SAND2015-8178PE

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Sandia National Laboratories

Source: Tokyo Electric Power Company

Critical Equipment Performance

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U.S. DEPARTMENT OF ENERGY | Nuclear Energy

NNSA National Nuclear Security Administration

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Motivation

NRC State-of-the-Art Reactor Consequence Analyses included BWR short-term and long-term station blackout scenarios and were performed ***before*** Fukushima accidents

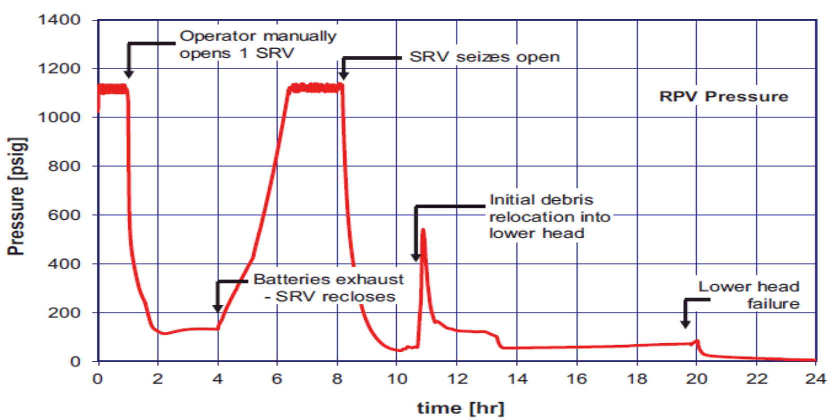
- Both sequence types were observed in the Fukushima accidents
  - *Striking similar trends and operator responses*
- These accidents are classic and among the collection of ‘usual suspects’ for analysis

Critical equipment performance under beyond design basis conditions brought new insights into realistic operation

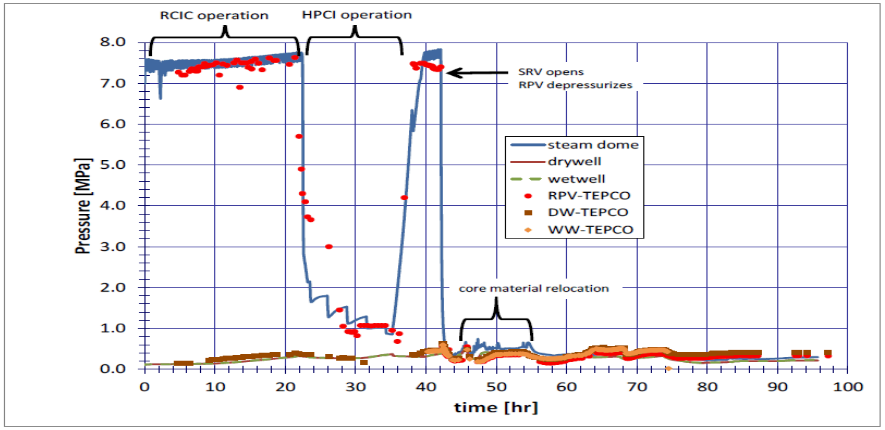
- Understanding of real-world operations can delay or prevent severe accidents

More information will come from post-accident decommissioning activities

- Main steam line failure, safety relief valve seizure, and containment liner failure



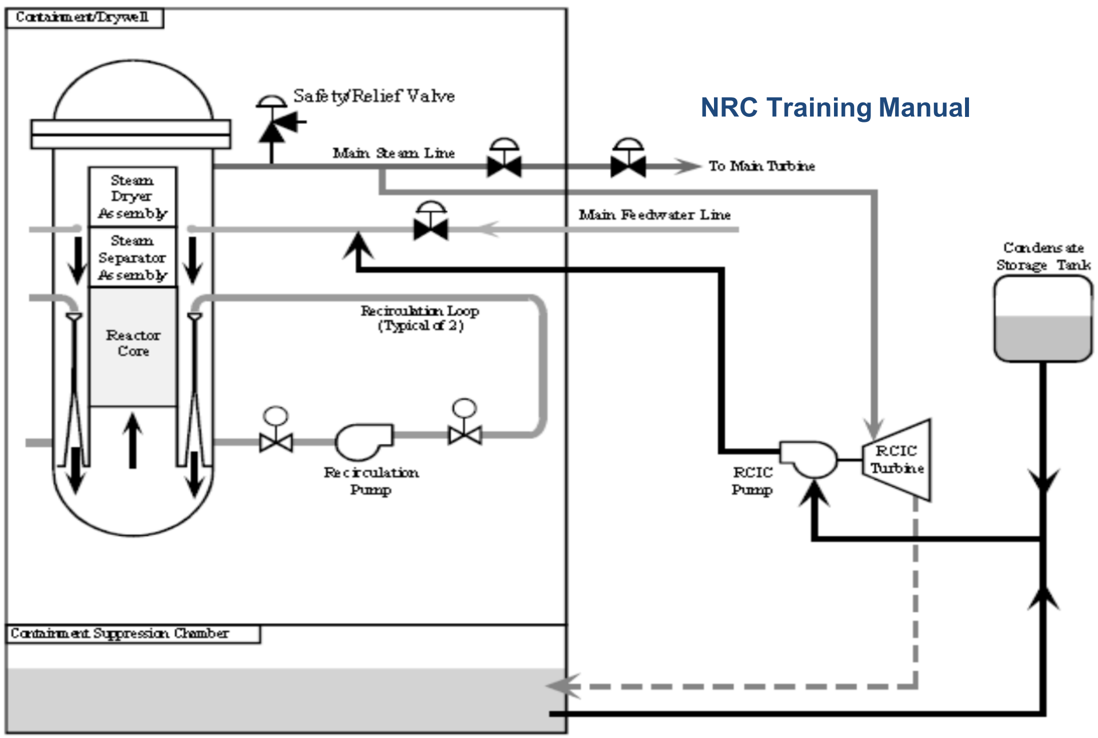
SOARCA BWR LTSBO



Fukushima Unit 3

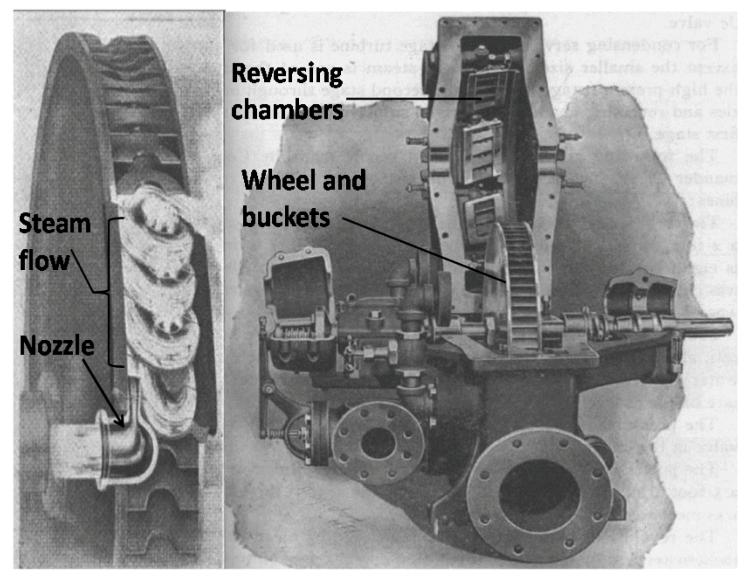
Reactor Core Isolation Cooling

- RCIC pump is driven by Terry Turbine developed circa 1900
  - *Robust design tolerates wet steam (i.e. water/steam)*
- Prior assumptions held that steam line flooding would kill RCIC
  - *SOARCA predicted ~1.2 hrs till RCIC failed due to steam line flooding*
- Fukushima Unit 2 experience shows otherwise
  - *Operated in a 'self regulating' mode for days*



NRC Training Manual

Journal of the American Society of Naval Engineers



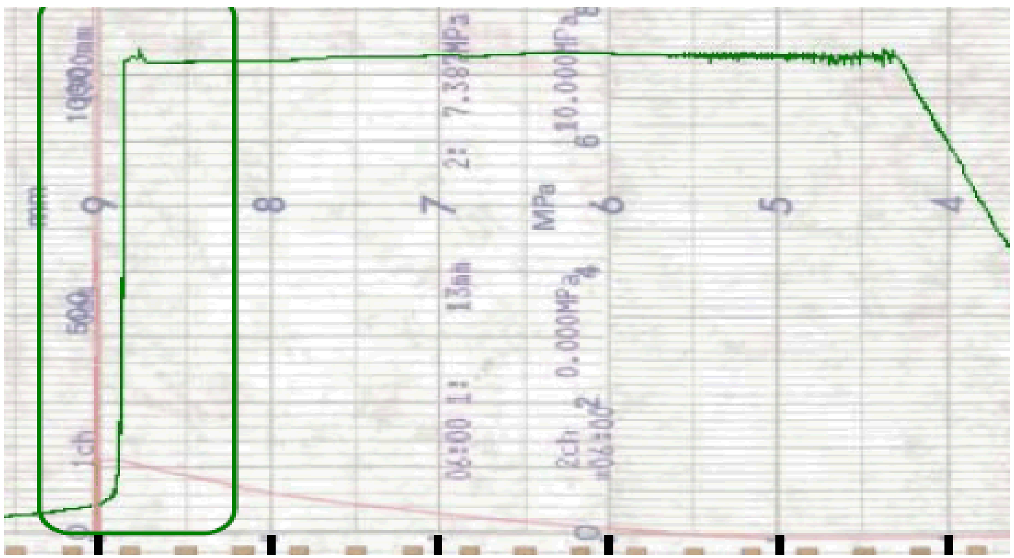
Safety Relief Valve Failure

Timing of SRV failure is important:

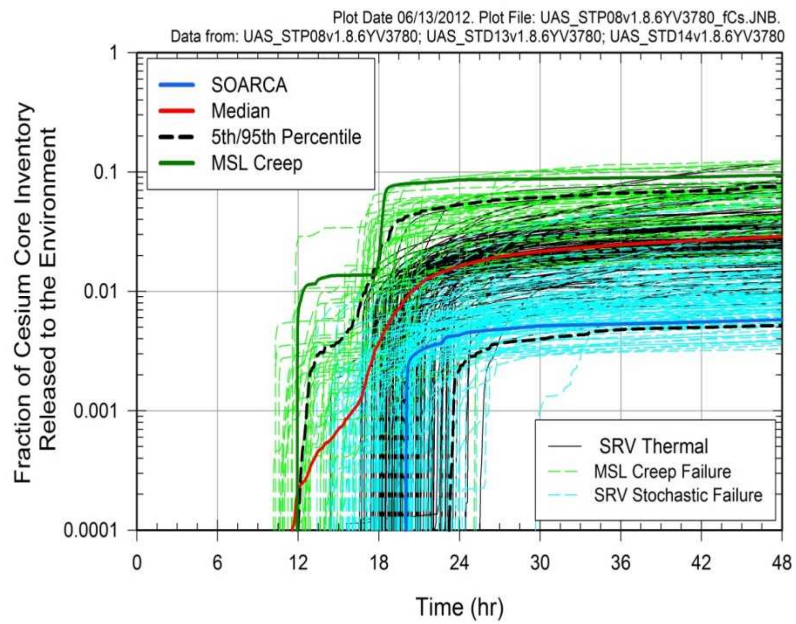
- Stochastic – excessive cycling data is nonexistent beyond Fukushima
- Thermal – failure due to cycling with high temperature gases passing across the valve
  - *Severe accident conditions*

Potential for main steam line failure (MSL):

- SOARCA predicts SRV will fail thermally first in all cases for MSL failure
- SOARCA identifies this as a major bifurcation in accident source term transport



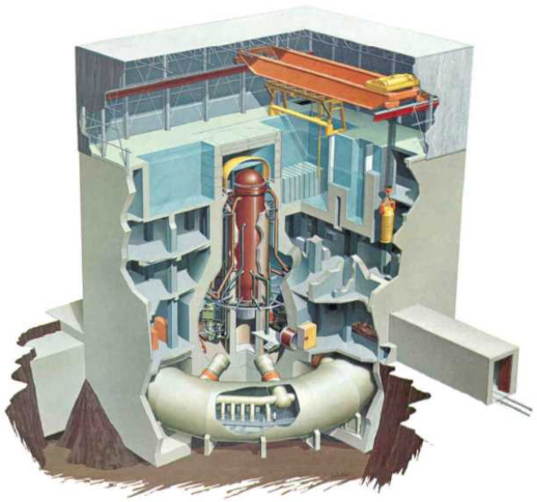
Unit 3 SRV behavior

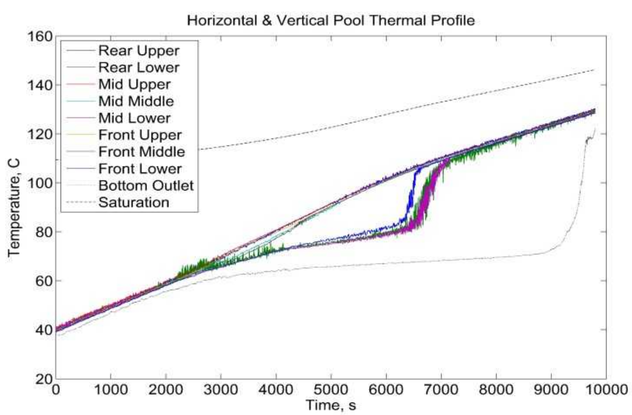


SOARCA BWR Uncertainty Analysis

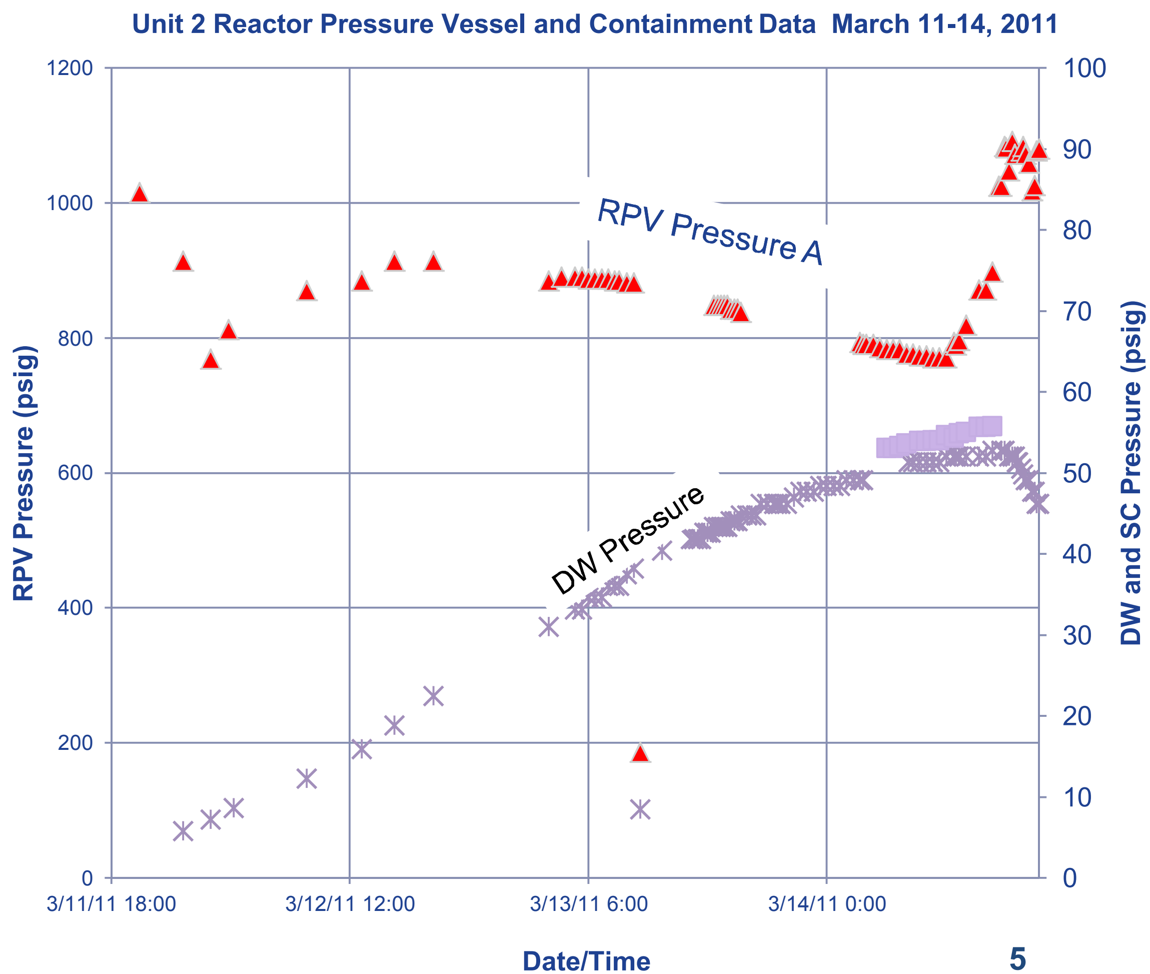
Suppression Pool Stratification

- Extended RCIC operation at Fukushima resulted in suppression pool stratification
  - *Observed when Unit 2 lifted SRV and containment pressure went **down!***
- The upper 'hot' layer could result in lost of net positive suction head for RCIC pump





Scaled Suppression Pool Experiment - TAMU



RCIC Expanded Operating Band

Reduce and Deter Costs:

- Provide for an improved transition to portable FLEX equipment
  - *Deferring the use of FLEX by expanding the Terry Turbine operational margin at just one BWR plant (RCIC) will save over $450M and the associated fleet costs in response to the FLEX event*
- Expand the high temperature and low pressure Terry Turbine operational bands
  - *Provide for improved operational guidance during low speed operation*

Reduce Risk of Operations:

- Update emergency operating procedures to reduce the likelihood that any beyond-design basis event will progress to core damage
- Establish the technical basis for the steam driven systems operational changes that prevent events from progressing to core damage (reduce core damage frequency and plant risk)

Simplify Plant Operations:

- Add flexibility to respond to events by examining RCIC operational conditions identified in the Fukushima accidents; Terry Turbine self-regulation with water level
  - *This can also be a game changer similar to feed and bleed identified after TMI-2 for PWRs*
  - *Addresses NRC Flood and Seismic Mitigating Strategies Assessments in response to Mitigating Strategies Rulemaking and Near-Term Task Force Reevaluated Hazards per 50.54(f) criteria*

Ranked 3rd in the LWRS-RST Gap Analysis:

- *Rank #1: Uncertainties related to phenomenology of late-phase in-core melt progression*
- *Rank #2: Uncertainties related to phenomenology of core melt behavior in the lower RPV head*

RCIC Modeling

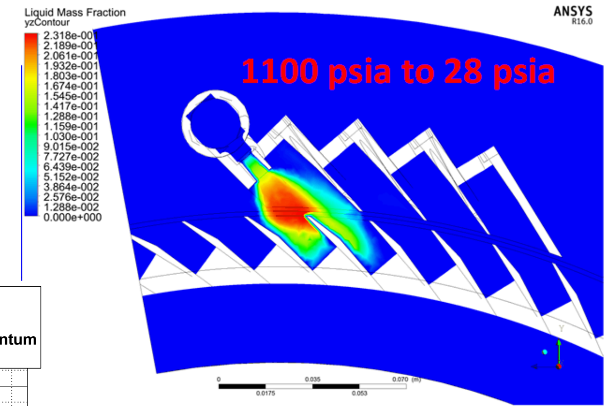
Governing equations for RCIC Model:

- First principles derivation for an impulse turbine model to implement into system-level codes
- Quasi-steady state and differential equation schemes

$$\omega_{n+1} = \frac{-(I + r^2(\dot{m}_v + \dot{m}_l)\Delta t) + \sqrt{(I + r^2(\dot{m}_v + \dot{m}_l)\Delta t)^2 + 4\frac{\eta\Delta t}{1+cos\beta}\frac{T_o}{\omega_o^2}[I\omega_n + 2r\psi(\dot{m}_v V_v + \dot{m}_l V_l)\Delta t]}}{2\frac{\eta\Delta t}{1+cos\beta}\frac{T_o}{\omega_o^2}}$$

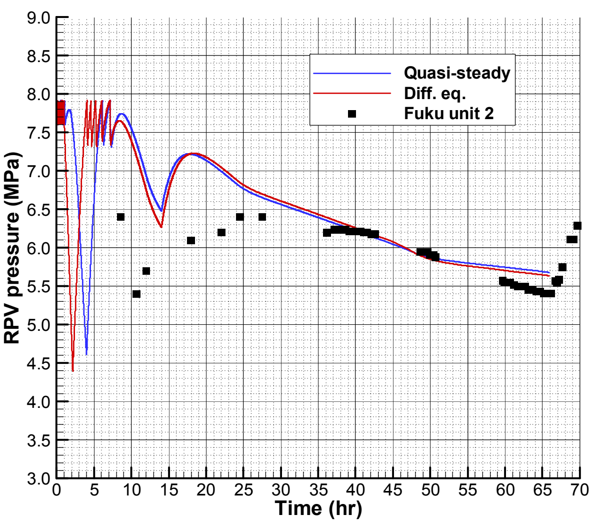
CFD analyses:

- Provides information to system-level modeling on nozzle

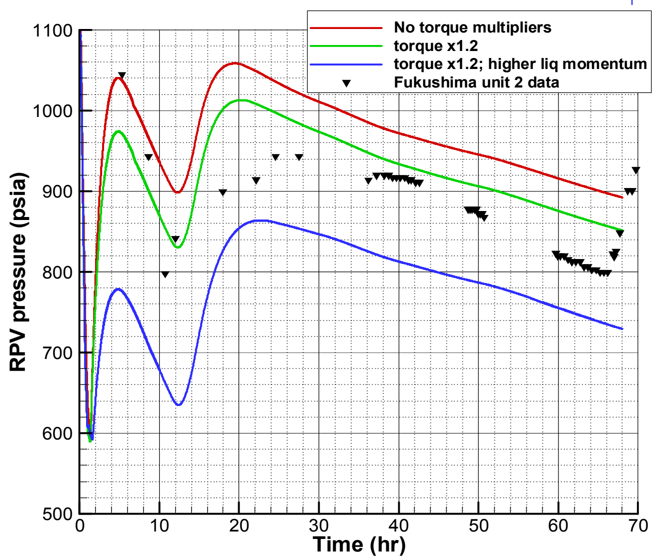


System-level analyses:

- Provides information to CFD modeling
- Homologous pump curves



MELCOR Model



RELAP5-3D Model

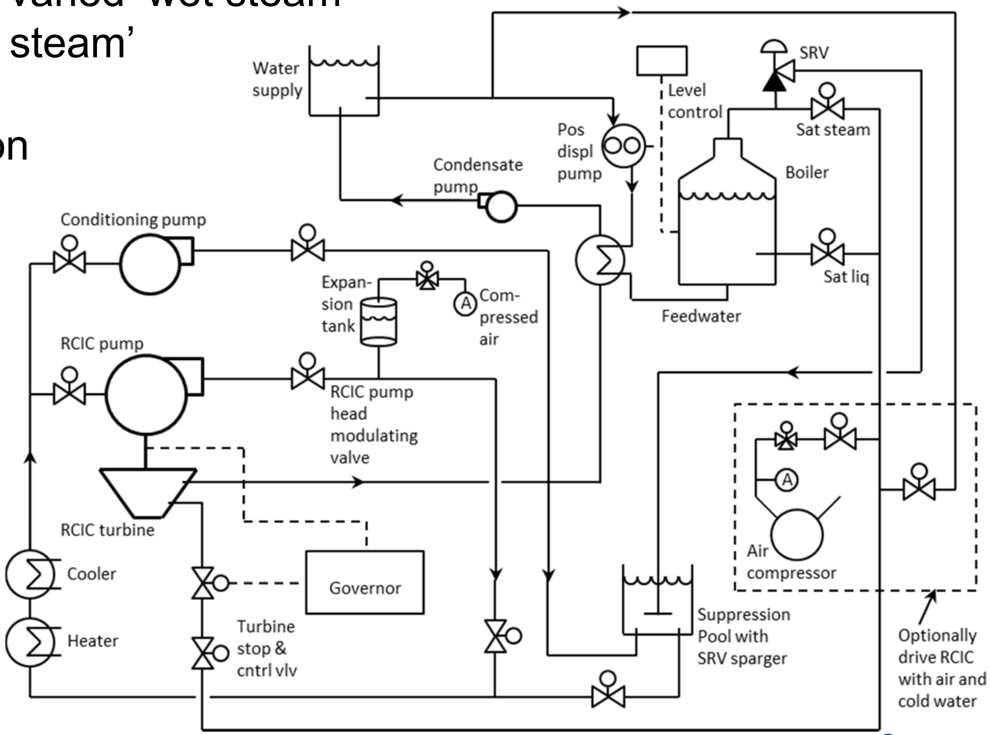
RCIC Experiments

RCIC Modeling will help inform experimental design:

- Boiler capacity is estimated 8-18 MW_{th}
- Heat rejection is estimated ~85% of heating capacity
- Long-term runtimes (~3-4 days)

Potential experiments:

- Regulate steam quality from saturated to varied 'wet steam'
- Oscillations from saturated to varied 'wet steam'
- Lubricating oil degradation
- Replicate Fukushima Unit 2 self-regulation



Additional Modeling & Experiments

SRVs:

- Use of conservative assumptions regarding equipment functioning as found in PRA applications may limit the anticipated mitigation options
- SRV performance in BWRs can defines a bifurcation in source term transport, suppression pool scrubbing effectiveness, and potential releases to the environment
- Varied SRV types across the PWR and BWR fleet
- Limited operational data and test data under normal conditions
- No data on excessive cycling or severe accident conditions

Suppression Pool Stratification:

- Insights into the interactions between the suppression pool, the RCIC turbine steam exhaust entering the pool
  - *The possibility of local saturation at the pool location were the turbine exhaust*
  - *The potential results of uncondensed steam collecting in the air space above the pool and subsequent pressurization of the wetwell above the overall saturation pressure of the suppression pool water*
- Small-scaled efforts at Texas A&M University

Questions