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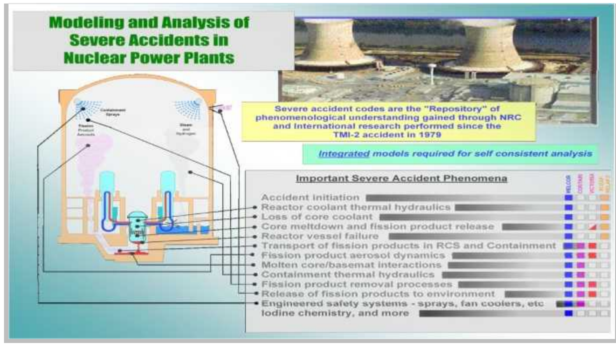

RCIC Operation in Fukushima Accidents as Modeled by MELCOR and Proposed Testing

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U.S. DEPARTMENT OF ENERGY · NNSA National Nuclear Security Administration · U.S.NRC

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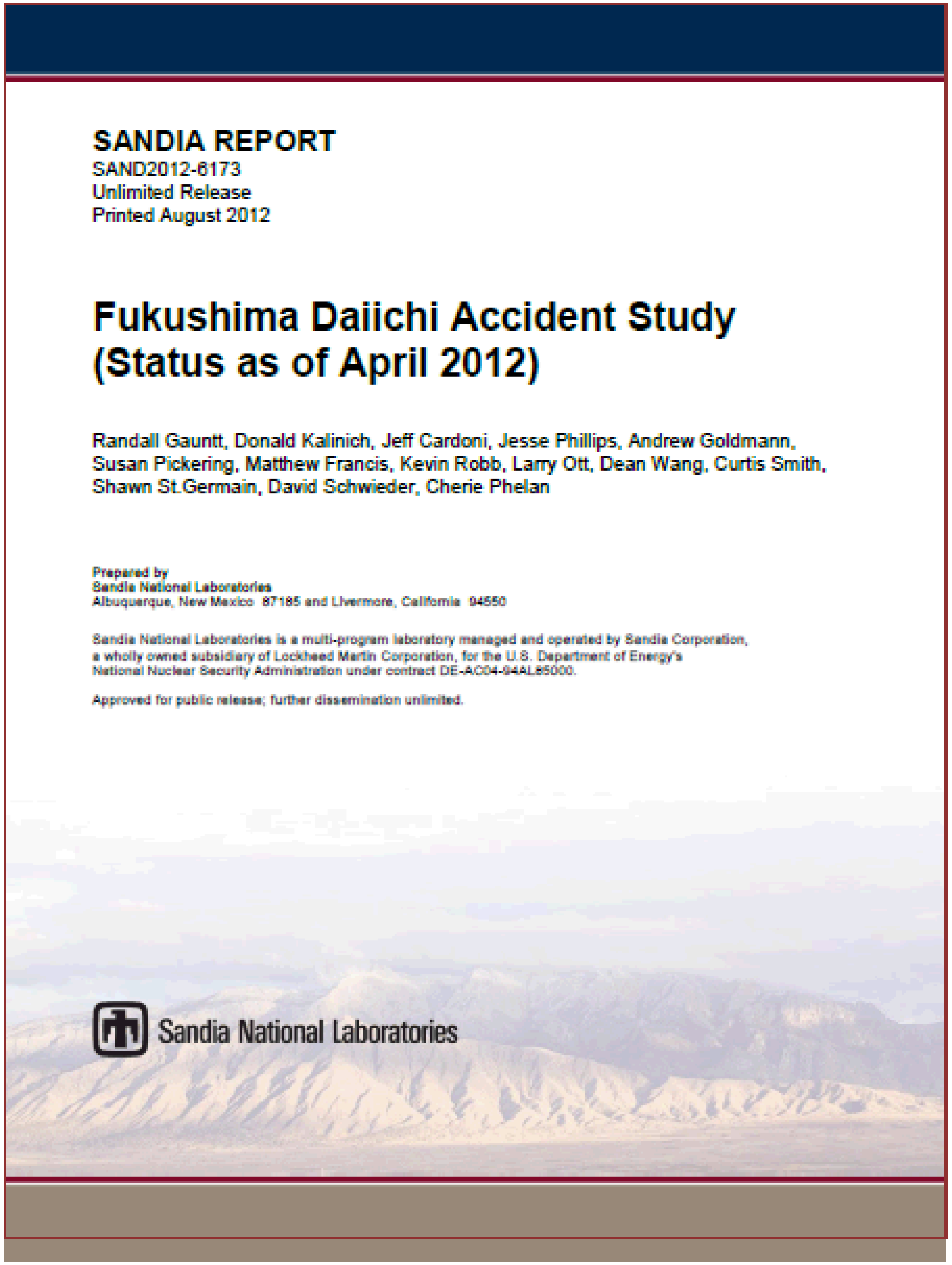
Topics for discussion

- Background
- Key observations from Forensics Analyses of Fukushima Accidents
- Modeling RCIC water ingestion and equipment functioning in real-world accidents
- Proposed path forward



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Fukushima Daiichi Accident Study (Status as of April 2012)

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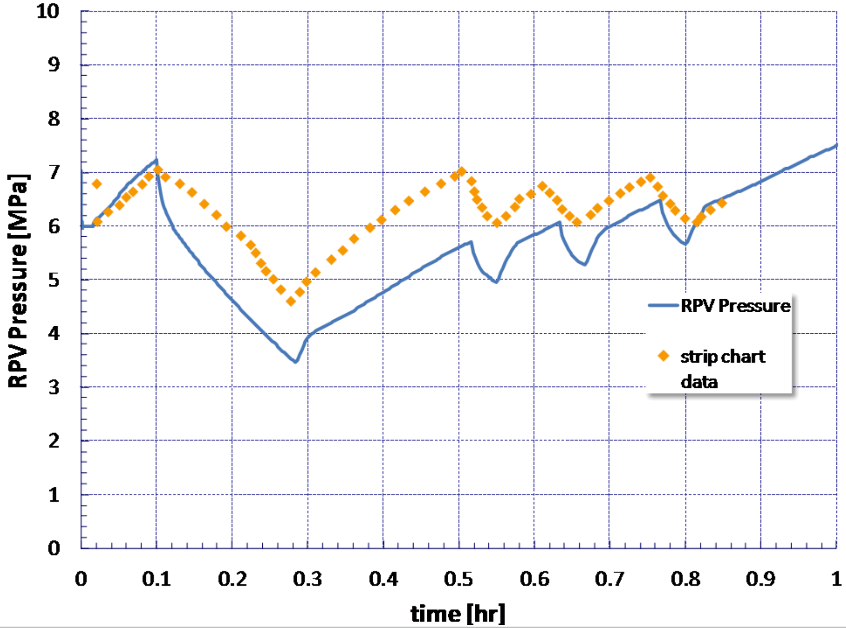
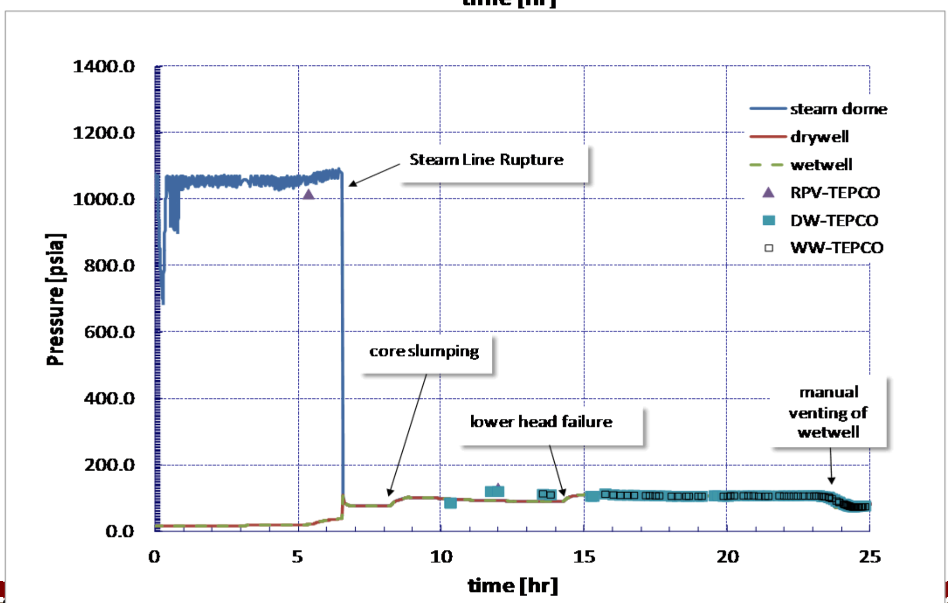
- Sandia commissioned by DOE to conduct forensics analyses of Fukushima accidents using MELCOR severe accident analysis code
- Comparison to pre-Fukushima analyses of SBO in Peach Bottom strikingly similar
- However, important differences observed in key areas
  - RCIC in particular

MELCOR Analysis of Fukushima Unit 1



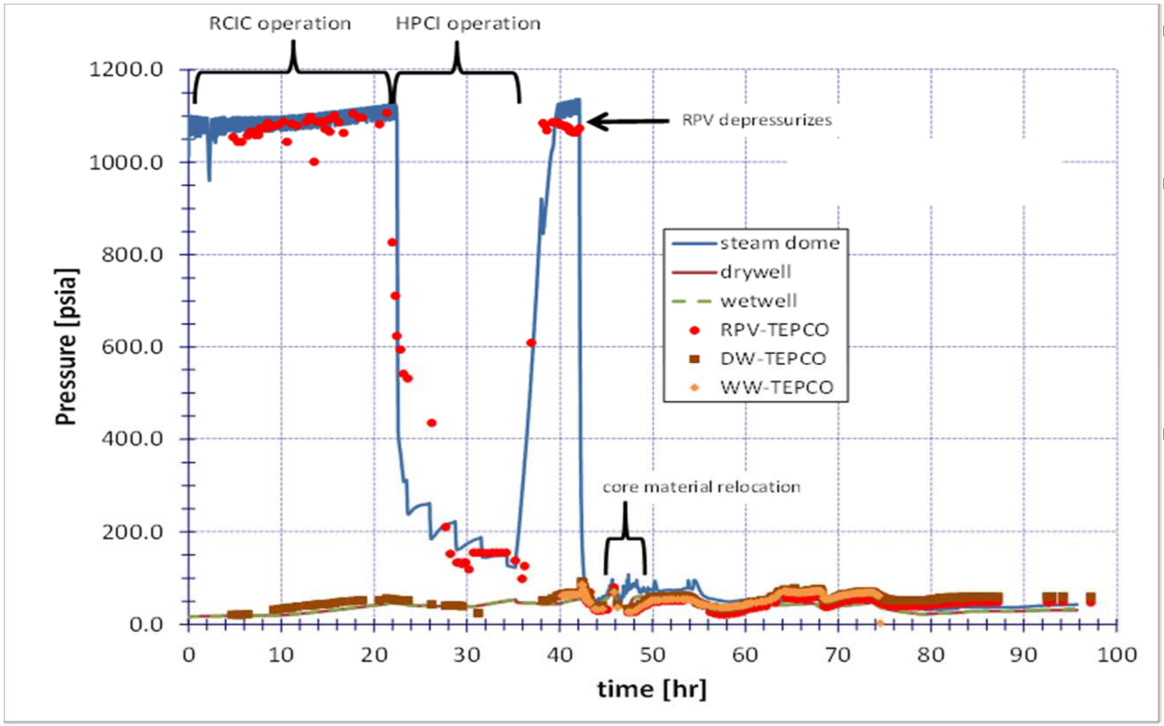


- Prior to tsunami and loss of AC/DC
  - Isolation condensers cooling reactor
  - First two IC's then one
  - Exceeding cooldown rate of 100F/hr – too conservative?
- SBO at ~1 hour due to tsunami
  - Loss of control of functioning IC's
  - IC return valve closed
  - Loss of decay heat removal
- Core damage at ~4 hours
- MSL rupture at ~ 6.5 hours
  - Or SRV gasket failure
- Core slumping by ~8 hours
- Lower head failure ~12.5 hours

Fukushima Lessons Learned: Unit 1

- Isolation condenser was functioning and cooling reactor
  - Operators were cycling IC on and off to avoid cooldown rate exceeding 100 F/hr
  - IC “caught “ in off-position when tsunami flooding disabled DC power
  - Tech Spec cooldown of 100F/hr may be over-conservative – should be re-evaluated
- Unit 1 accident could *perhaps* have been avoided had IC been operating
  - Operators would have to refill IC secondary HX shell
- Potential Industry Response
  - Relax cooldown limits to preserve essential cooling capability (keep IC operating) – *needs evaluation*
  - Make IC easier to actuate with loss of power

MELCOR Analysis of Unit 3

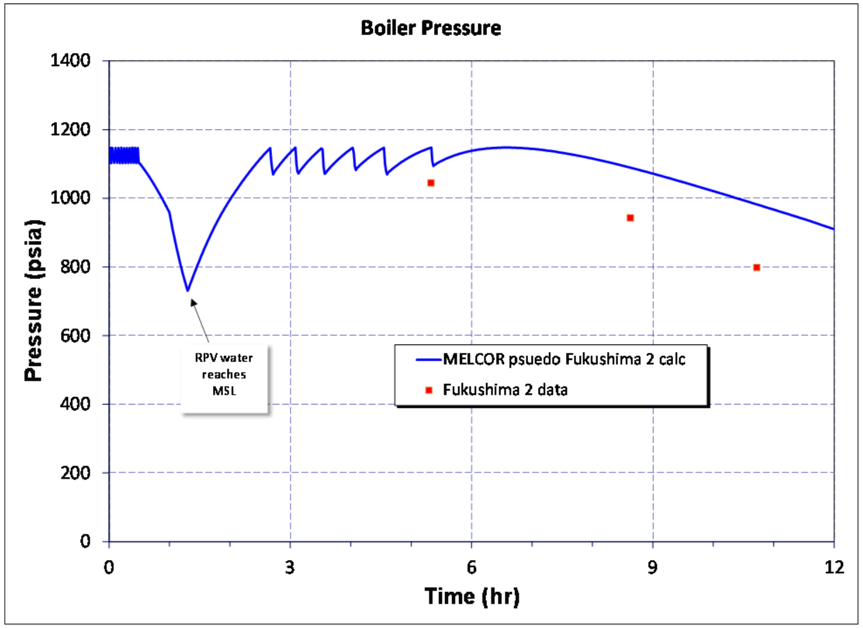


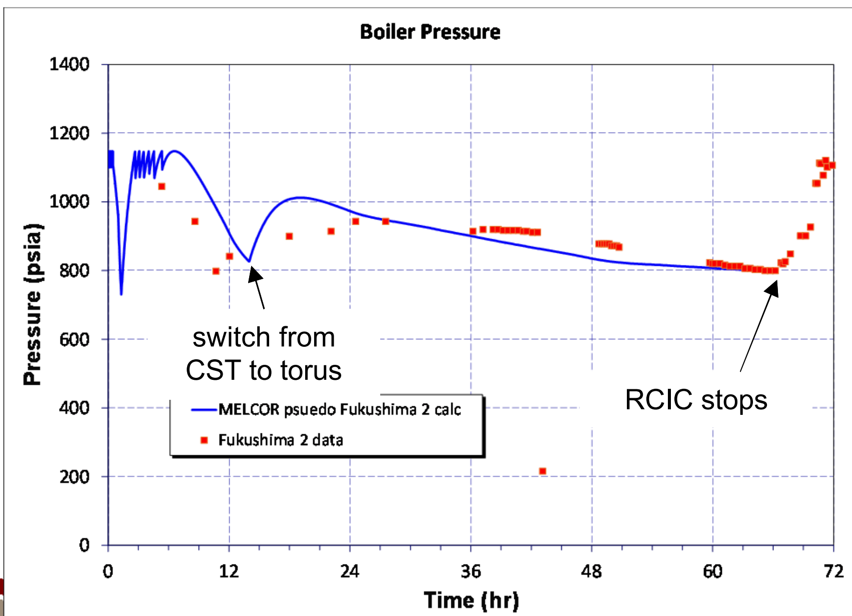
- Unit 3 maintained DC power
  - Active control of RCIC
- RCIC starts level control – runs 21 hours
  - Beyond most current SBO coping times
- RCIC shuts down automatically on high turbine exhaust pressure
  - Automatic system protection
  - Otherwise functioning injection system cannot be restarted
- HPCI is started
  - System run continuously using test line to recirculate water and avoid cycling HPCI on/off
  - Deep depressurization of RPV results
  - After 28 hours HPCI injection is ineffective
  - HPCI stops after ~35 hours
- Core damage underway prior to system depressurization
- Unit 3 probably worst damaged of units

Fukushima Lessons Learned: Unit 3

- RCIC and HPCI were both operational due to DC availability
  - RCIC ran for 21 hours before shutting down on high turbine exhaust signal
    - RCIC and HPCI have numerous automated shutdown criteria to protect turbine and pump
  - HPCI started up but created such extreme RPV depressurization that HPCI pump was not injecting water
  - Core uncovering and early damage occurring as HPCI manually stopped
- Core damage could *perhaps* have been prevented had RCIC not automatically shut itself down
- Possible Industry Response
  - Disable some auto shutdown features in extended ELAP to keep critical equipment operating
  - Better understand operational capabilities of RCIC/HPCI under deyond design basis circumstances

MELCOR Analysis of Unit 2 RCIC





- First 45 minutes RCIC operates normally
- Arrival of tsunami results in loss of AC/DC power
  - RCIC runs uncontrolled (full open)
  - RPV pressure drops until water level reached main steam line (MSL)
  - Water carryover into RCIC turbine degrades performance and RPV heats up
- RCIC operates in self-regulating cyclic mode thereafter
  - RPV water level maintained near MSL with cyclic water ingestion and subsequent clearing
- MELCOR model was developed to account for water ingestion
- Long term pressure trends captured
- RCIC runs for nearly three days
- Eventual shutdown thought due to turbine over-speed
  - Pump cavitation?

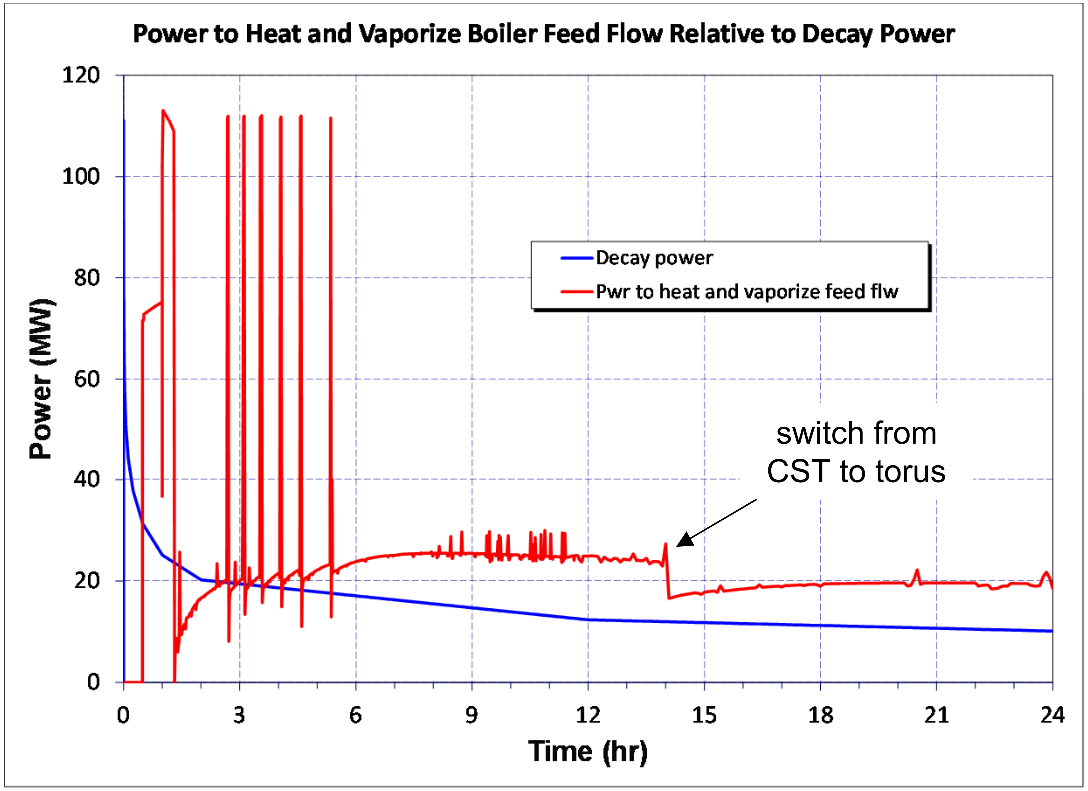
Fukushima Lessons Learned: Unit 2

- RCIC operating at time of loss of power and continued to operate
  - Turbine governor opens fully
  - Electrical shutdown interlocks non-functional due to loss of DC: especially high RPV water level shutdown
  - Water level rose to top of steam lines by 1.5 hours producing liquid water ingestion by RCIC turbine
- RCIC ran for 72 hours running in uncontrolled mode
  - Water carryover did not shut down turbine
  - That's because the Terry Turbine design is *really robust*
- RCIC termination likely by cavitation-induced over-speed trip
  - Suppression pool saturation may have eventually led to pump cavitation and turbine over-speed trip (Mizokami 2013 TEPCO)
- System protection interlocks were defeated by loss of DC allowing RCIC to remain in service

Observations

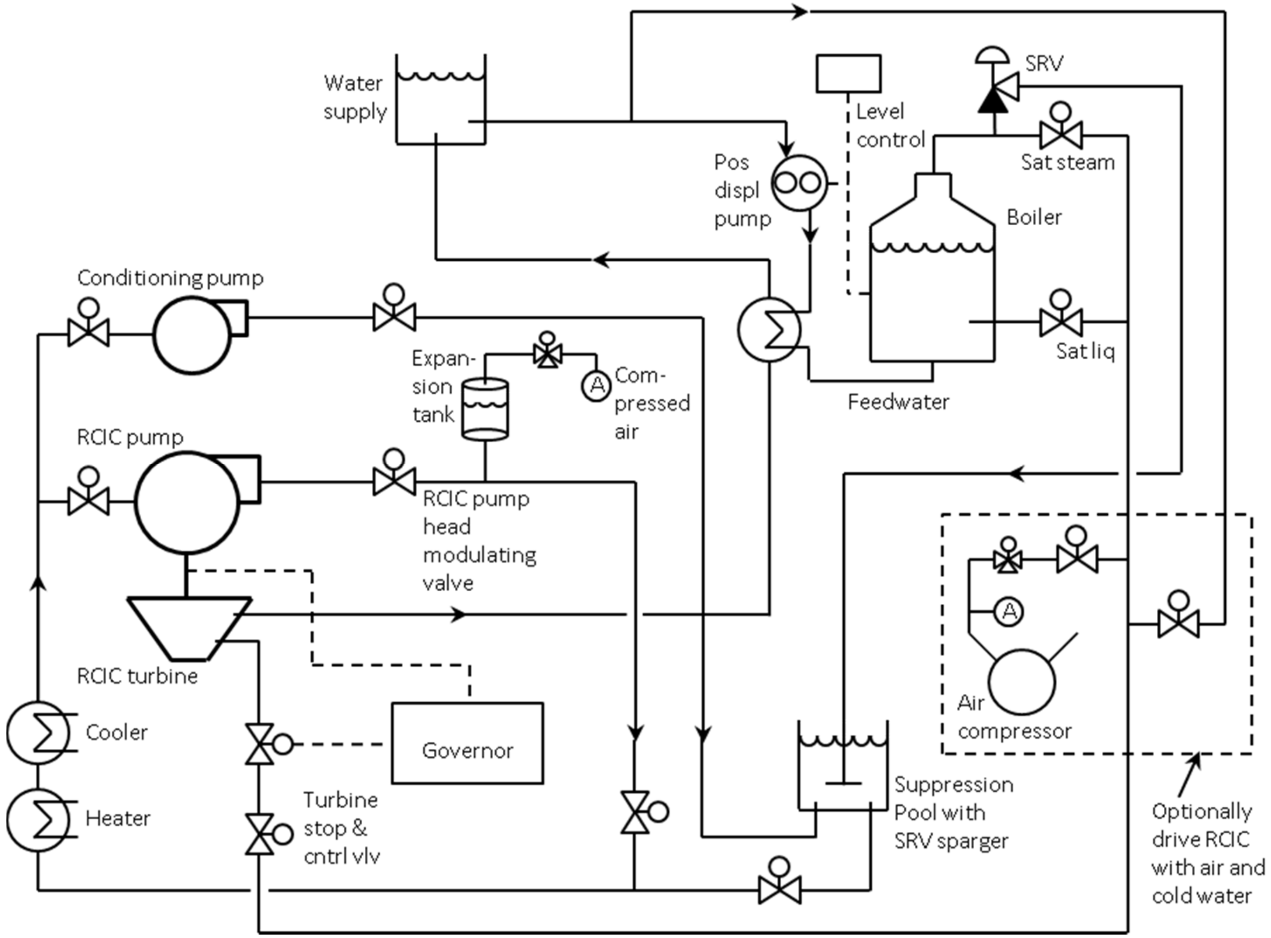
- RCIC system ubiquitous at BWR installations world-wide
  - And widely used in PWR Aux Feed systems
- RCIC system more robust than previously credited
  - PRA and safety studies assume RCIC failure with loss of batteries after 4 to 8 hours – coping times short
- Post-Fukushima NRC Rulemaking will require extension of coping time considerably
- Existing RCIC system seems capable of extended operation even with loss of DC control
- Demonstrating extended RCIC operation under ELAP conditions can bridge gap between current coping times and FLEX implementation by 24 hours
- Propose full scale testing to demonstrate technical basis for extended RCIC operation

Power Requirements for Full Scale Testing



- Normal RCIC energy requirements in MW range
  - 500 hp typical pump power
- Energy draw with water ingestion is considerably larger
  - Larger specific enthalpy of water carryover
- Steam/water system required to demonstrate operation under water ingestion is roughly decay heat levels
  - 20 to 30 MW

Conceptual Design for General Test Facility – 30MW 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

Objectives of RCIC Testing

(and other critical systems and components)

- Confirm self-regulating operational mode of RCIC
  - Early testing of RCIC response to "water slug" suggests RCIC not damaged
  - Operational characteristics need to be demonstrated
    - Effect of liquid water fraction in steam flow
  - Long-term RCIC operation needs to be demonstrated
- Potential scope of investigations
  - Operating pressure and water carry-over fraction
  - Pump head versus water carryover
  - Turbine speed and pump effectiveness (flow and head)
  - Potential response of interlocks in self-regulating mode
  - Response to turbine exhaust pressure and other environmental conditions

Potential Participants

- Department of Energy
- Industry and Owners Groups
- EPRI
- International – Japan Institute of Applied Energy/TEPCO
- SNL performing scoping studies on RCIC model development, Costs and Requirements
  - Facilities – existing or new ?, will assess situation.
  - FY-15 initial DOE funds ($250K) for model/design development and test protocol
  - FY-16 to 19 TBD

Summary

- Fukushima analyses have revealed deep insights into real-world operation of critical systems
  - Currently too conservative assumptions of operational capabilities
- Capable cooling systems disabled by:
  - loss of DC (IC control in Unit 1)
  - Shutdown interlocks (*availability of DC* caused shutdown of Unit 3 RCIC)
  - Long term operability of RCIC under water ingestion conditions suggested by Unit 2 *due to loss of DC*
- RCIC system can potentially bridge gap between current coping times and FLEX implementation
  - Full scale testing can confirm technical basis
  - Analogous benefit likely for turbine-driven Aux feed in PWR's