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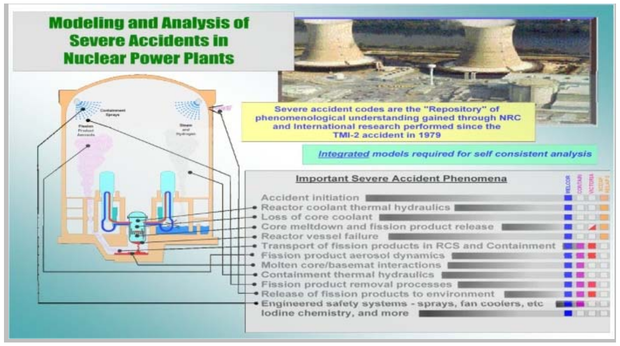

RCIC Operation in Fukushima Accidents as Modeled by MELCOR and Proposed Testing

Presented at the EPRI Terry Turbine User Group Meeting
Seattle Washington
July 14-16, 2014

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Topics for discussion

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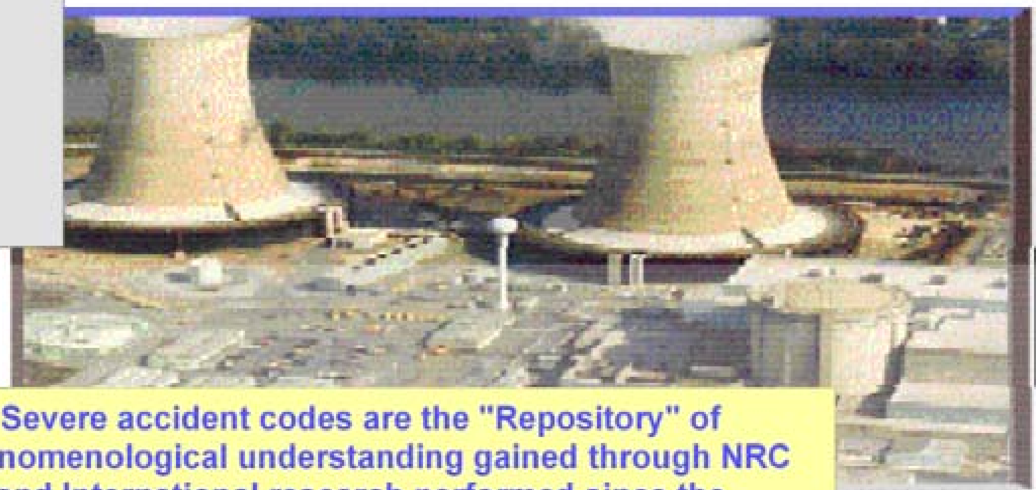
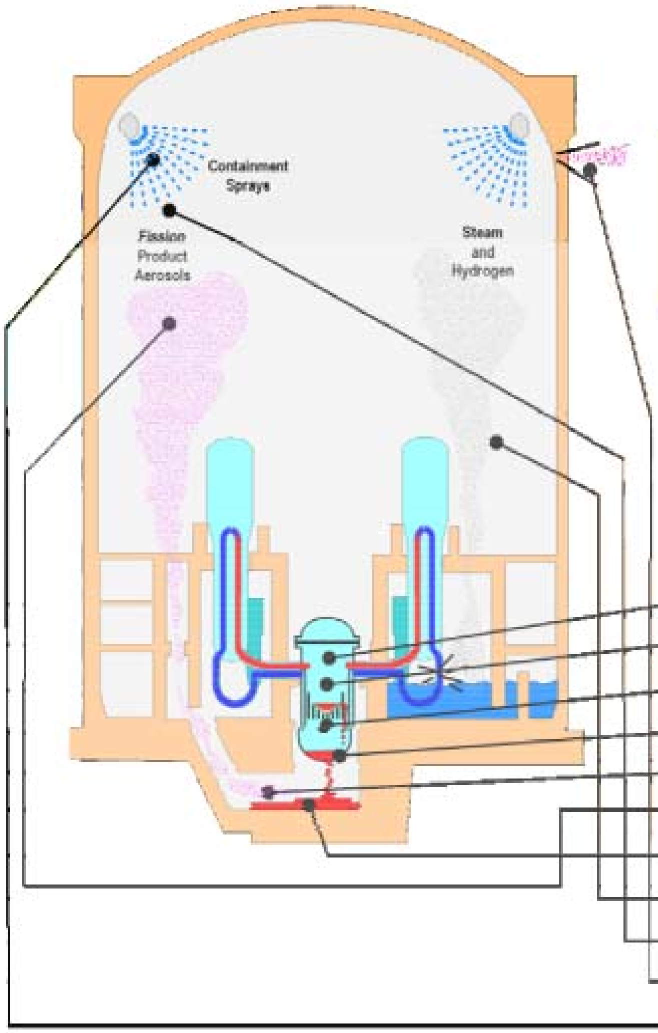
- Background
- Overview of Fukushima Accidents
- Comparisons of SOARCA Study with Fukushima accidents
- Equipment functioning in real-world accidents
- Conclusions

Modeling and Analysis of Severe Accidents in Nuclear Power Plants



Severe accident codes are the "Repository" of phenomenological understanding gained through NRC and International research performed since the TMI-2 accident in 1979

Integrated models required for self consistent analysis



Important Severe Accident Phenomena

Phenomenon	MELCOR	CONTAIN	VICTORIA	SCDAP RELAP 5
Accident initiation	■			■
Reactor coolant thermal hydraulics	■			■
Loss of core coolant	■			■
Core meltdown and fission product release	■		◢	■
Reactor vessel failure	■			■
Transport of fission products in RCS and Containment	■	■	■	
Fission product aerosol dynamics	■	■	■	
Molten core/basemat interactions	■	■		
Containment thermal hydraulics	■	■		
Fission product removal processes	■	■	■	
Release of fission products to environment	■	■	■	
Engineered safety systems - sprays, fan coolers, etc	■	■		
Iodine chemistry, and more	■			

SNL Fukushima MELCOR Reactor Models

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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

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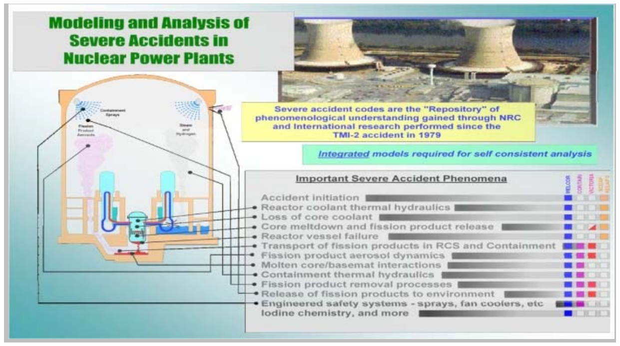


The Accidents

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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

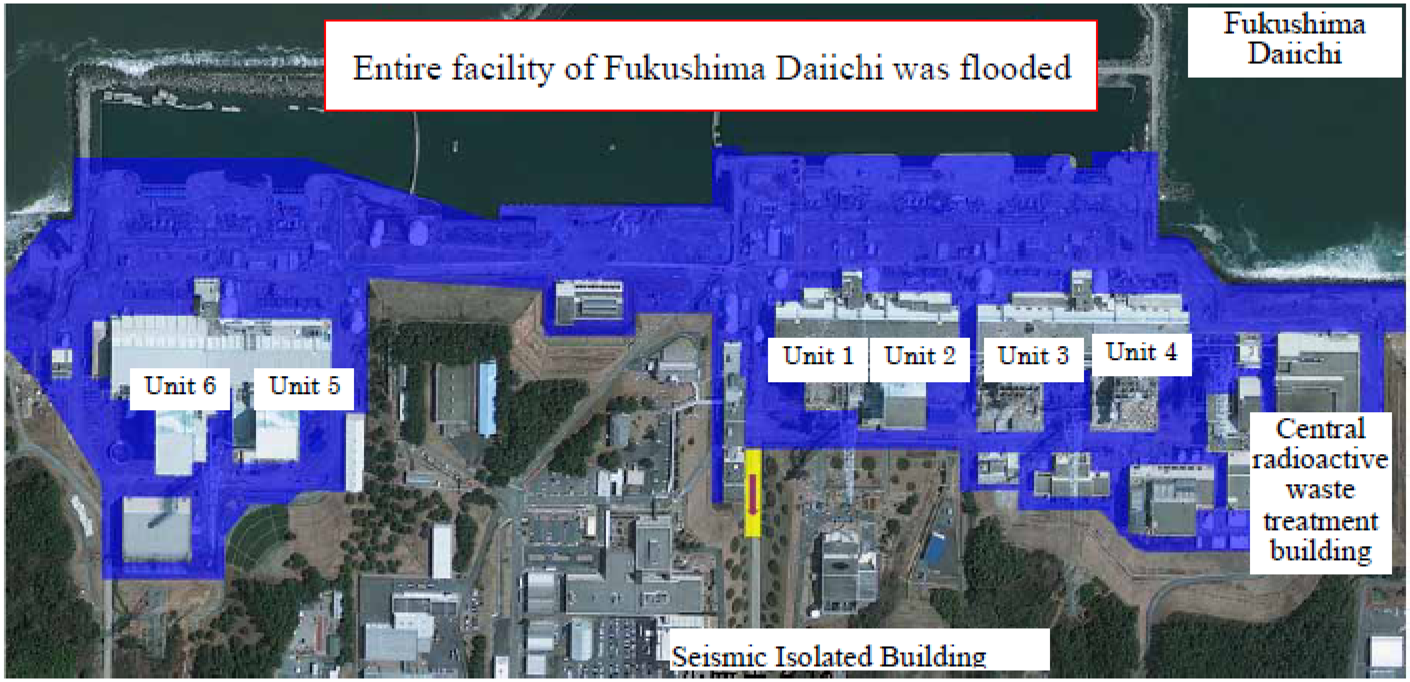
Circuit Breaker damaged

Used by permission from TEPCO
Kenji Tetawa

Collapsed tower

Daiichi Site was Inundated

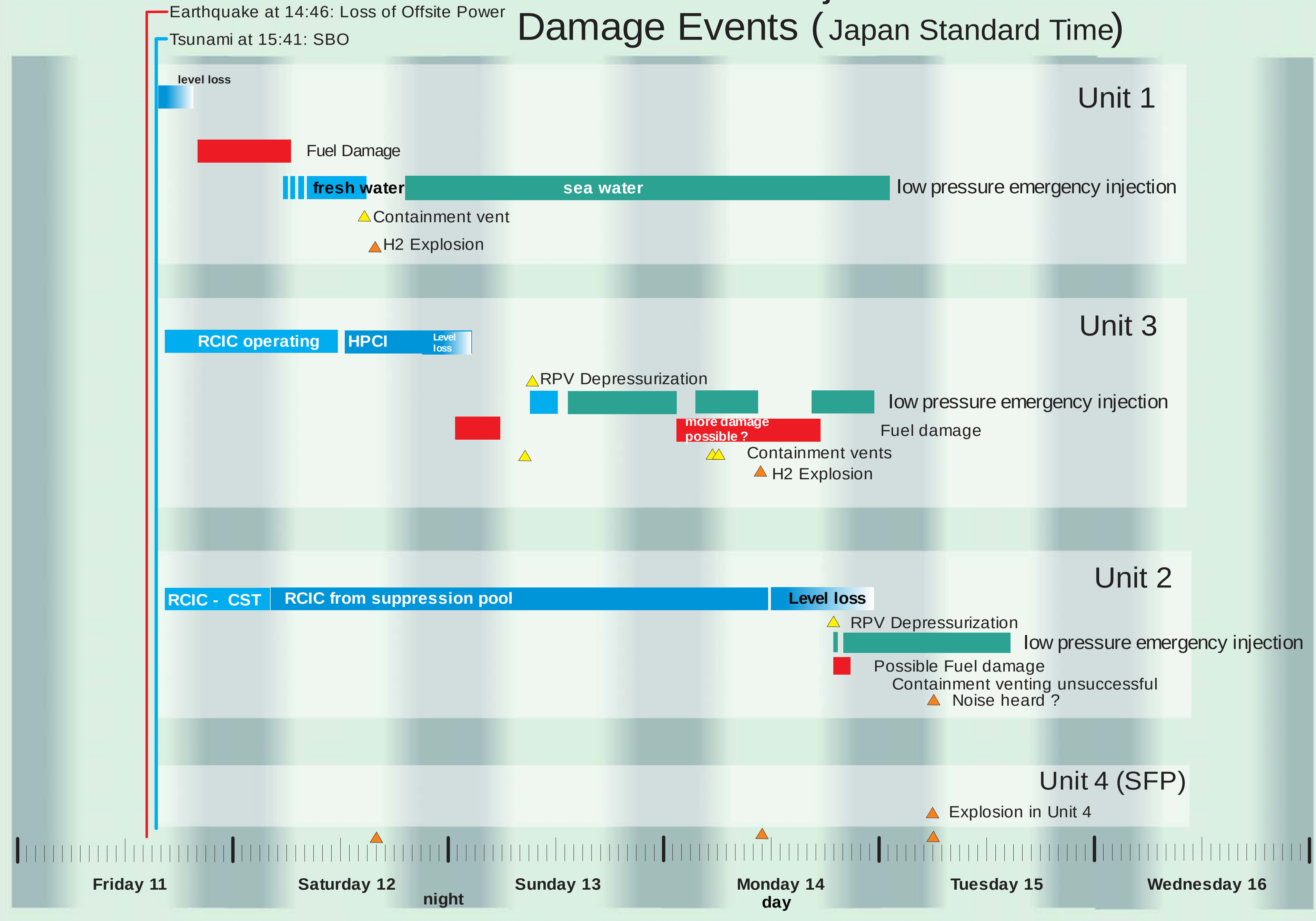
Sandia National Laboratories



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)

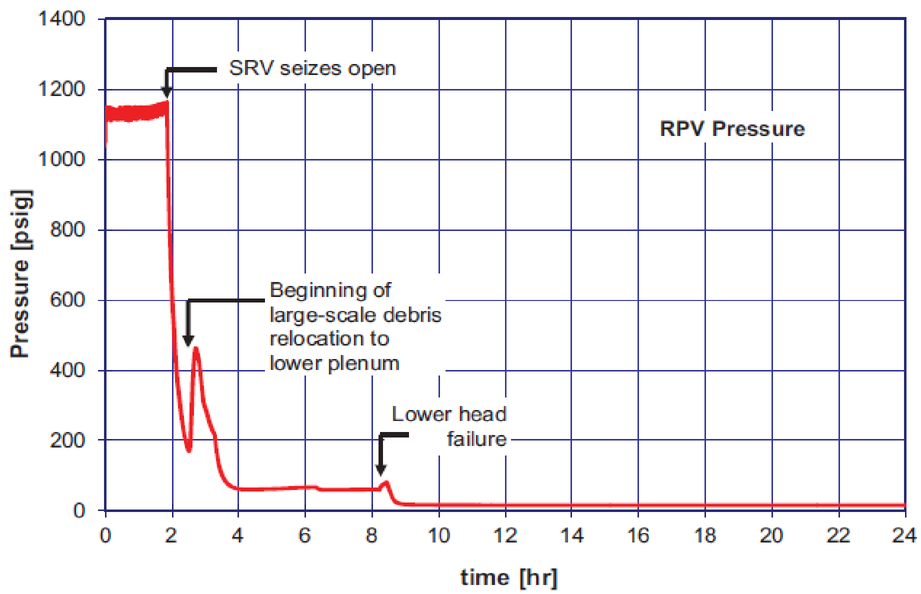
Timeline of Major Fukushima Damage Events (Japan Standard Time)



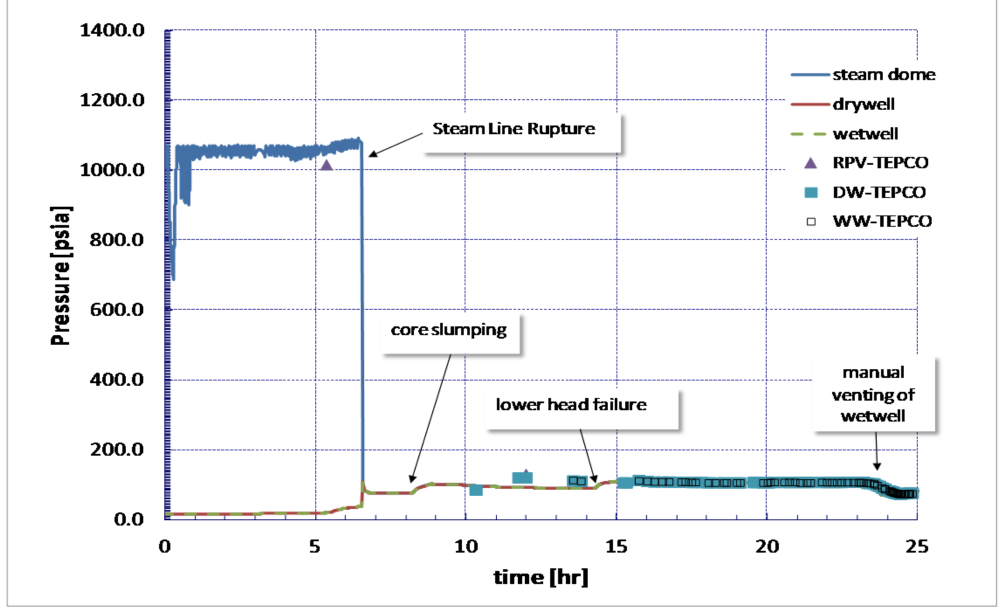
MELCOR PEACH BOTTOM VERSUS FUKUSHIMA ACCIDENTS

Comparison of SOARCA PB-STSBO with 1F1

Peach Bottom STSBO



1F1 STSBO

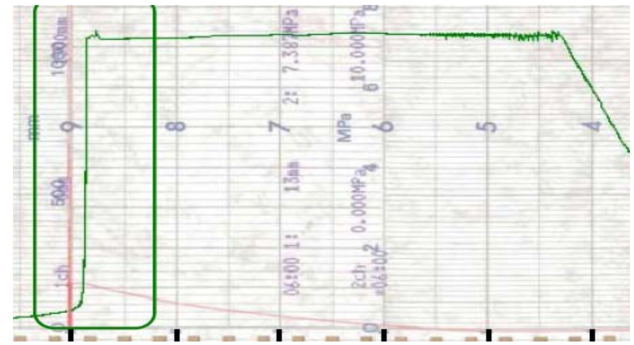


- SBO at start of accident
- Core damage by 1 hour
- SRV seizure just before 2 hours
- Core slumping by ~2.5 hours
- Lower head failure ~8.5 hours
- MCCI and Dry well liner failure ~8.5 hours+

- 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

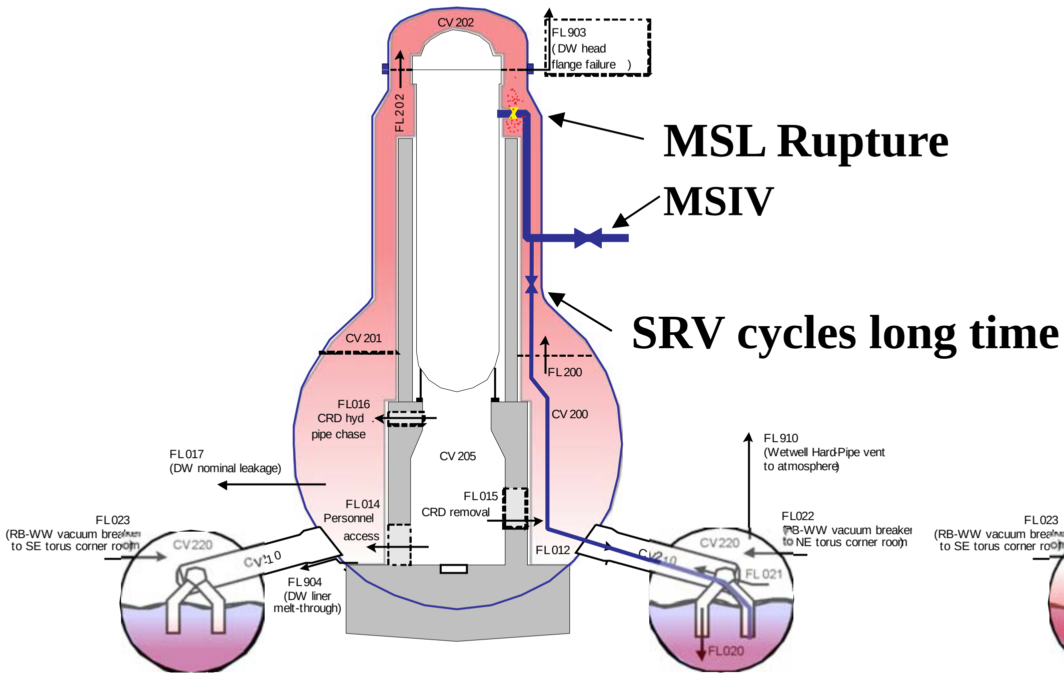
Critical Equipment Performance in Severe Accidents – SRV Functioning

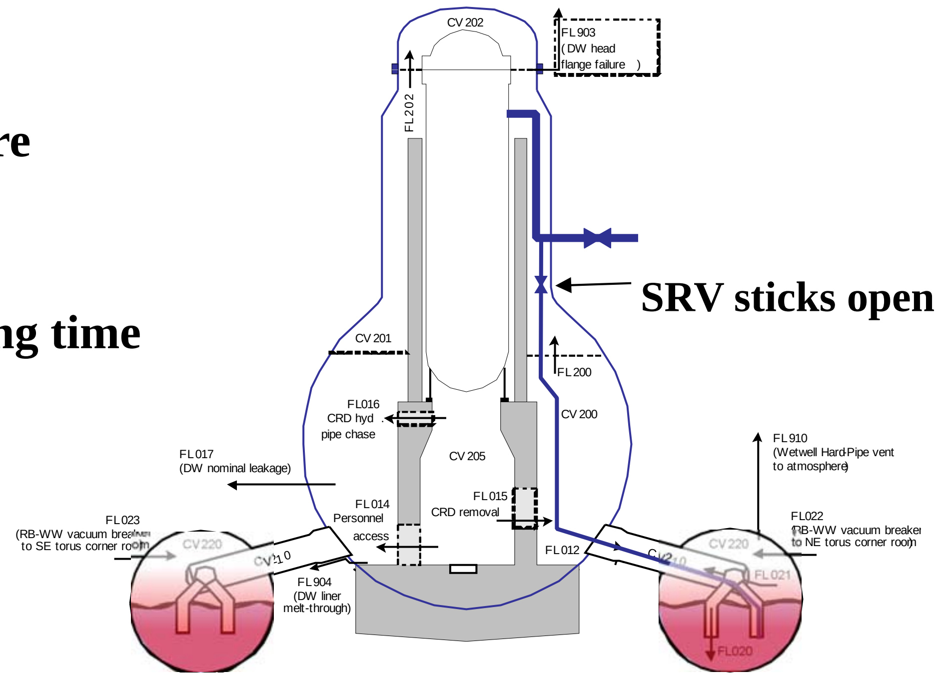
- SRV response to severe accident conditions shown in SOARCA study to be important bifurcation in accident



- Fukushima Unit 3 SRV operated under significant severe accident duress
- SRV functioning could influence MSL rupture potential (SOARCA)
  - Affects success of containment venting strategies (drywell versus wetwell venting)

SRV Seizure Versus MSL Rupture





Main Steam Line Rupture vents
Fission products to drywell

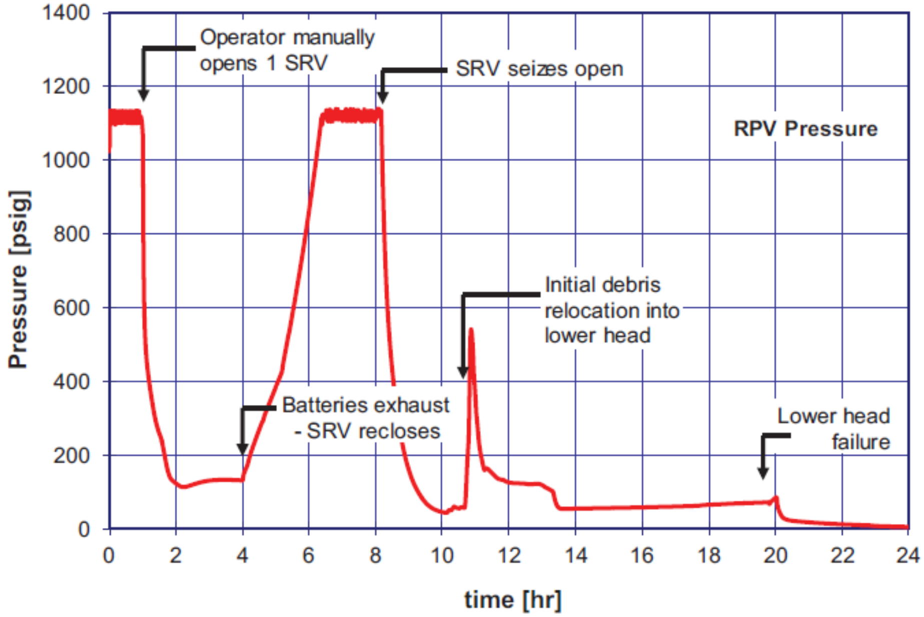
Release to environment via head
Flange failure or drywell liner melt through

SRV Seizure vents fission products
Into wetwell

Wetwell scrubbing prevents release
To the environment

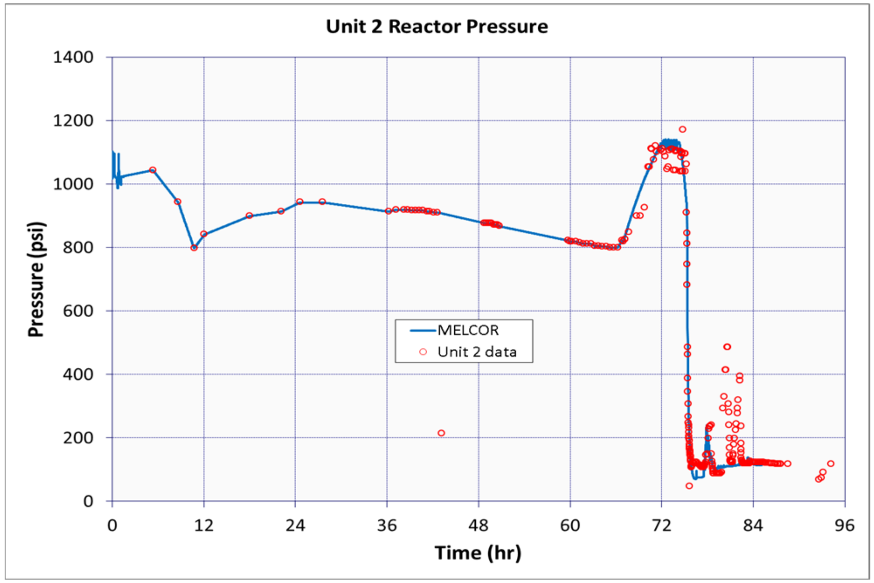
SOARCA PB LTSBO vs 1F2

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

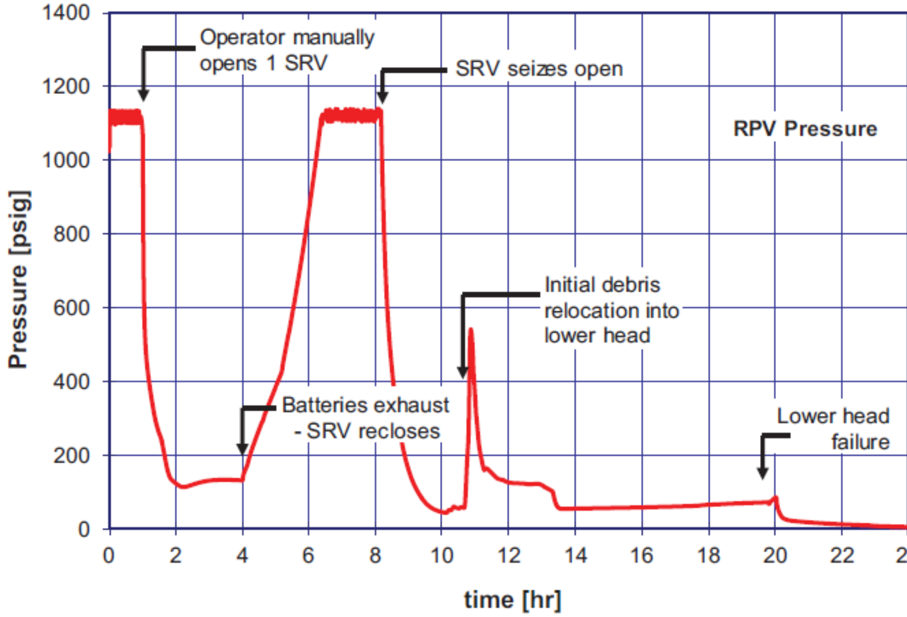
1F2 LTSBO



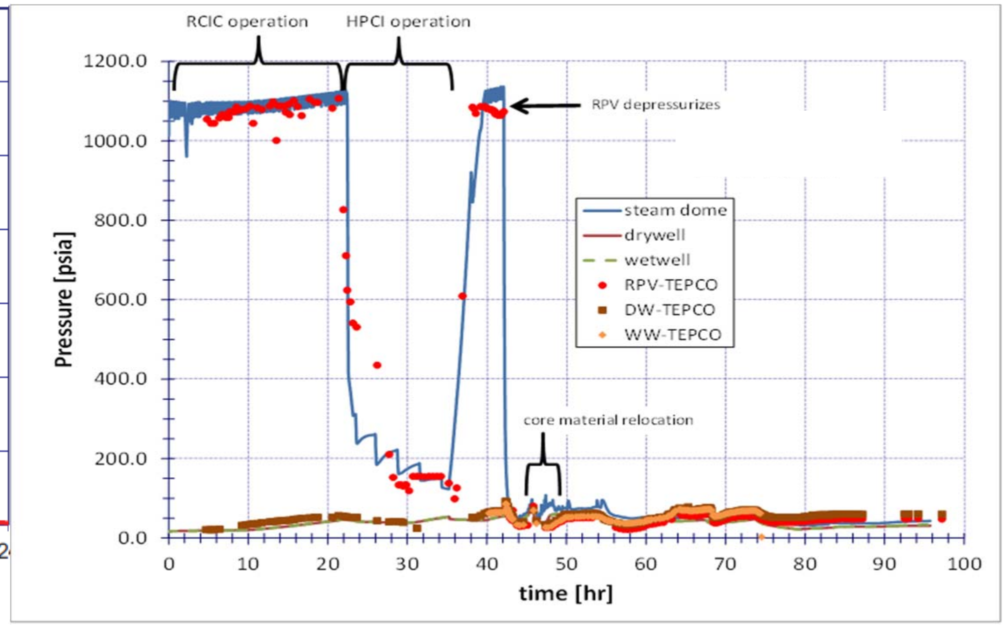
- RCIC starts level control – runs 68 hours (uncontrolled due to SBO after 1 hour)
- RPV overfilling passes 2-phase water to turbine
  - Enthalpy removal set to match RPV pressure
  - Cyclic turbine response proposed
- RPV re-pressurizes following RCIC failure
- Water level loss, manual SRV open, reflood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

SOARCA PB LTSBO vs 1F3

Peach Bottom LTSBO



1F3 LTSBO



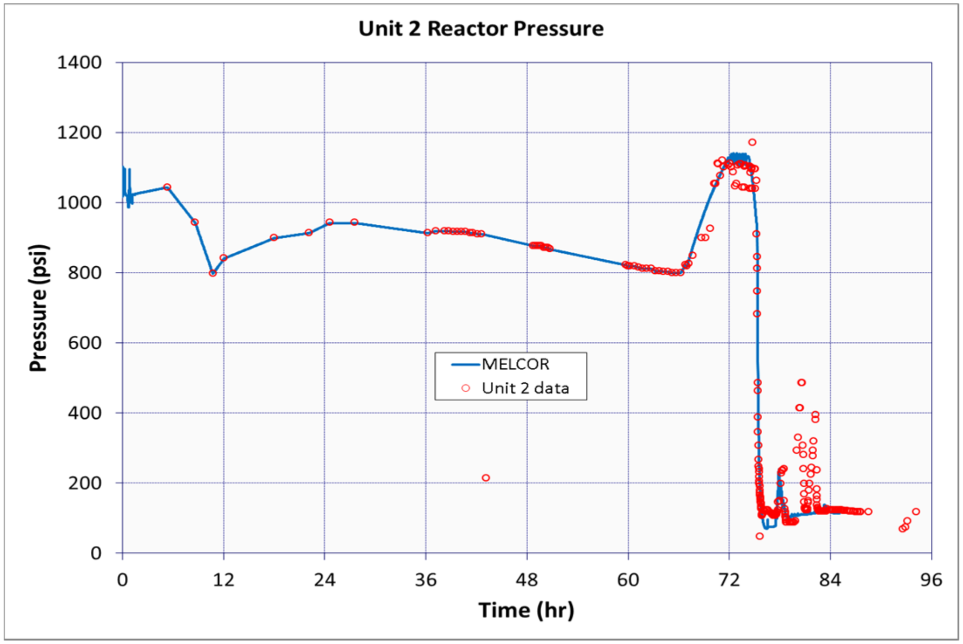
- RCIC starts level control
- Operator SRV control on pressure
  - RCIC controlling level
- Battery depletion @4 hours
  - SRV closes and RCIC runs full on
  - MSL floods and RCIC fails
- Water level loss and core damage
- Time to core slump – 7 hrs after RCIC fails

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

Summary of SOARCA-Fulushima 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



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

- 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 ?

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Photos placed in horizontal position with even amount of white space between photos and header

Reactor Core Isolation Cooling (RCIC) System Model

And Simplified Fukushima Accident Simulation

U.S. DEPARTMENT OF ENERGY

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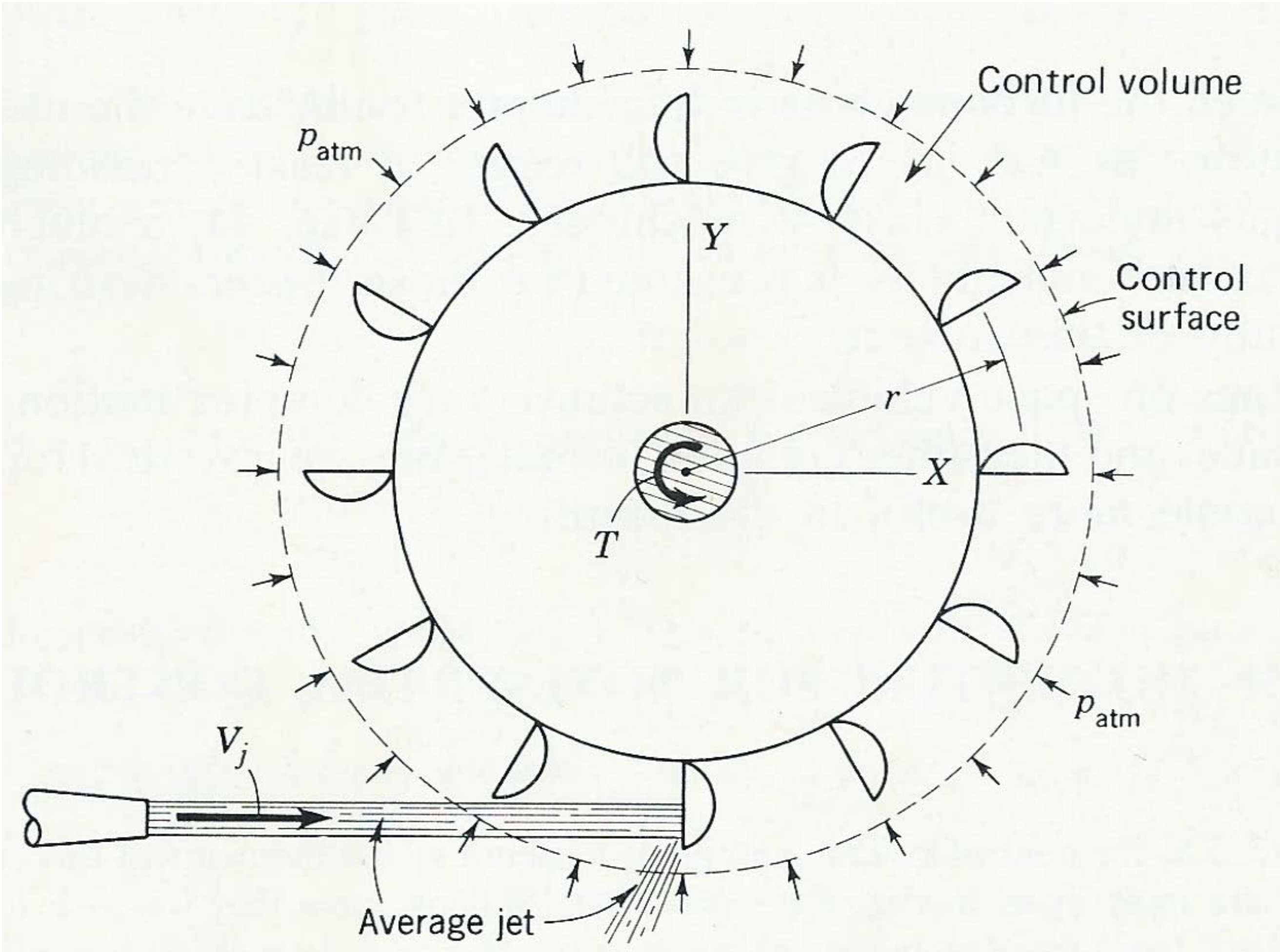
Constitutive Relations



Constitutive Relations (2)

- Through a control-volume application of the moment-of-momentum equation for an inertial control volume to RCIC turbine operation, derive a relationship for the power developed by the turbine
- Determine the applicable relationship for pumping power developed by the RCIC pump
- Equate the two power relationships given that the turbine powers the pump on a common shaft
- In equating the relationships, include an efficiency term (a multiplier) accounting for the variable efficiency of the RCIC pump dependent upon speed and flow

Model Calibration

- Since the steam turbine nozzle size and number were unknown, 10 nozzles were assumed and they were sized by:
  - Opening the governor valve wide (2 ½” dia)
  - Setting boiler pressure constant at 85 psig
  - Adjusting nozzle size until RCIC delivered 425 gpm to the boiler
- With nozzle size and number determined, the multiplier in the constitutive equations included to account for torque amplification by the reversing chambers was sized by:
  - Setting constant fluid conditions in the boiler consistent with saturated steam at 1,020 psia
  - Throttling the governor to a position that allowed a steam mass flow rate equivalent to 50 gpm of cold water
  - Adjusted the multiplier such that 425 gpm was delivered to the boiler

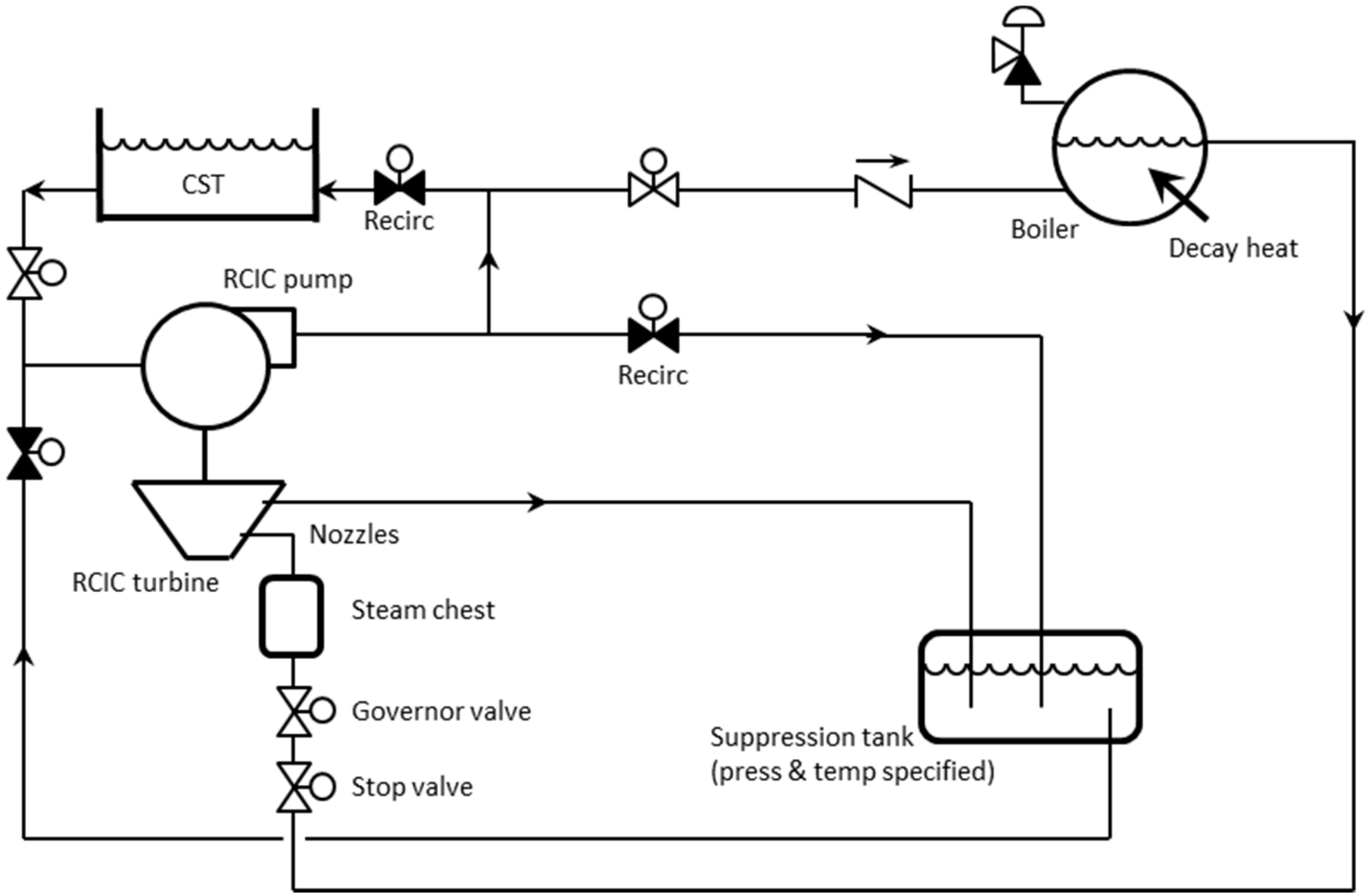
Rated Conditions for Duane Arnold RCIC System

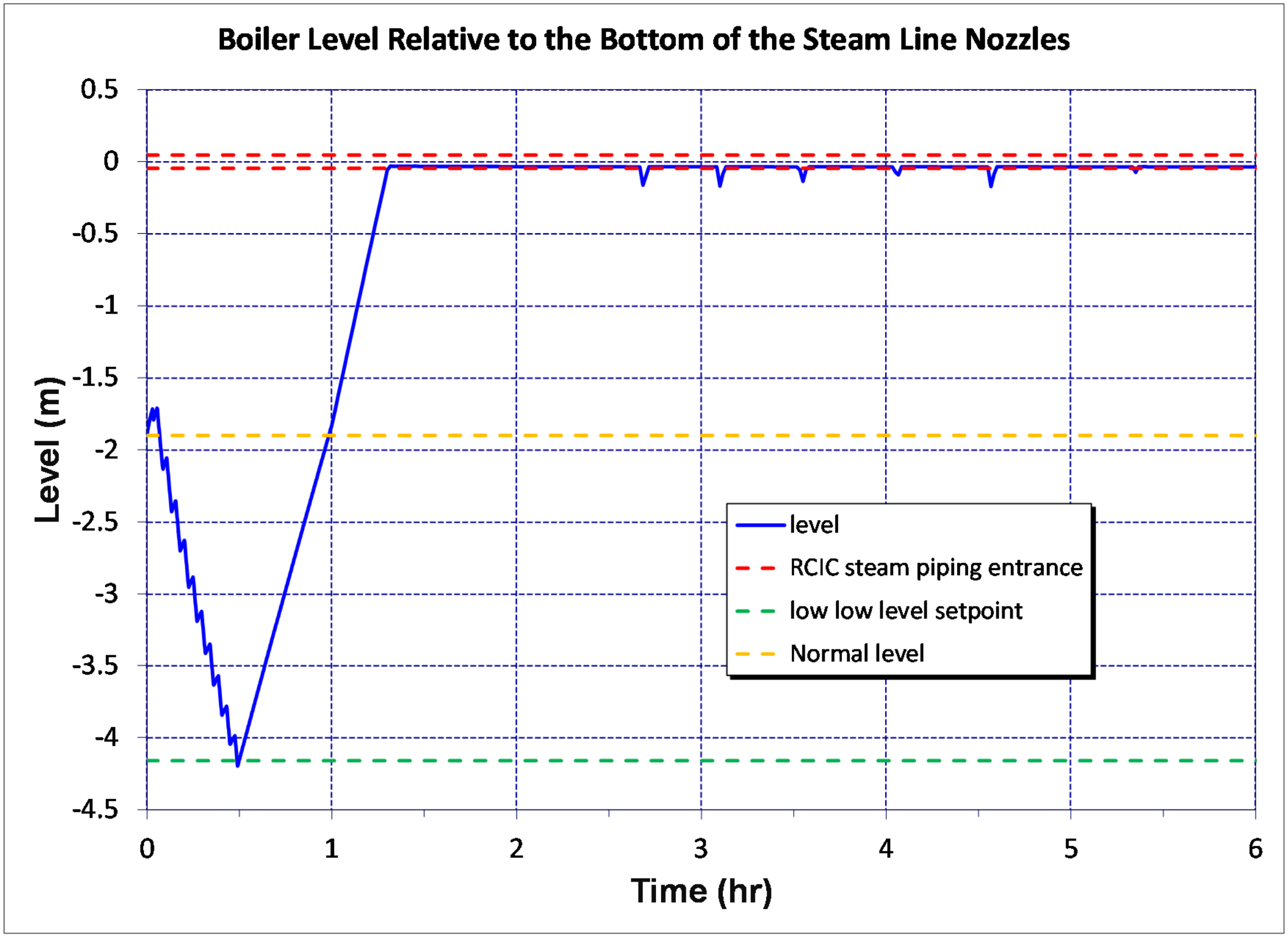
- The turbine is rated at 460 hp at 4500 rpm
- The RCIC turbine consumes steam at rated conditions equivalent to 50 gpm
- The RCIC pump has a rated flow of 425 gpm

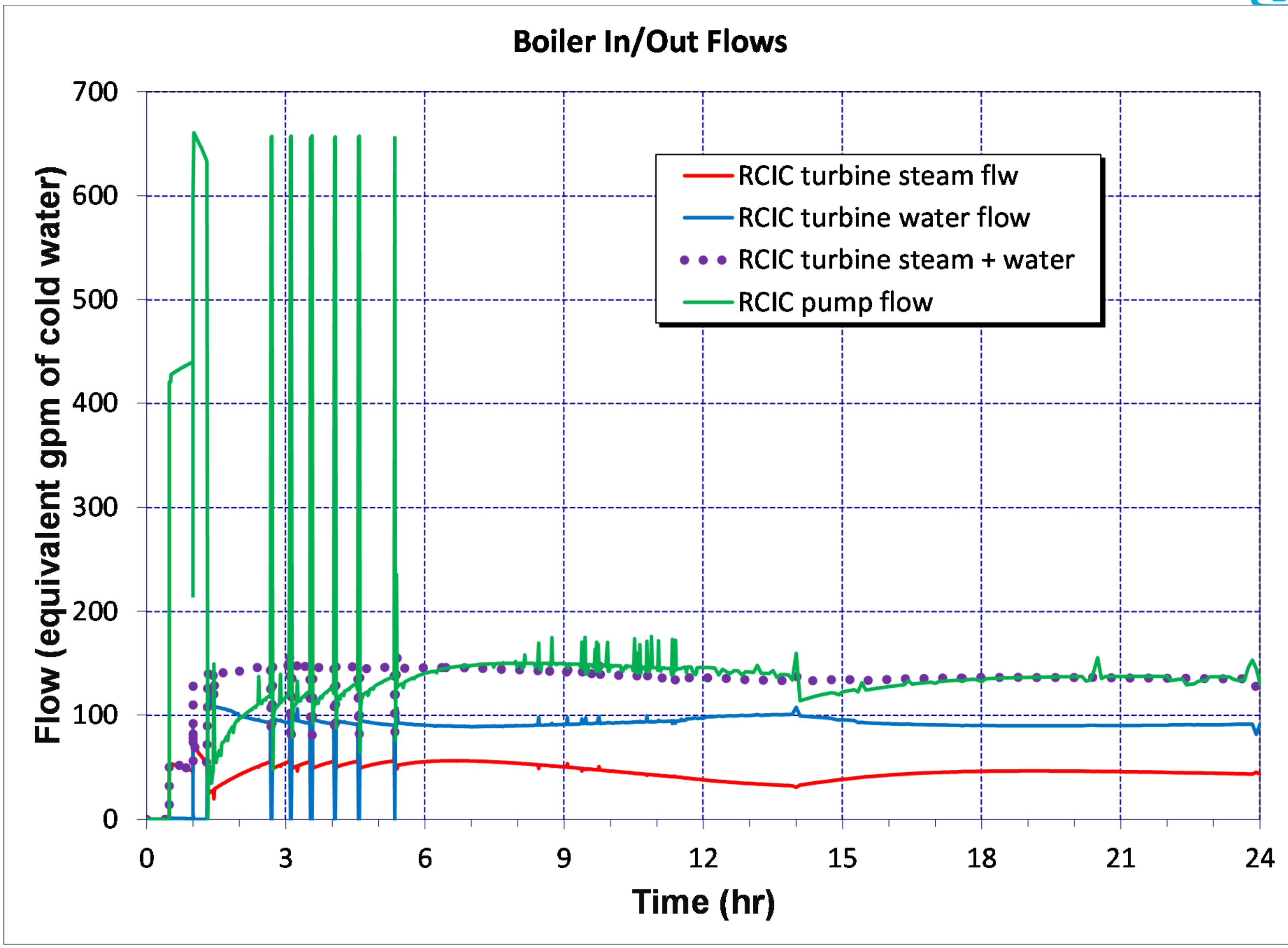
Estimated RCIC Performance with Water Ingestion

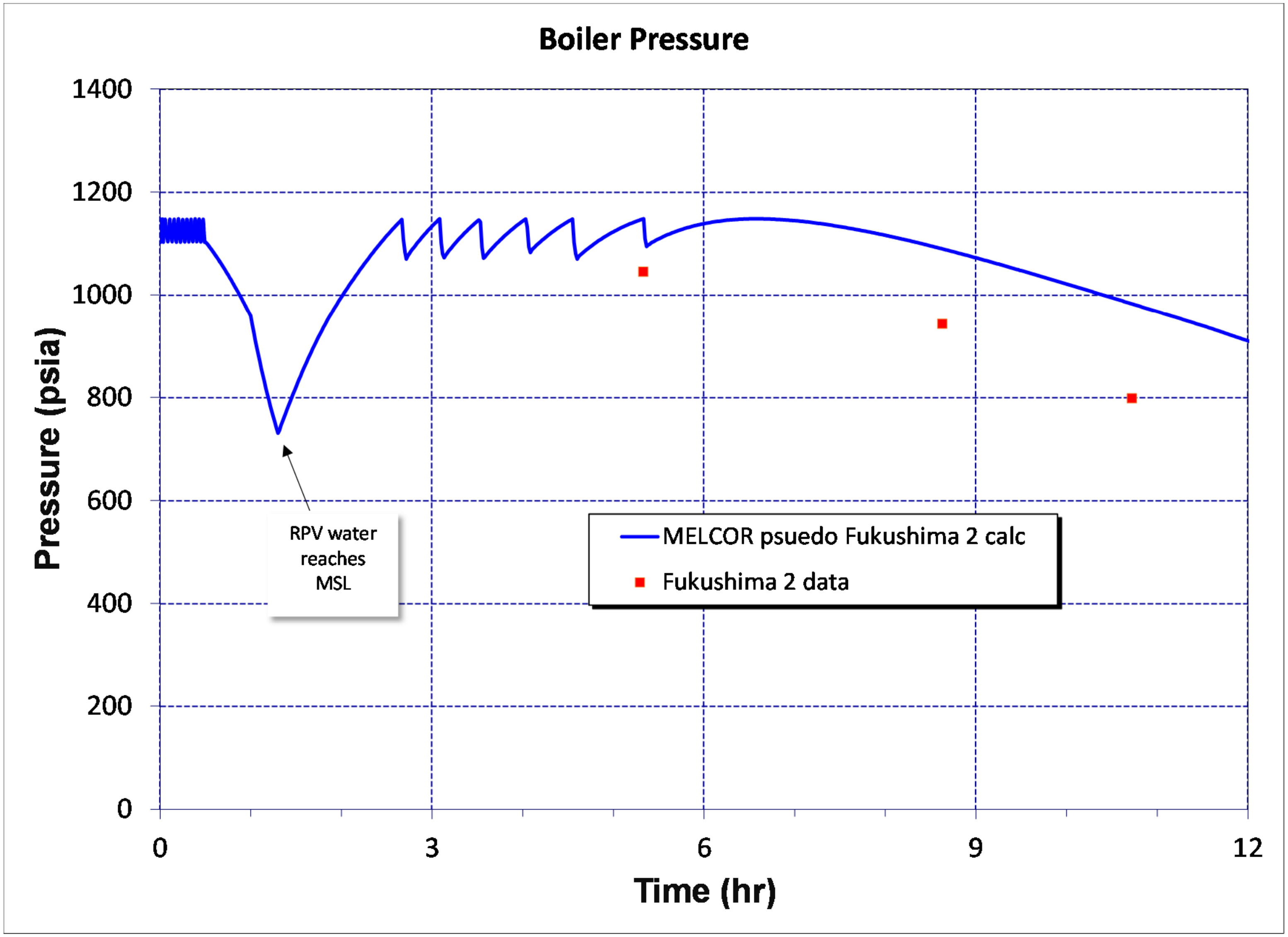
Design RCIC operating conditions					
Void fraction of flow admitted to the RCIC steam supply line from the boiler	Head (ft / psid)	Pump flow (gpm)	Speed (rpm)	Turbine power (hp)	Pump eff (%)
1.00	2,532 / 1,096	426	4,288	399	68.4
RCIC degradation with degree of water ingestion by the turbine (wide open governor)					
Void fraction admitted to the RCIC steam supply line from the boiler	**Shutoff head (ft / psid)**	**Pump flow at 83% shutoff head (gpm)**	**Speed at 83% shutoff head (rpm)**	**Turbine power at 83% shutoff head (hp)**	**Pump eff at 83% shutoff head (%)**
1.00	4,111 / 1,780	358	4976	551	56
0.75	1,282 / 555	311	2779	116	72
0.50	761 / 329	300	2140	62	77
0.25	483 / 209	260	1706	35	76
0.00	335 / 145	253	1421	23	76

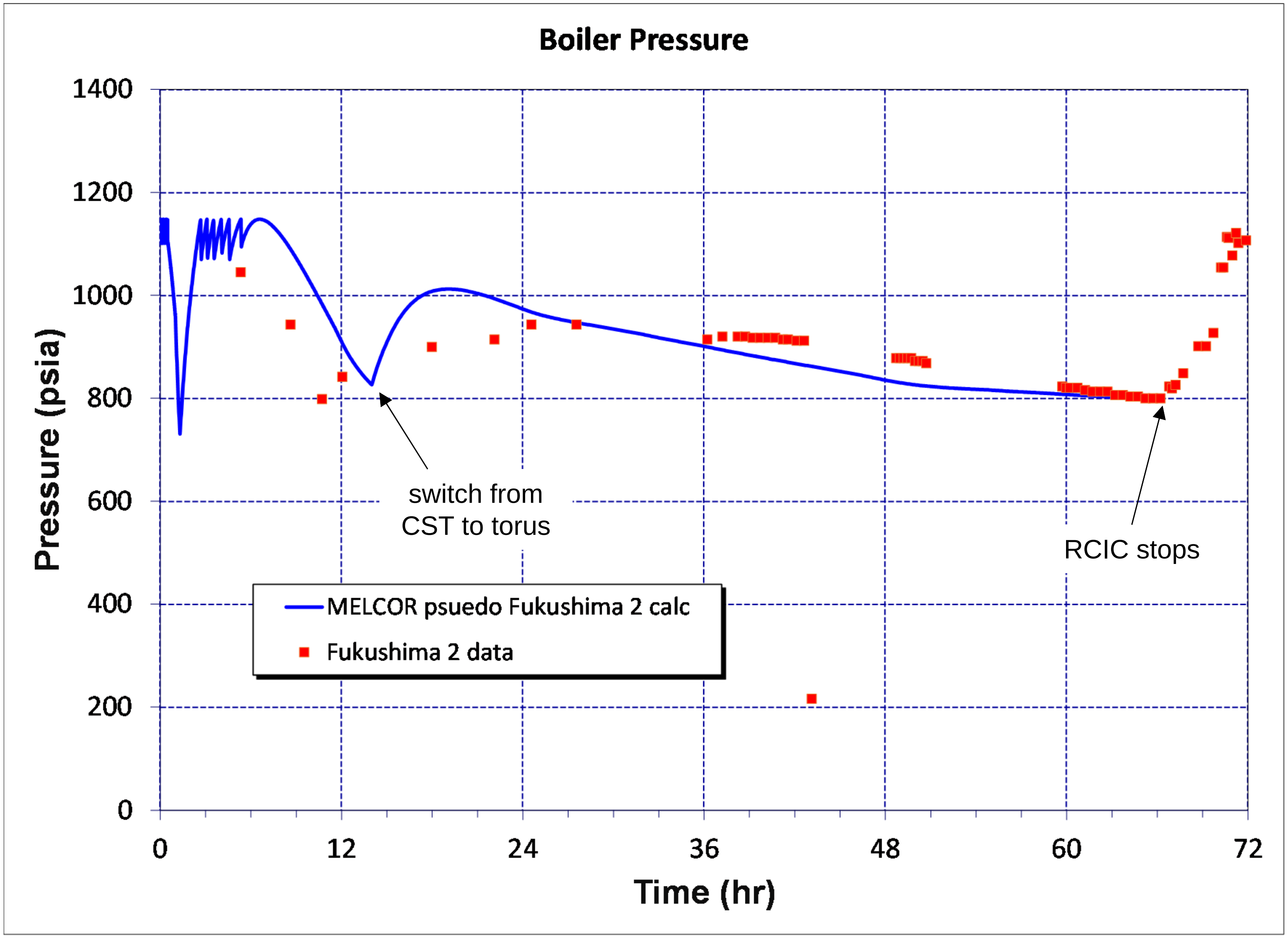
Simplified Fukushima 2 MELCOR Model

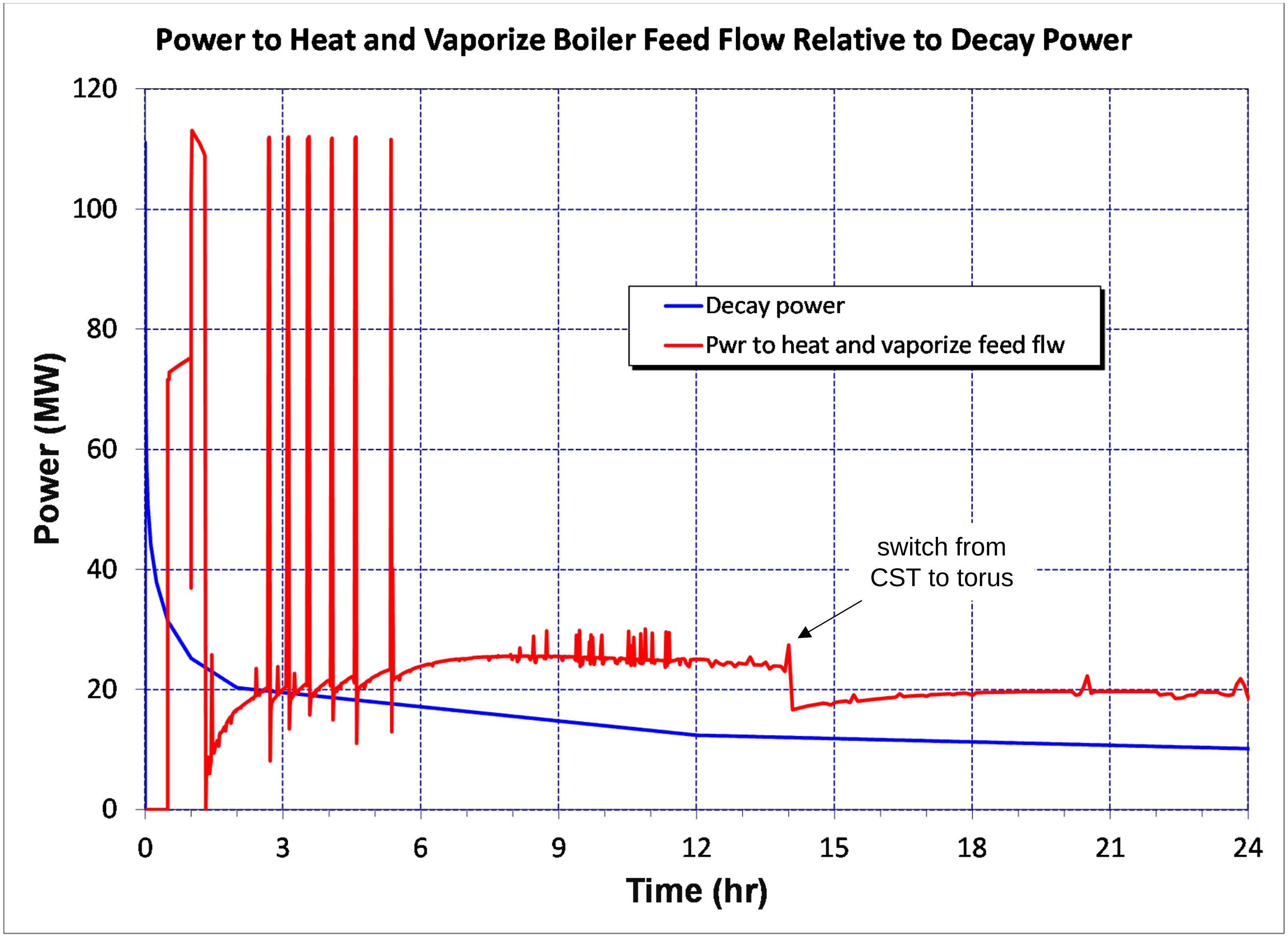



Boiler Level Relative to the Bottom of the Steam Line Nozzles
Level (m)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0
1
2
3
4
5
6
Time (hr)
level
RCIC steam piping entrance
low low level setpoint
Normal level


Boiler In/Out Flows
Flow (equivalent gpm of cold water)
700
600
500
400
300
200
100
0
0
3
6
9
12
15
18
21
24
Time (hr)
RCIC turbine steam flw
RCIC turbine water flow
RCIC turbine steam + water
RCIC pump flow


Boiler Pressure
1400
1200
1000
800
600
400
200
0
Pressure (psia)
0
3
6
9
12
Time (hr)
RPV water reaches MSL
MELCOR psuedo Fukushima 2 calc
Fukushima 2 data


Boiler Pressure
Pressure (psia)
1400
1200
1000
800
600
400
200
0
0
12
24
36
48
60
72
Time (hr)
switch from
CST to torus
RCIC stops
MELCOR psuedo Fukushima 2 calc
Fukushima 2 data



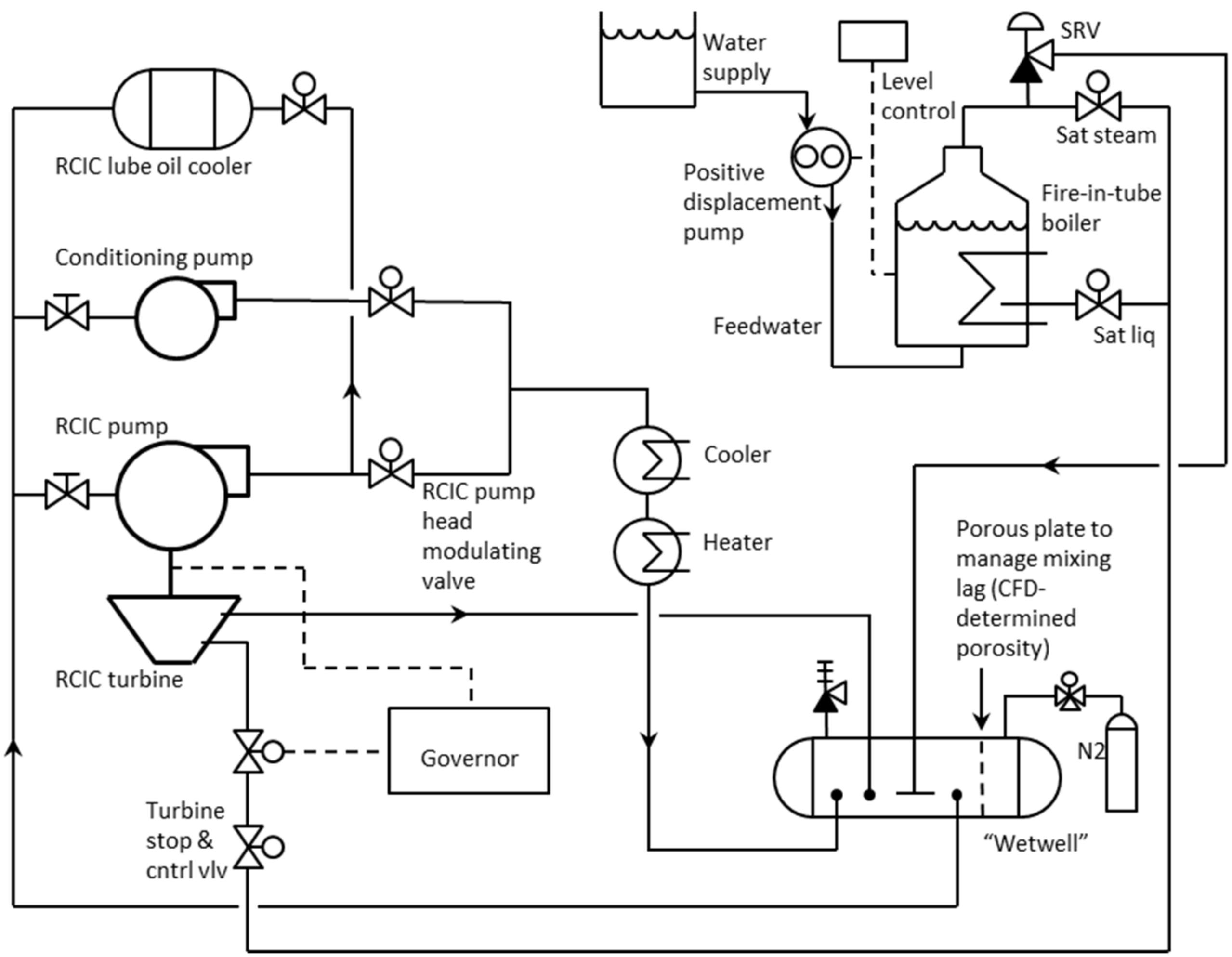
Power to Heat and Vaporize Boiler Feed Flow Relative to Decay Power
Power (MW)
120
100
80
60
40
20
0
0
3
6
9
12
15
18
21
24
Time (hr)
Decay power
Pwr to heat and vaporize feed flw
switch from
CST to torus

DOE Severe Accident R&D Area FY15 Activities

Task 2-14 and 2-15 (SNL) Performance of Critical Safety Equipment Under Severe Accident Conditions

- RCIC operation in Fukushima Unit 1 was far beyond traditionally presumed (~3 days)
  - RCIC survived MSL flooding due to uncontrolled operation
- Model development explaining real-world observed performance needed
  - Turbine performance under 2-phase inlet conditions
  - Pump-side limitations due to suppression pool heating
  - Bearing lube oil limitations
- Performance during severe accident important to understand requirements for FLEX implementation
  - Significant effect on timing requirements

Conceptual Design for General Test Facility – 20MW Boiler



- Considers wide range of testing capability
  - Turbine
  - Pump
  - WW
  - SRV
- Simpler design can be made for RCIC only
- MELCOR model to be developed
- 30 MW facility under consideration

Potential Participants

- Department of Energy
- Industry and Owners Groups
- EPRI
- International
  - Japan IAE and TEPCO (cash contribution)
  - OECD CSNI
- Symposium to align potential stakeholders
- Performing scoping studies on Costs and Requirements
  - RCIC turbine/pump (industry provided?)
  - Facilities – existing or new ?
  - FY-15 initial funds for design development
  - FY-16 to 19 execution of work