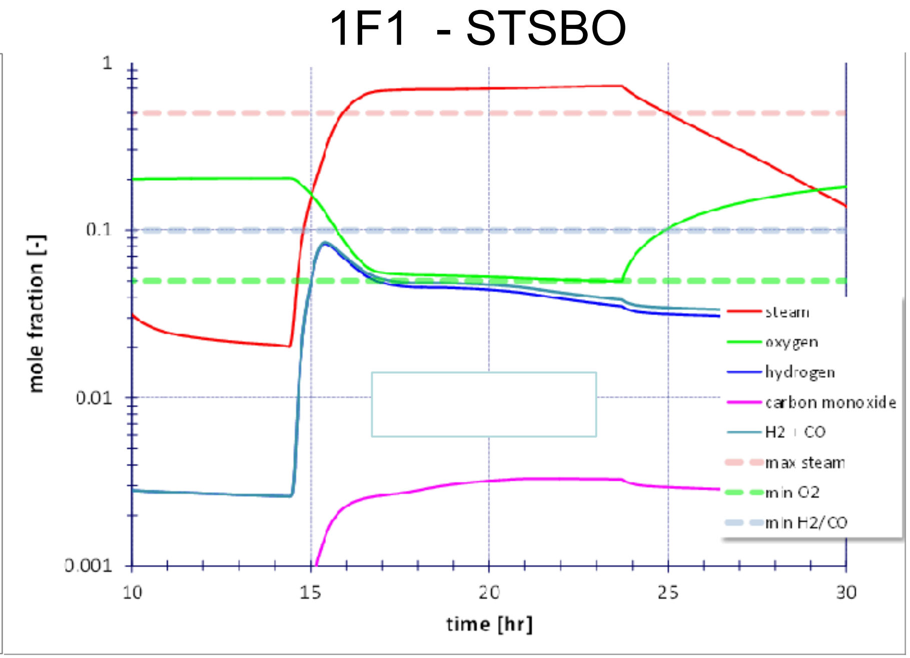


- RCIC pump is driven by "Terry Turbine"
- Robust design tolerates wet steam (i.e. water/steam)
- Prior assumptions held that steam line flooding would kill RCIC
- 1F2 experience shows otherwise
- Should this be modeled in safety analyses ?

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

Hydrogen Behavior





- 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

- 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

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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

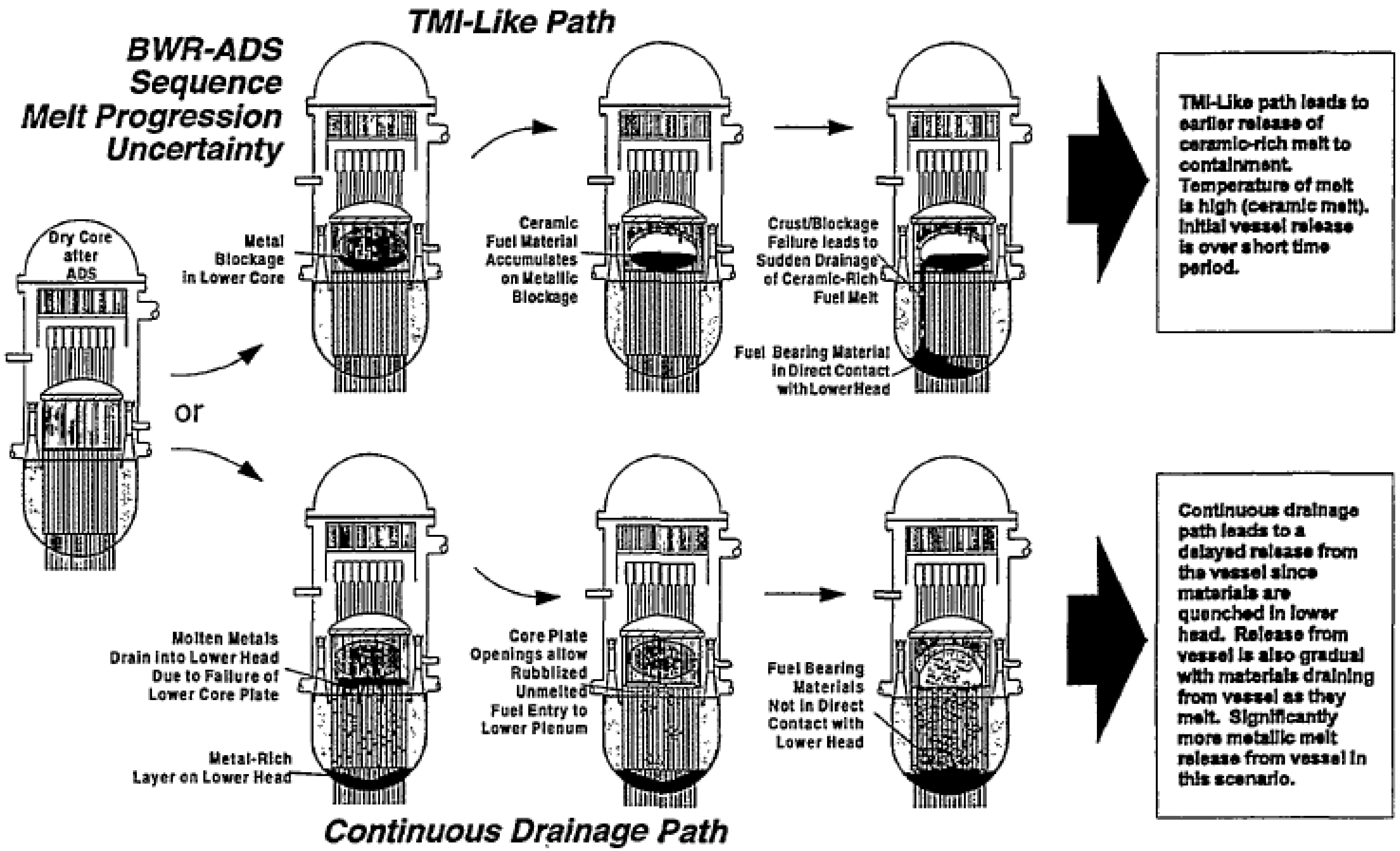
Conclusions

- 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

End of Presentation
Backup Slides Follow

Is BWR Melt Progression Similar to PWR Melt Progression ? *(1995)*

Sandia National Laboratories



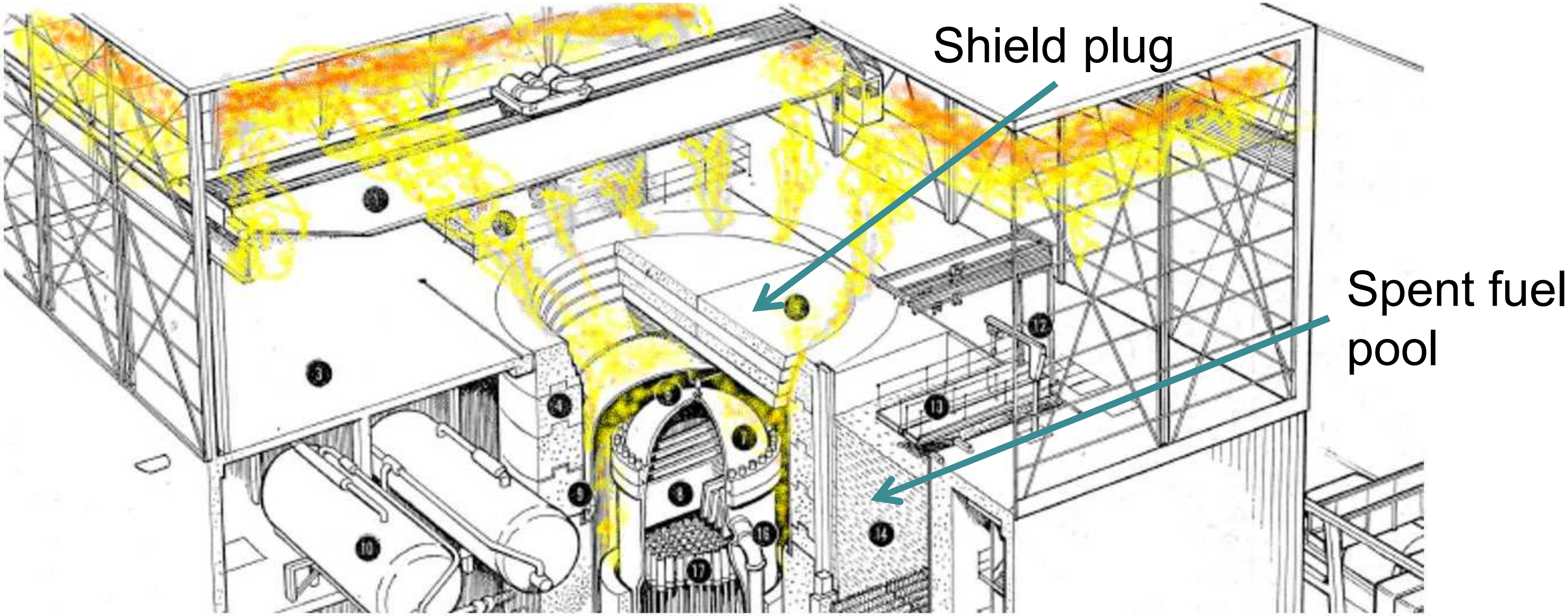
Final Results of the XR2-1 BWR Metallic Melt Relocation Experiment

Manuscript Completed: April 1997
Date Published: August 1997

NUREG/CR-6527
SAND97-1039

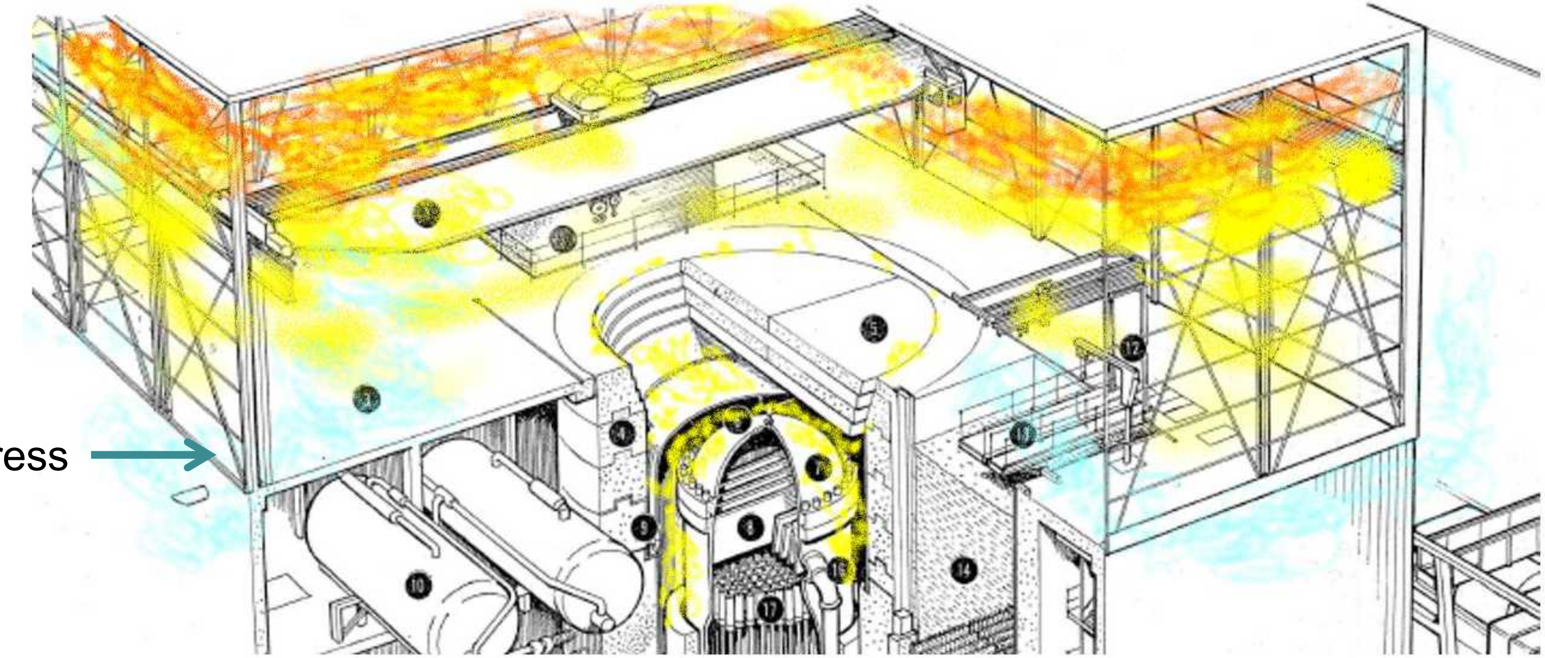
Prepared by
R. O. Gauntt, SNL
L. L. Humphries, SAIC

Hydrogen Accumulation in 1F1



- Between ~12 hours and ~23 hours, steam and hydrogen leaks from drywell head flange and enters RB via shield plug seams
- Hydrogen, CO and steam rises to roof and spreads laterally
- Steam produced in MCCI and from emergency water injection
- Condensation in refueling bay depletes steam in hot layer and enriches hydrogen
- Mixture displaces air from building
- Steam mole fraction exceeds 50% - inert conditions prevent combustion

Combustible Conditions Follow PCV Venting in 1F1



Air ingress

- At around ~23 hours, steam and hydrogen leakage from PCV greatly reduced
  - Water injection was stopped
  - PCV was depressurized by operator venting action
- Continuing condensation without steam source….
  - Reduces steam molar fraction to below 50% in refueling bay, and
  - Produces partial vacuum that draws in outside air
- Air ingress and steam condensation leads to conditions favoring combustion
- Hydrogen stratification produces flammable or detonable concentrations of H_2/O_2

Damage from Explosions

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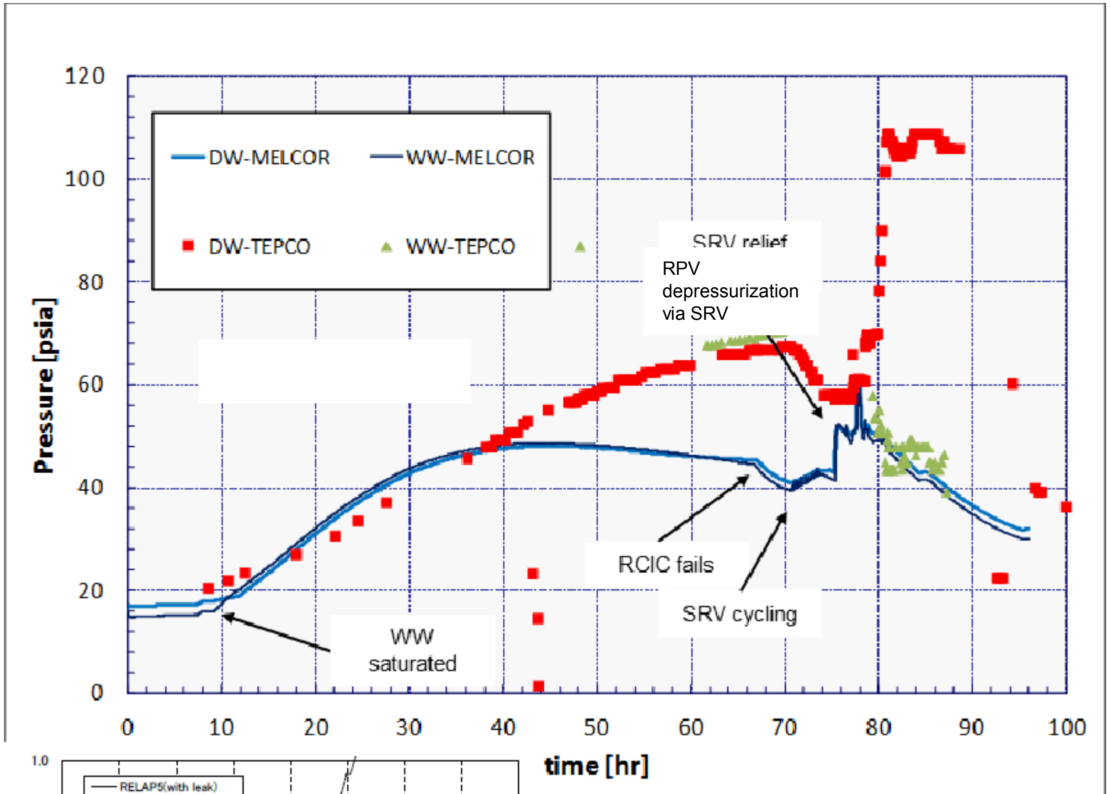
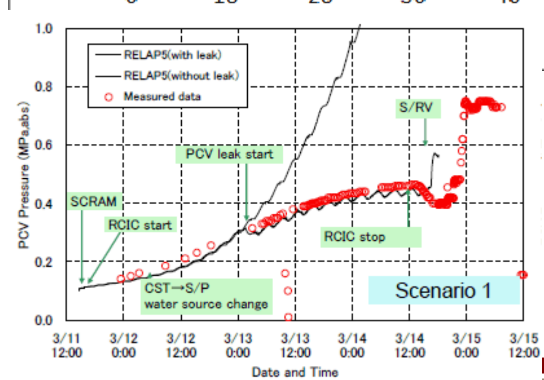
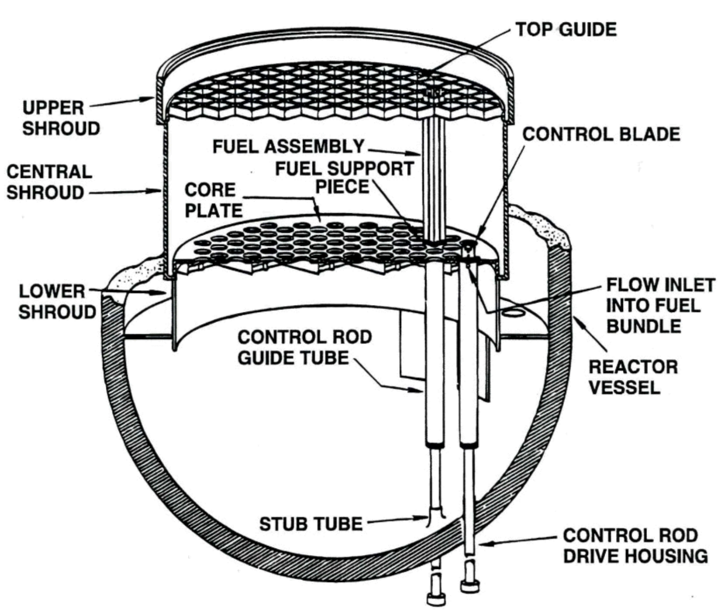
Unit 2 Results
Containment Pressures





- 2-inch hole in containment assumed to explain low containment pressure
  - Alternate proposal is that torus room flooding caused greater energy transfer
- Containment pressure data do not follow expectations:
- during SRV cycling (70-75 hours), PCV pressure data is decreasing;
- SRV relief mode (75 hours), predicted PCV rapid pressure increase is not observed;
  - Could Torus be subcooled?
  - Is decay heat *actually* going into torus ?
- drywell and wetwell pressure deviate; and (drywell assumed correct)
- Too large water injection cools core
- Data suggests Drywell Head Flange leak at 80 hours, similar to Unit 1
  - Large steam generation from quenching and/or core degradation
- *RCIC turbine exhaust leak into RCIC room ?*

Lower Head Failure Mechanisms

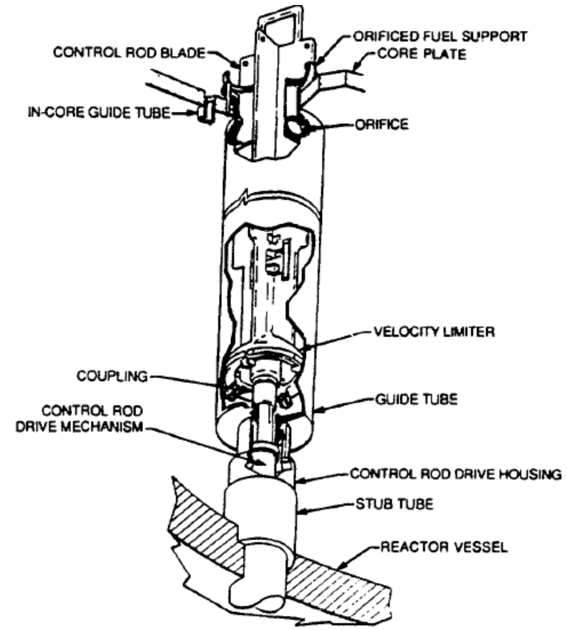


BWR REACTOR VESSEL BOTTOM HEAD FAILURE MODES

CONF-890546--3

DE89 009623

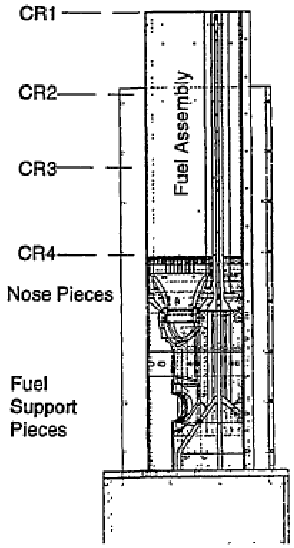
Stephen A. Hodge
Boiling Water Reactor Severe Accident Technology (BWRSAT) Program
Oak Ridge National Laboratory

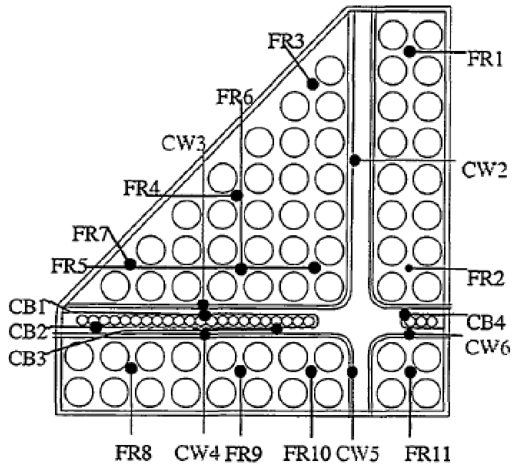


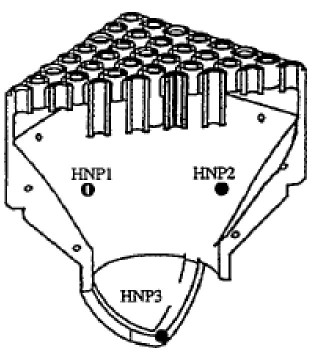
- 200+ penetrations in head
- Penetration failure may be first breach of pressure boundary
- However, RPV is likely depressurized

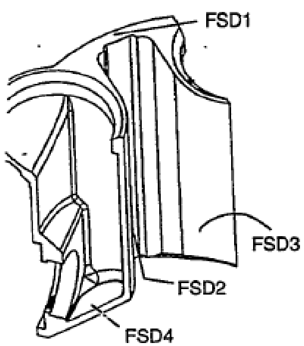
- Penetration failure may not release much fuel material
- Most fuel may be released following global rupture
- Drain plug likely filled with CB steel

Findings from XR2-1 Experiment









- XR2-1 test used prototypic BWR components
  - Nose pieces, grid spacers, control blades, core plate and elephants foot
- Molten CB and Zr materials drained into test section
- Channel box walls eroded by CB melt
  - Zr-Fe eutectic
- 70% of metals drained below core plate via nose piece pathway
- Accumulations also on core plate
- Fuel rod geometry seriously degraded