SAND2017-10566PE

Source: Tokyo Electric Power Company

Terry Turbopump Expanded Operating Band Program Experimental and Modeling Efforts

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

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Overview

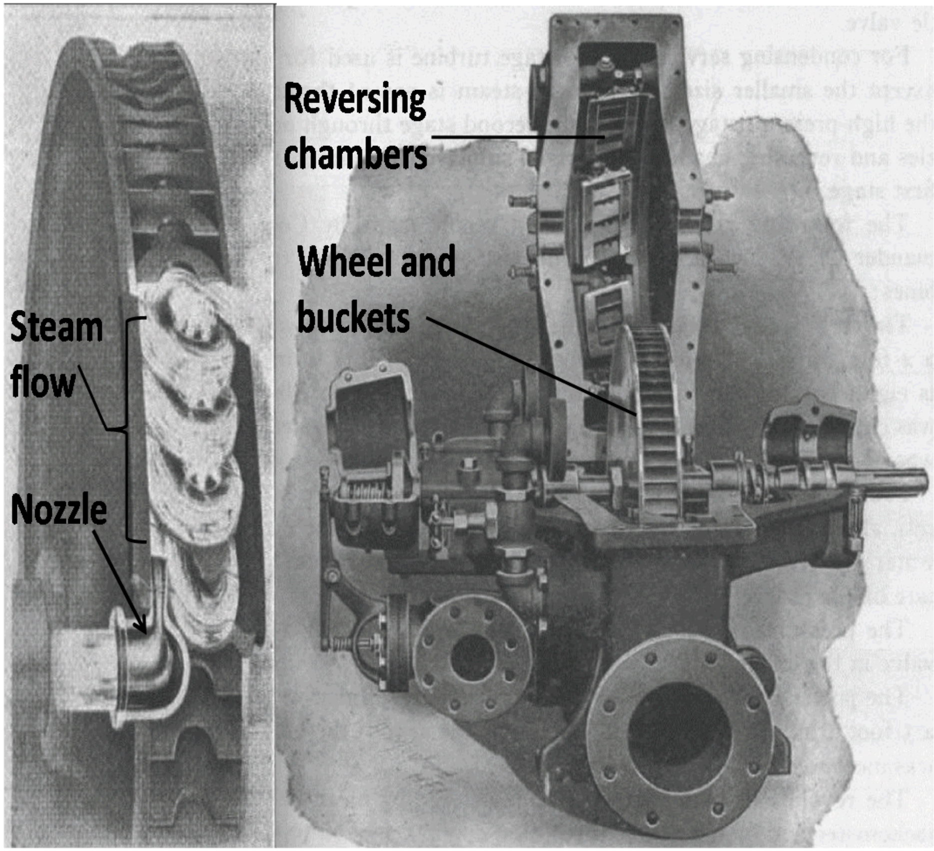
- Background
- Experimental Efforts and Facilities
- Schedule
- USDOE Modeling Efforts

Terry Turbopump Basics

Impulse vs. Reaction Turbine

Terry turbines were principally designed for waste-steam applications with the following key attributes:

1. The turbine and casing are not pressurized out of necessity: it may be at low or even atmospheric pressure;
2. Rapid startup (less than 60 s) is of primary importance;
3. Reliability, resilience under off-nominal conditions, and low maintenance are of primary importance;
    - Known to ingest and work through water slugs
4. Efficiency is of secondary importance.



Journal of the American Society of Naval Engineers

Sandia Motivation

NRC State-of-the-Art Reactor Consequence Analyses included BWR station blackout scenarios (SBO) performed *before* Fukushima accidents

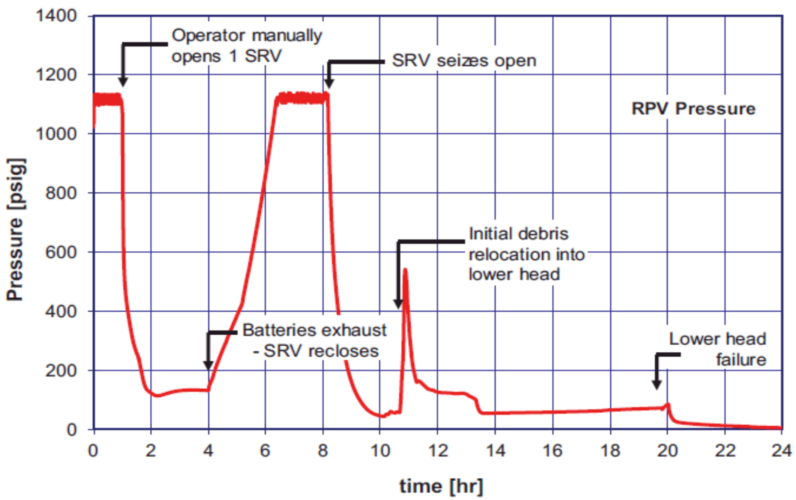
- Sequences observed at Fukushima
  - *Striking similar trends*
- Accidents are classic and 'usual suspects' for analysis

Fukushima critical equipment performance brought new insights

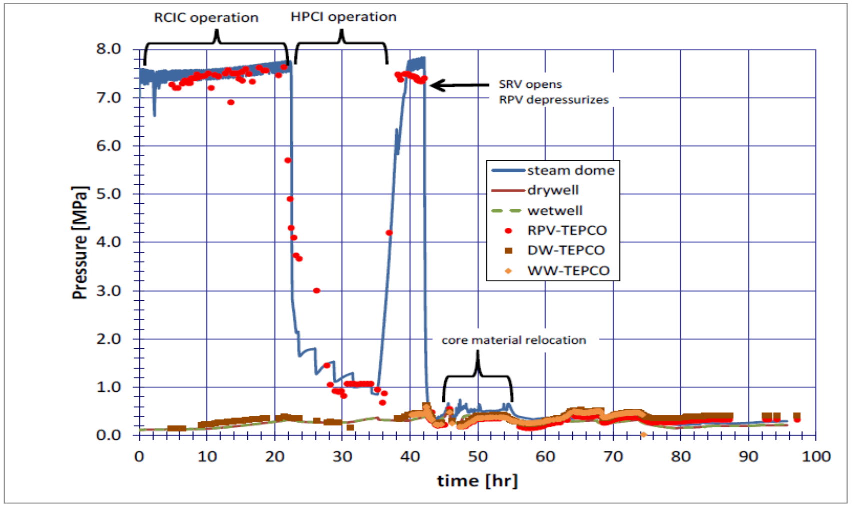
- Understanding of real-world operations can delay or prevent severe accidents

More information will come from decommissioning activities

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

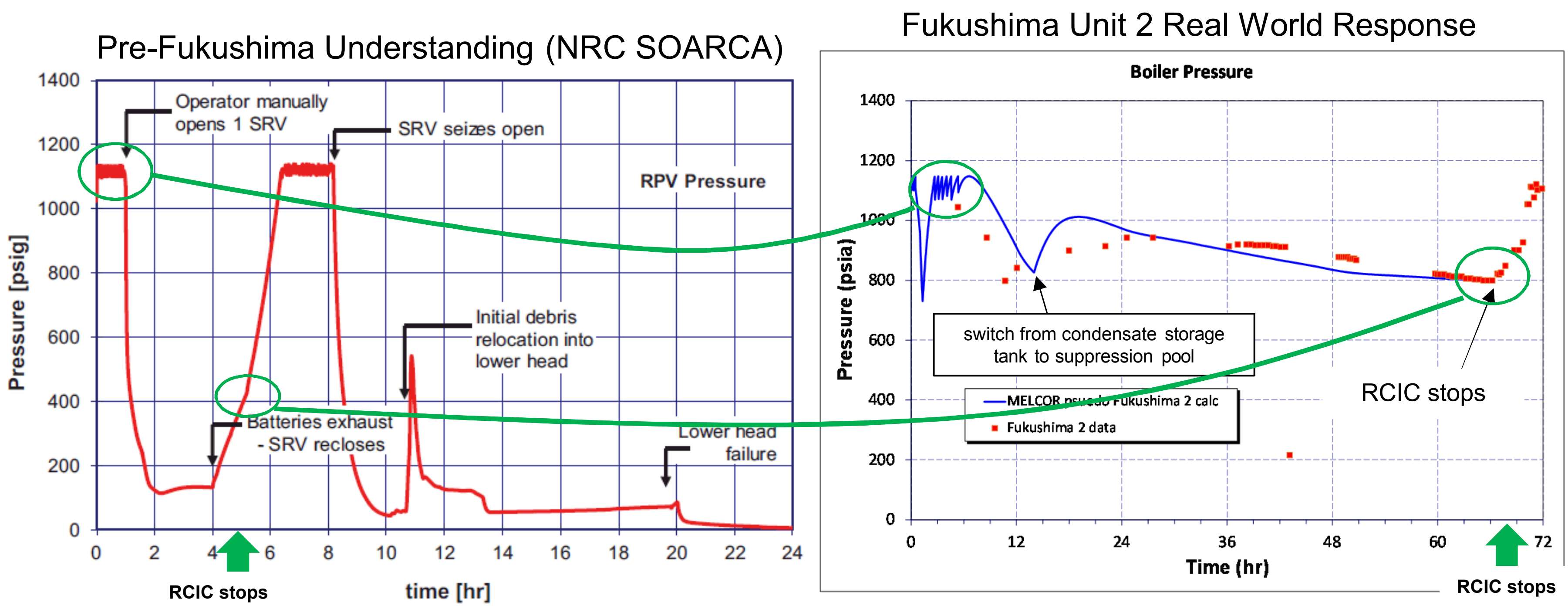


SOARCA BWR LTSBO



Fukushima Unit 3

Modeling of SBO Accident before and after Fukushima
(MELCOR Analyses and Fukushima Data)



- Turbine-driven RCIC injection maintains desired water level in reactor pressure vessel (RPV)
- Battery depleted @ 4 hours
  - *SRV closes and RCIC runs full on*
  - *RPV overfills, MSL floods, water enters RCIC turbine, and RCIC assumed to fail*
- Core meltdown at 10 hours

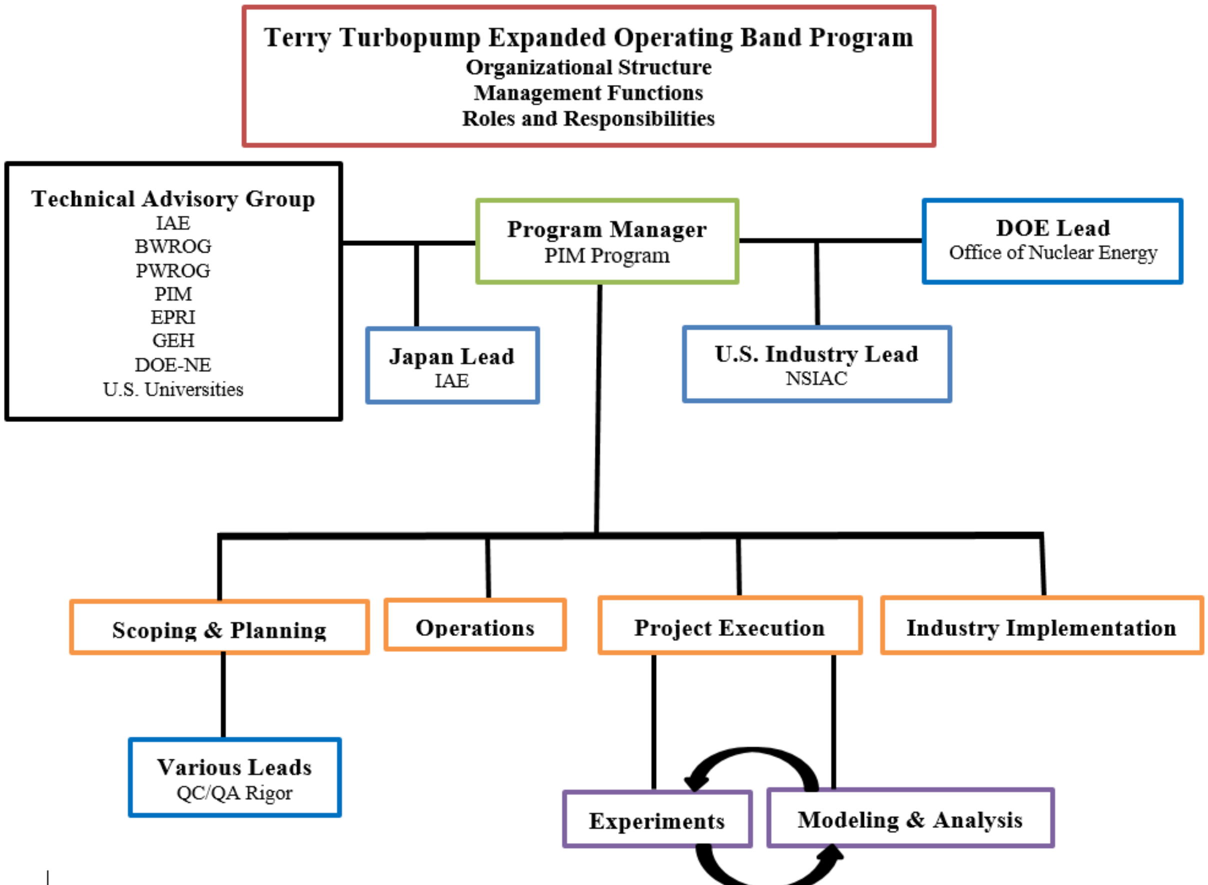
- Turbine-driven RCIC injection maintains desired water level in RPV at start of event
- Batteries fail @ 45 minutes from tsunami flooding
  - *RPV overfills, MSL floods, water enters RCIC turbine, but RCIC turbine does not fail*
  - *RCIC self-regulates RPV water level in cyclic mode*
- Core damage avoided for nearly 3 days

Initiative Mission Statement

The goal of the international TTEXOB (Terry Turbine Expanded Operating Band) Team (*Consortium*), is to define and provide input to expand the actual operating limitations (margins) of the Terry turbine systems (i.e. RCIC/TDAFW) used in the nuclear industry. The TTEXOB Initiative (*Project*) is the method for accomplishing the *Consortium's* goals.

Project Participants

TTEXOB consortium group is comprised of the BWROG, US DOE, and IAE-Japan as major participants, with involvement of Sandia National Labs, Idaho National Lab, and PIM as illustrated below:



Value of Extended Performance
(beyond design basis conditions)

<u>Reduce and Deter Costs</u>

- Provide improved transition to portable FLEX equipment
  - Deferring the use of ultimate FLEX measures using raw water at one BWR plant saves $$$$$$

<u>Reduce Risk of Operations</u>

- Update emergency operating procedures (EOPs)
- Establish technical basis for operational changes that prevent progression to core damage and reduce core damage frequency

<u>Simplify Plant Operations</u>

- Add flexibility to respond to event conditions identified in the Fukushima accidents
- Increased time available for implementation of FLEX

Terry Turbopump Planning

Milestones: Model development report issued in FY15

- First Principle model indicates what occurred at 1F2 is real and potentially something that could be used to preclude severe accidents
  - SAND2015-10662

Milestone: Experimental Testing Plan and Cost Estimate

- Phased Testing Program
  1. Planning overall program (May 2016)
  2. Incorporate model into system code (FY16)
  3. Compare to plant operation data and small scale test data (FY17)
  4. Prototypic testing to validate the model (FY17 – FY20)

Milestone 2: Principles & Phenomenology (FY15)

Milestone 3: Full-Scale Separate-Effect Component Experiments (FY19)

Milestone 4: Terry Turbopump Basic Science Experiments (FY19)

Milestone 5: Integral Full-Scale Low-Pressure Long-Term Operations

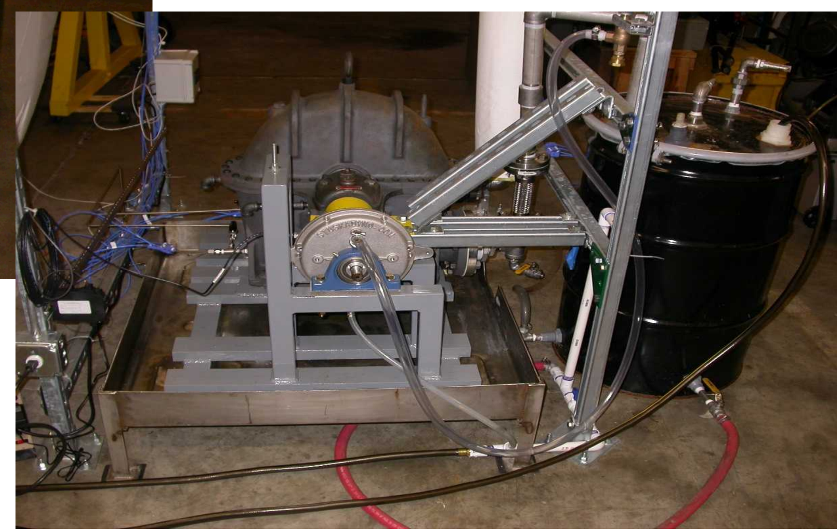
Milestone 6: Integral Full-Scale Operations to Replicate 1F2

Milestone 3

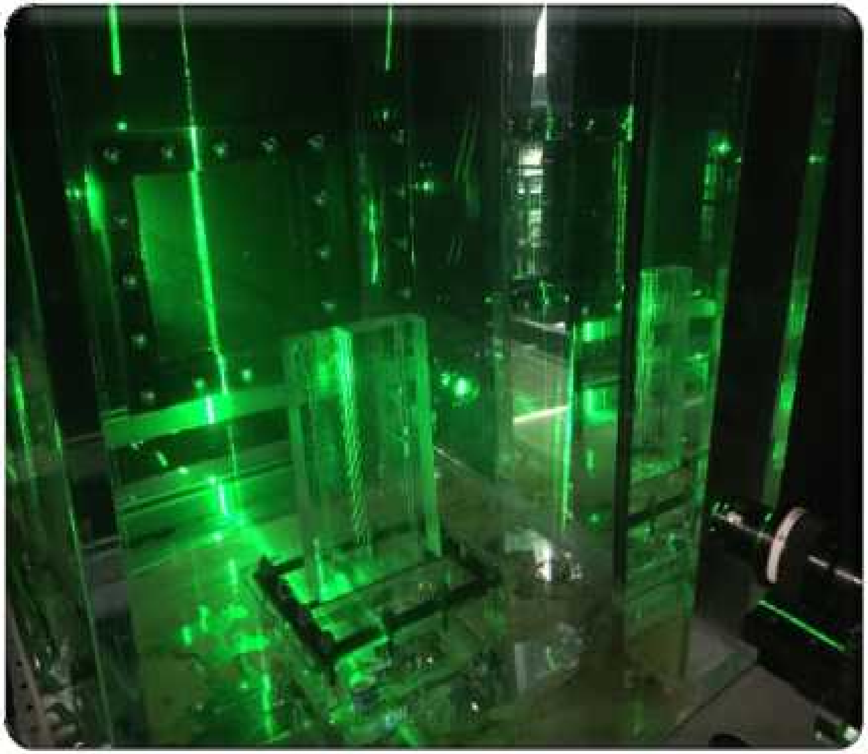
Full-Scale Component Experiments

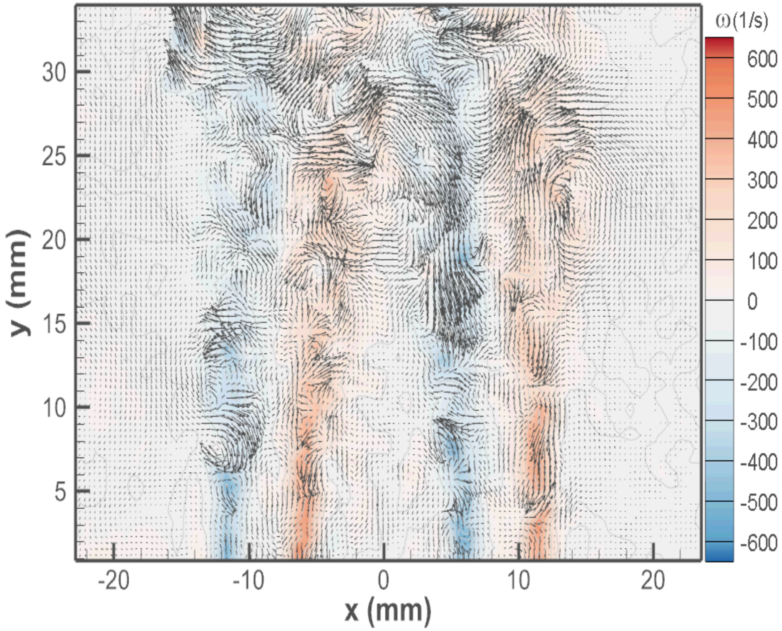
- Free Jet Testing
  - Flow Visualization
  - Additional video capabilities from Sandia
- GS-series Governor/Trip Throttle Valve Testing
  - Air Testing
  - Steam Testing
- Oil and Bearing Testing
- Turbine Exhaust Purge Line Testing

Texas A&M Nuclear Heat Transfer System Facility

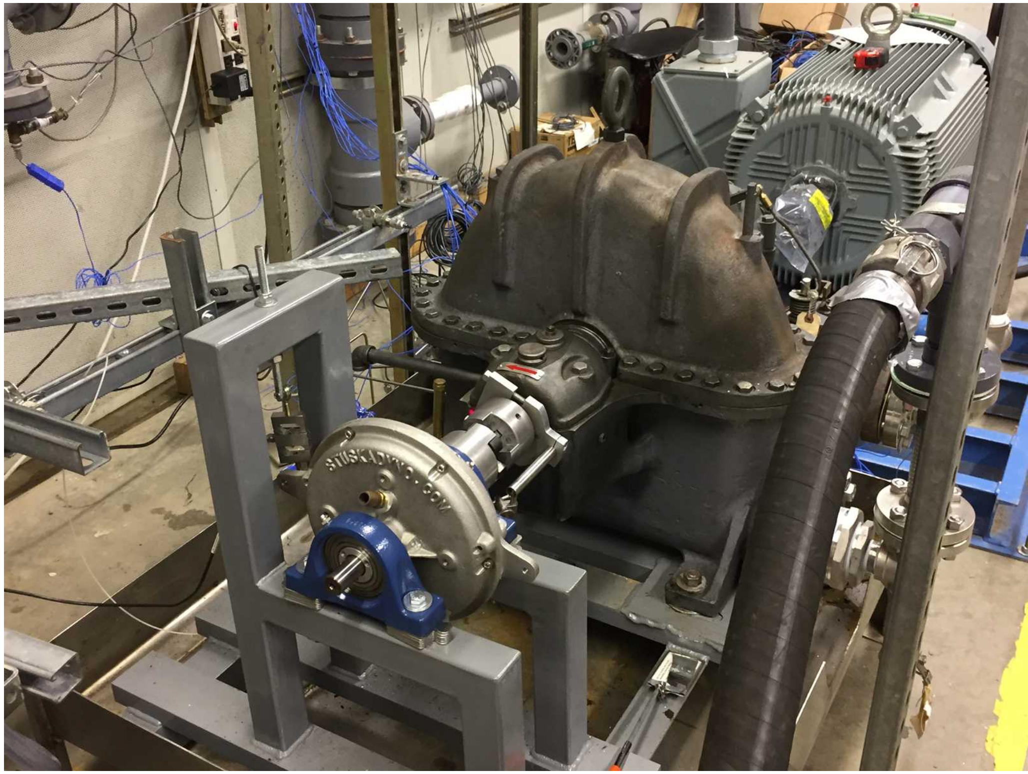


Texas A&M Thermal Hydraulic Laboratory





Texas A&M Turbomachinery Laboratory



Milestone 3 Gantt Chart

Table 2.9 Milestone 3 Gantt Chart (1-26 months)

Terry Turbopump Expanded Operating Band Gantt Chart														
		Month (June 2017 = Month 1, January 2018 = Month 8, January 2019 = Month 20)												
Experimental Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Milestone 3 – Full-Scale Component Experiments														
NHTS Lab Facility Preparations	4 months													
Free Jet Test facility preparation	2 months													
Free Jet Test facility test execution	8 months													
Turbomachinery Lab Facility Preparations	1 month													
GS-series Governor & Trip/Throttle Valves Testing facility preparation	2 months													
Governor & Trip/Throttle Valves Testing facility test execution	4 months													
Oil Test facility preparation	2 months													
Oil Test facility test execution	5 months													
Bearing Test facility preparation	2 months													
Bearing Test facility test execution	4 months													
Report Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
TAMU Free Jet Test facility data analysis and report	2 months													
TAMU Governor & Trip/Throttle Valves Testing facility data and analysis report	3 months													
Oil Test facility data and analysis report	3 months													
Bearing Test facility data and analysis report	3 months													
SNL & IAE experimental experts at TAMU	24 months													
Industry Staff input on experimental efforts	4 months													
Industry Contributions and Review of Milestone 3 reports	4 months													

Milestone 4

Terry Turbopump Basic Science Experiments

- Z-1 Turbine Testing
  - Air Testing
  - Steam Testing
- GS-series Turbopump Testing
  - Air Testing
  - Crystal River Aux. Feed skid
- Scoping of Uncontrolled Feedback
  - Replicate what occurred at 1F2
  - Z-1 turbopump
  - Steam Testing

Milestone 4 Gantt Chart

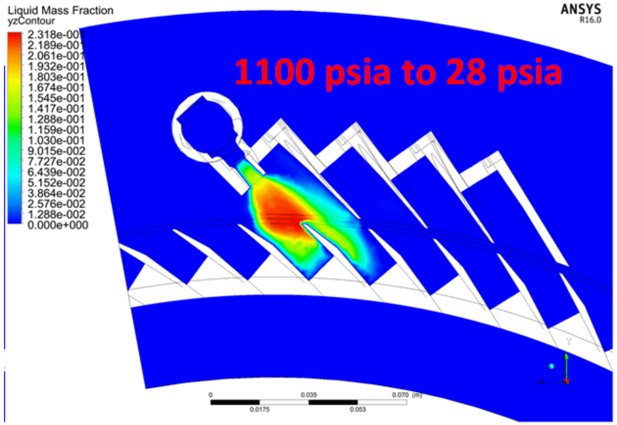
Table 3.7 Milestone 4 Gantt Chart (1-26 months)

Terry Turbopump Expanded Operating Band Gantt Chart														
		Month (June 2017 = Month 1, January 2018 = Month 8, January 2019 = Month 20)												
Experimental Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Milestone 4 – Terry Turbopump Basic Science Experiments														
NHTS Lab Facility Preparations	3 months													
Z-1 Turbopump Test facility preparation	6 months													
Z-1 Turbopump Test facility test execution	6 months													
Turbomachinery Lab Facility Preparations	1 month													
Full-Scale Technique Test facility preparation	2 months													
Full-Scale Technique Test facility test execution	5 months													
Scoping Uncontrolled Feedback Test facility preparation	1 months													
Scoping Uncontrolled Feedback Test facility test execution	3 months													
Report Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Z-1 Turbopump Test facility data and analysis report	4 months													
Full-Scale Technique Test facility data and analysis report	4 months													
Scoping Uncontrolled Feedback Test facility data and analysis report	3 months													
SNL & IAE experimental experts at TAMU	24 months													
Industry Staff input on experimental efforts	4 months													
Industry Contributions and Review of Milestone 3 reports	4 months													

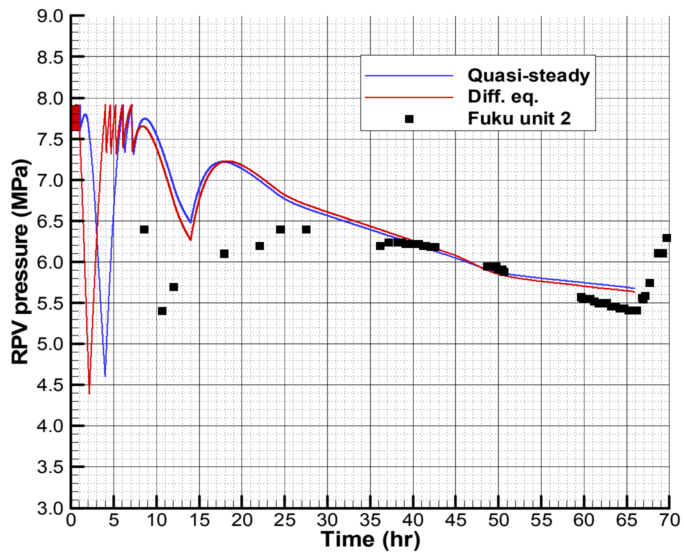
Modeling RCIC Performance in Beyond Design Basis Conditions

Governing equations for Terry Turbopump Model
- First principles derivation for an impulse turbine
- Quasi-steady state and differential equation schemes

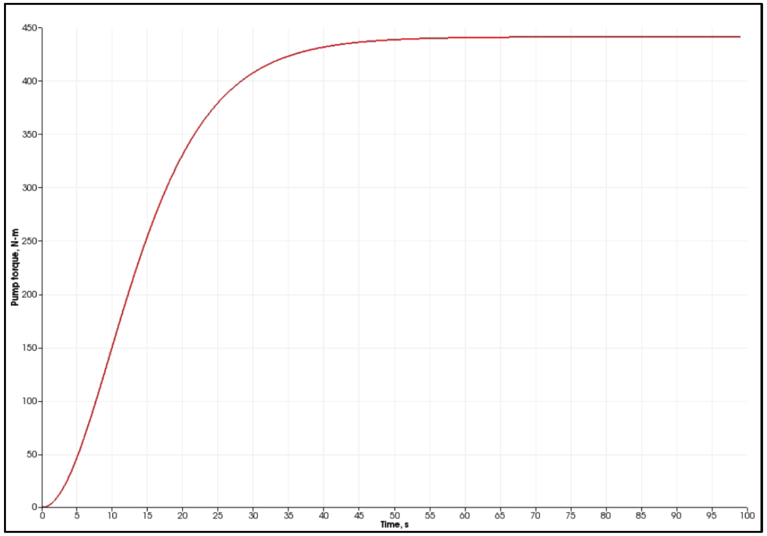
Complex Fluid Dynamics (CFD) analyses
- Provides information to system-level modeling on nozzle



System-level analyses
- Provides information to CFD modeling
- Centrifugal Pump Models



MELCOR Model



Pump torque calculated by the RELAP-7 Terry turbine RCIC system test model for turbine outlet pressure at 193 kPa

Terry Turbine CFD Efforts

- Corroborate, complement, and inform the experimental and system-modeling efforts
- Using 3D, two-phase, turbulent, compressible, Fluent calculations of key Terry turbine components to answer key questions including:
  - Steam ring: does water accumulate and flood?
  - Governor valve: what are the flow characteristics and what is its C_v?
  - Nozzles and buckets: obtain bucket inlet and outlet velocities for lower steam pressures and for air to support Terry turbine experiments
  - Turbine wheel windage: does water accumulate around the wheel and retard turbine-pump speed?

Steam ring analyses

- For a range of pressures and two-phase conditions (i.e. void fraction), examine flow regime inside steam ring – between governor valve and nozzles

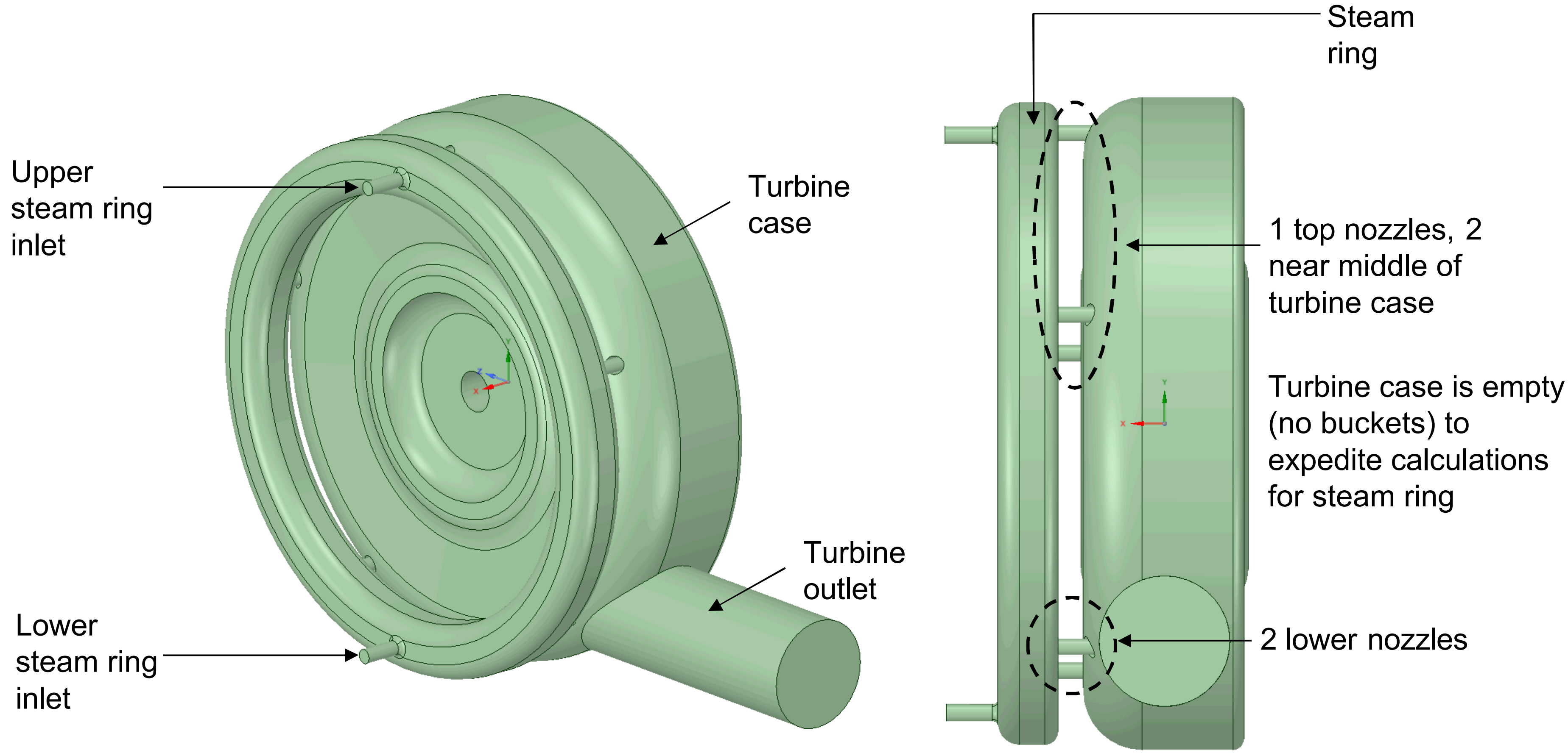
- Calculations largely corroborate system-level assumption concerning flooded nozzles in the lower part of the turbine
  - Water appears to quickly accumulate and result in stratified flow – flooding the lower nozzles – particularly for high liquid content (> 50% volume fraction)
  - Lower liquid content (< 5%) results in a two-phase mixture covering the lower nozzles
  - Often upper nozzle flow is still two-phase, but predominately steam

- Transient analyses were performed for a representative steam ring with two inlets and five nozzle
  - Additional calculations could make use of expanded geometry information for the steam ring, particularly the details of its inlets from the governor

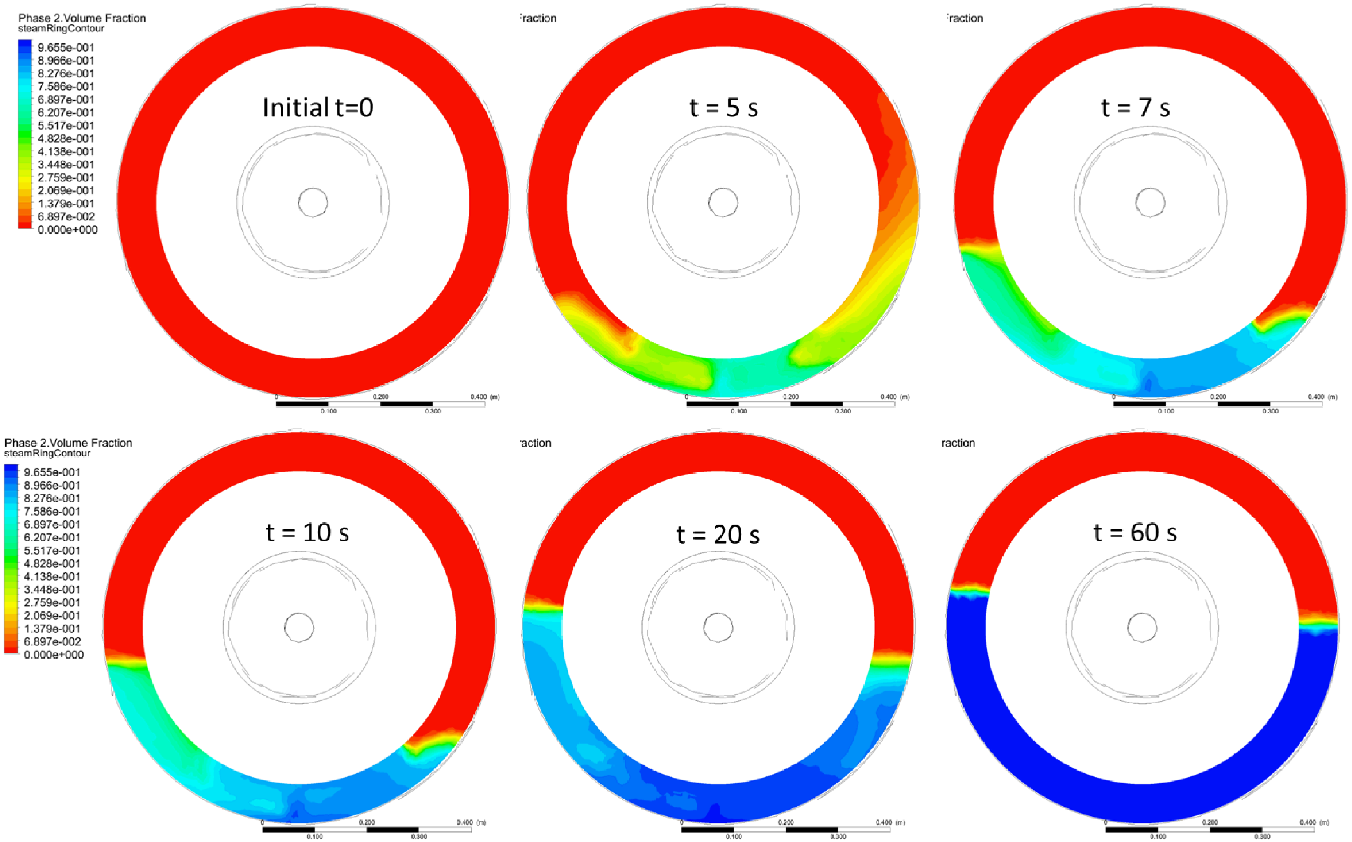
Model Updates in July 2017

- GS-1 turbine has nozzles in only the lower half of the steam ring but still some nozzles are higher than others
- The steam ring is supplied with steam thru a single inlet located low and to one side of the ring
- The steam ring is not continuous but is rather of two separate halves joined by a manifold
- Need to construct a C_v curve versus stem position

Steam ring geometry



Steam ring results



- Mid-plane slice of steam ring – contour of liquid volume fraction (1.0 = all liquid)
- 300 psig inlets
- Top steam ring inlet: 100% steam
- Bottom inlet: 100% liquid
- Saturated vapor-liquid properties assuming no mass/energy transfer between phases
- Fluent's Euler multiphase model (code's most rigorous option)

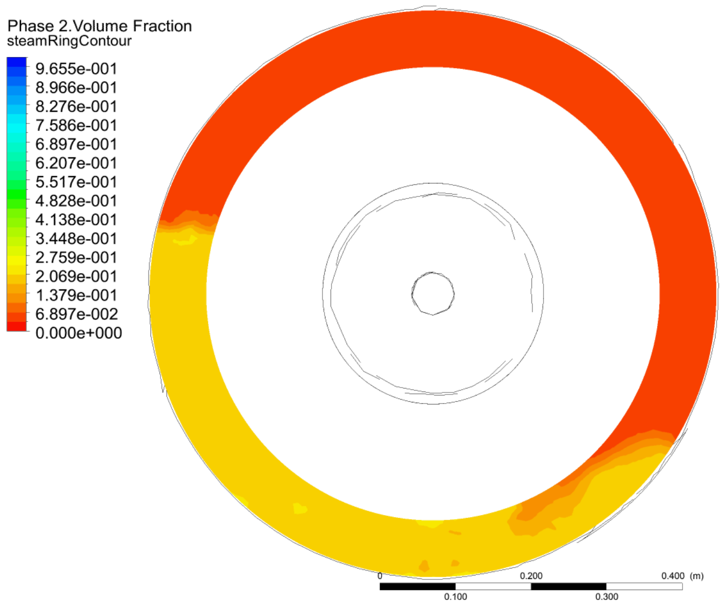
More steam ring results

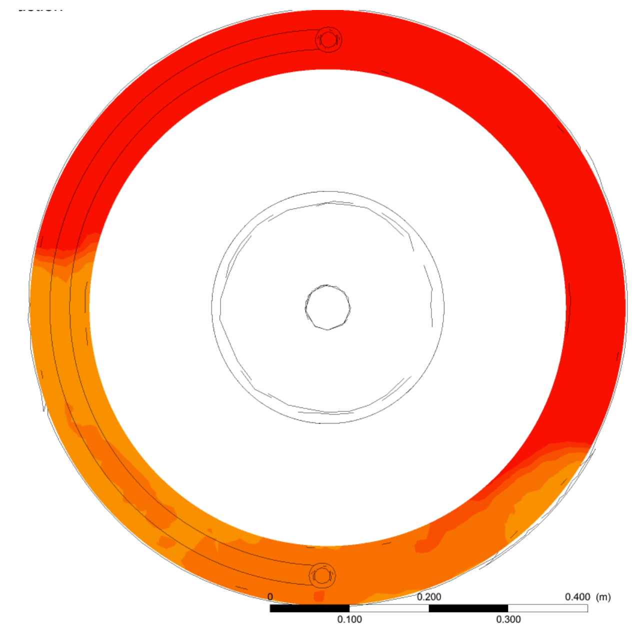
10% avg. liquid volume fraction across inlets

- Lower nozzles flow more water (20-30% liquid)
- Uppers nozzles flow more steam (only ~5% liquid)

5% avg. liquid volume fraction across inlets

- Lower nozzles: 5-20% liquid
- Uppers nozzles are almost fully steam flow



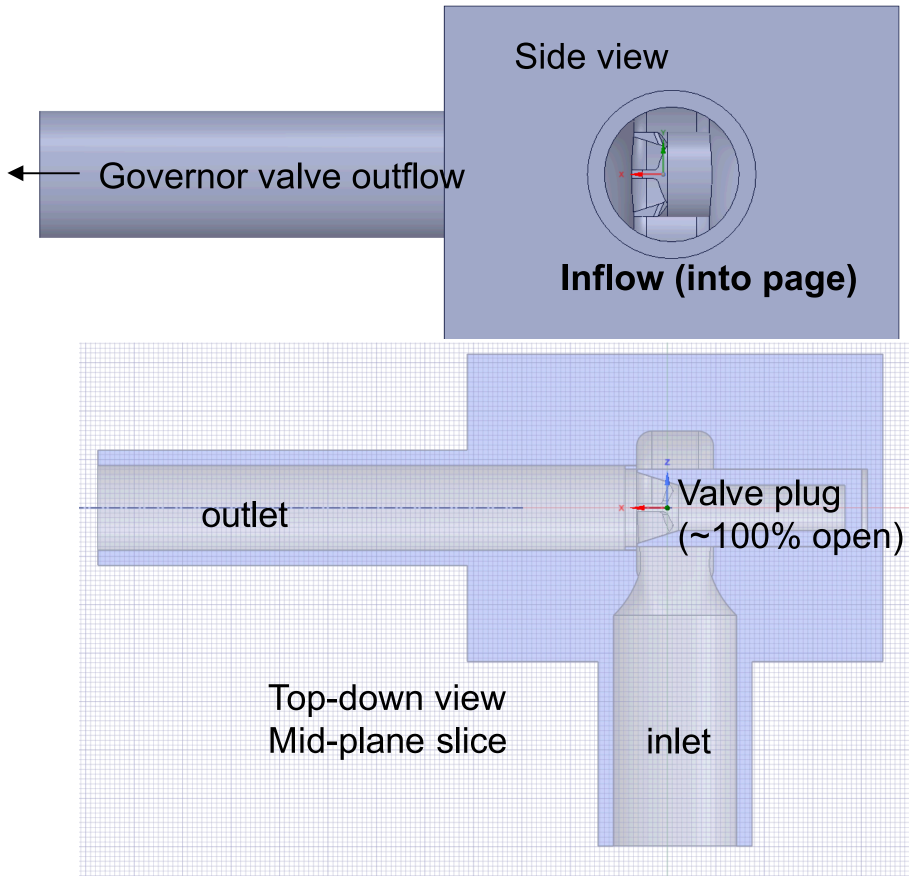


Transient calculations after 60 seconds
(initial condition is all saturated steam at 300 psig)

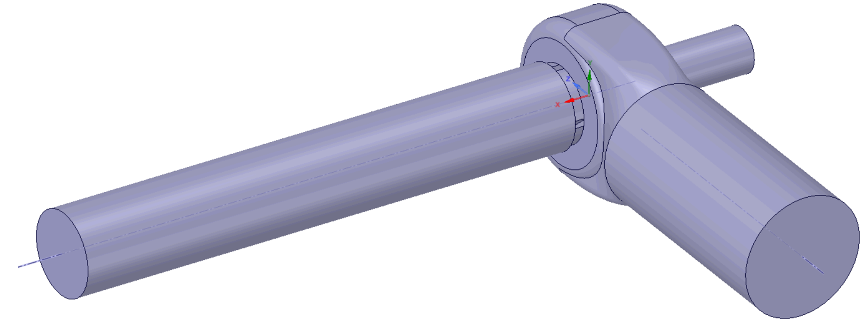
Governor valve calculations

- Obtain C_v information for governor valve
  - Leverage CAD/flow modeling using SolidWorks from 2016
- Examine two-phase flow characteristics
  - Expanded model may be able to inform analysis of the steam ring
  - Need piping details from governor valve to steam ring inlet(s)
- Will enable rigorous benchmarking to Unit 2 strip chart data before power was lost
  - Allows for more calibration of uncertain model inputs (multipliers, friction coefficients, etc.)
  - May increase understanding of Unit 2 avoiding overspeed trip after loss of power

Governor valve geometry

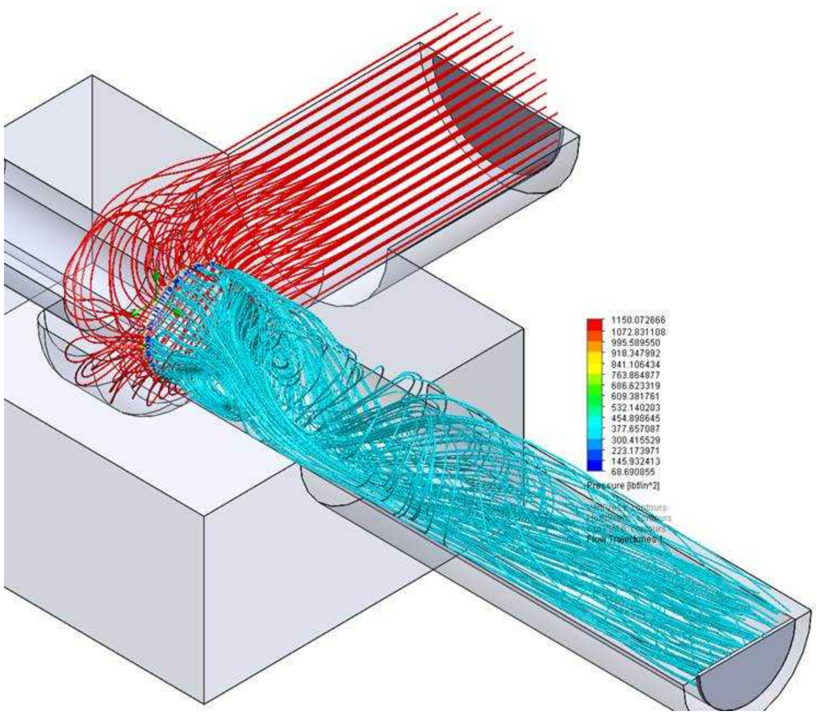


Extracted fluid geometry

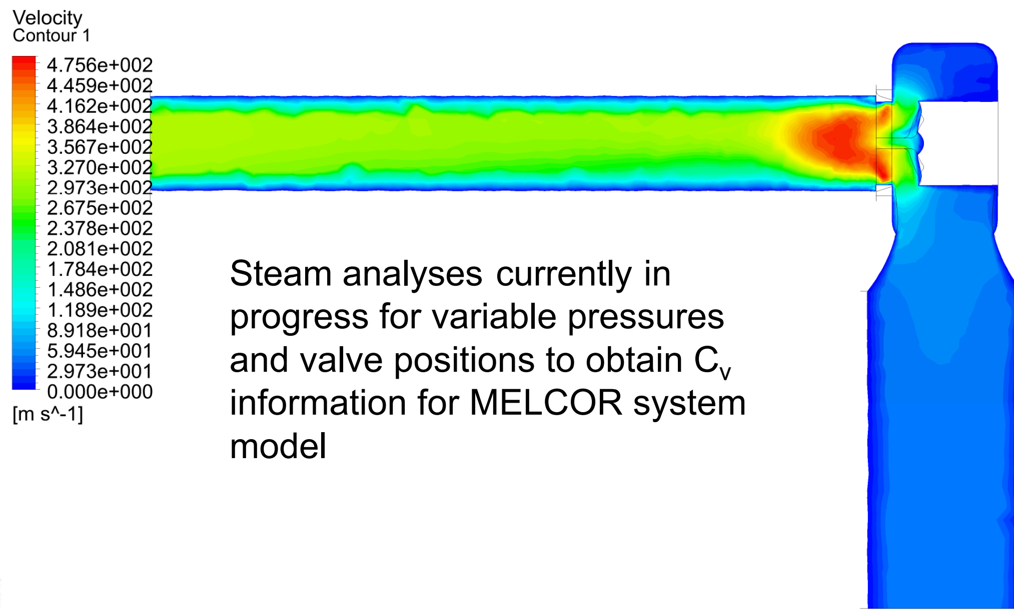


Preliminary governor valve results

From 2016 using Solidworks Flow
Streamlines with pressure contour
1100 psig inlet; 300 psig outlet



Fluent test calculation using ideal-gas steam to validate mesh and geometry
Velocity magnitude contour for 1100 psig inlet and 300 psig outlet
Valve position at about 70% open



Steam analyses currently in progress for variable pressures and valve positions to obtain C_v information for MELCOR system model

Nozzle calculations with low pressure steam

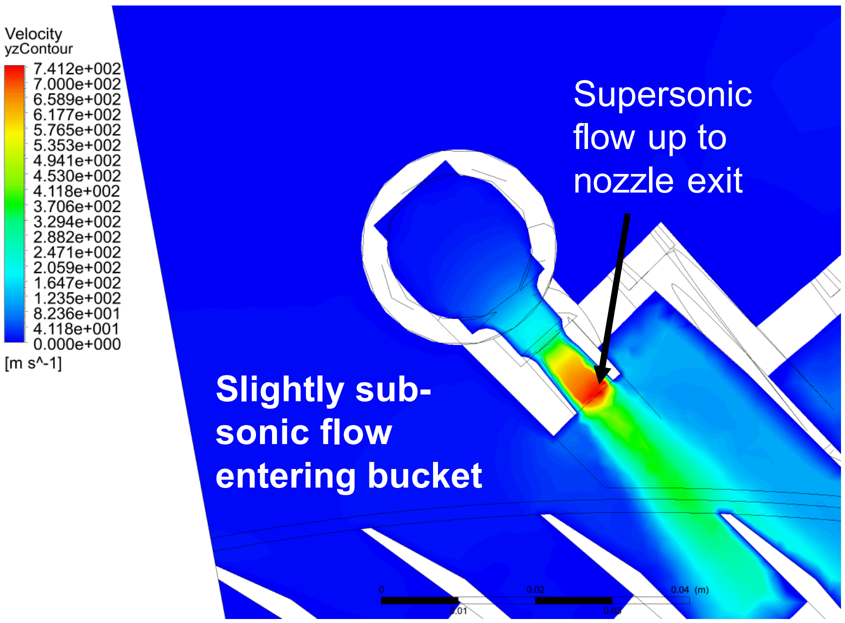
- Inform/support experimental efforts
  - Steam pressures from 40 to 70 psia
  - Outlet 15 psia

- Also examine air flow
  - 40 to 70 psia
  - Outlet 15 psia

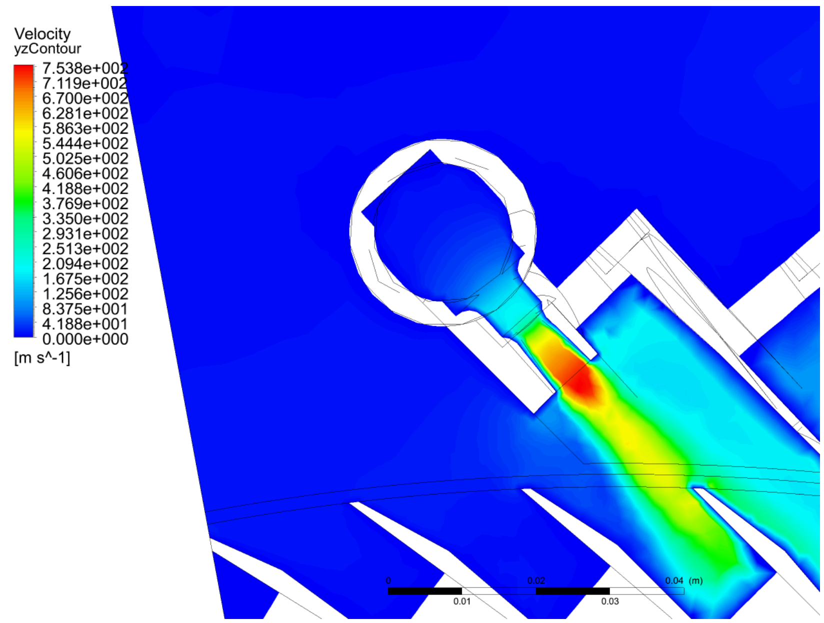
Some low steam pressure nozzle results

Such low pressure drop of the steam nozzle typically results in shock formation near the nozzle exit plane – supersonic velocities quickly reduce to sonic speed at nozzle exit

40 psia steam inlet



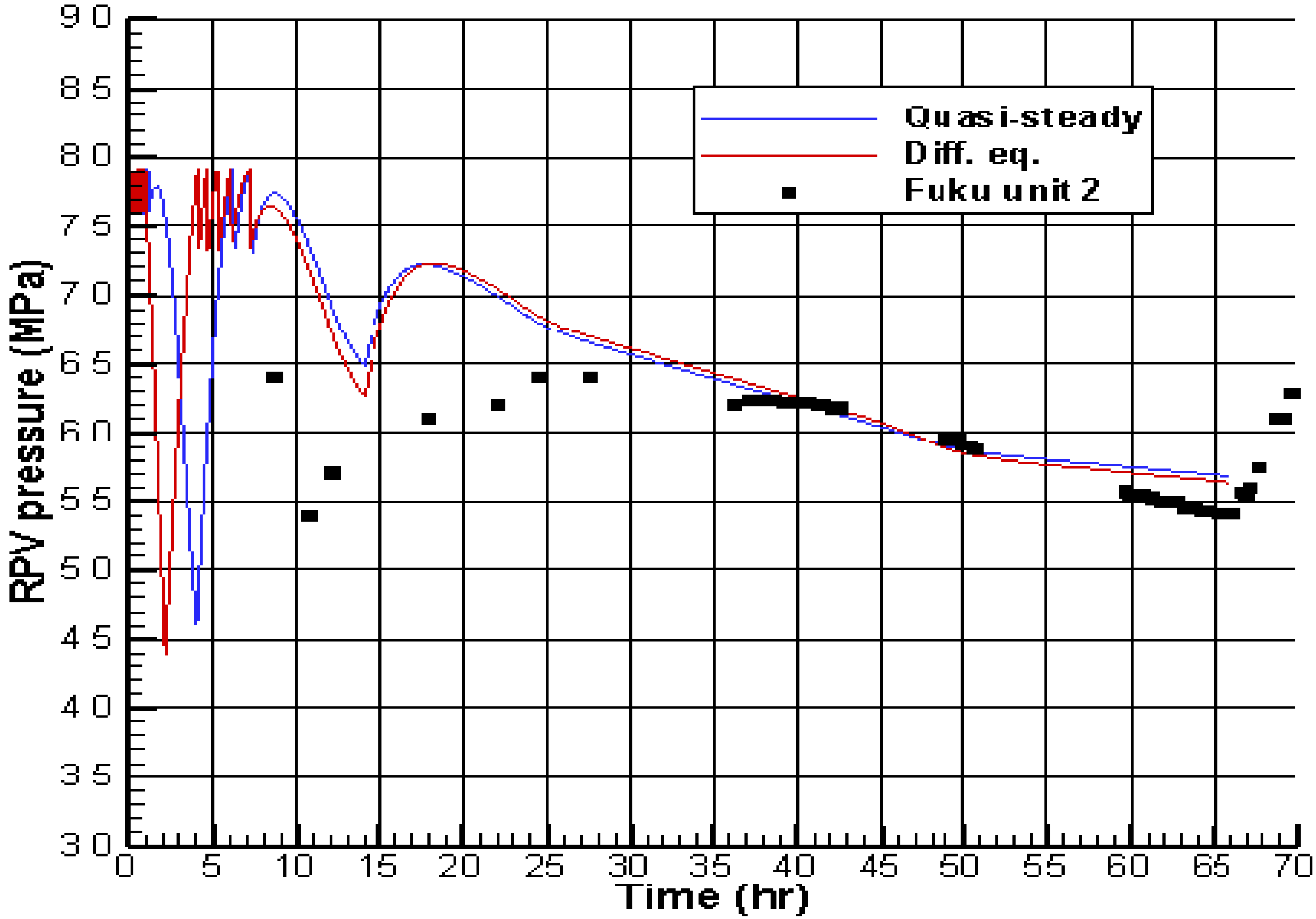
70 psia steam inlet;
higher pressure drop 'pushes' shock out of the nozzle



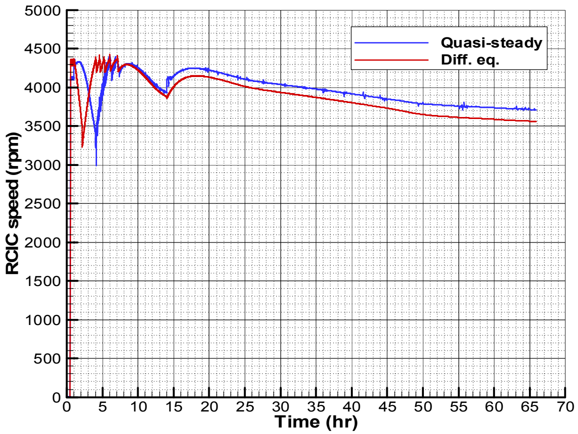
System-level Modeling

- These are test models and test results
- This work is explorative
- Investigating several different explanations and modeling approaches
  - The results are going to change
- The results are qualitative
  - They reproduce the general trends of Fukushima Unit 2

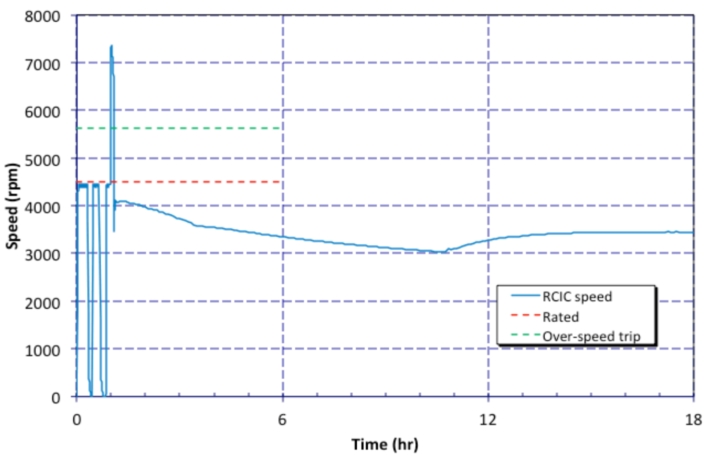
Quasi-Steady vs Time-Dependent Fukushima 2 MELCOR Calculations



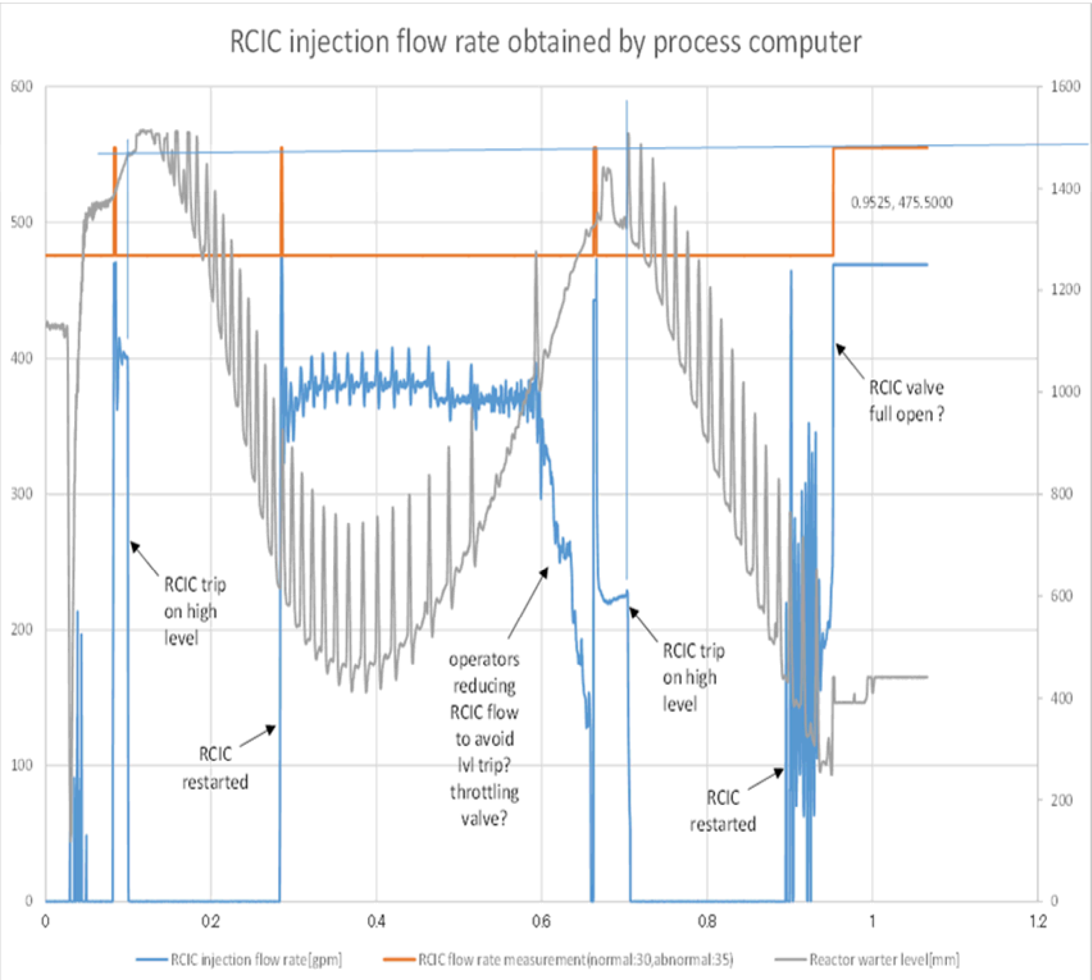
Overspeed



RCIC speed for MELCOR test models

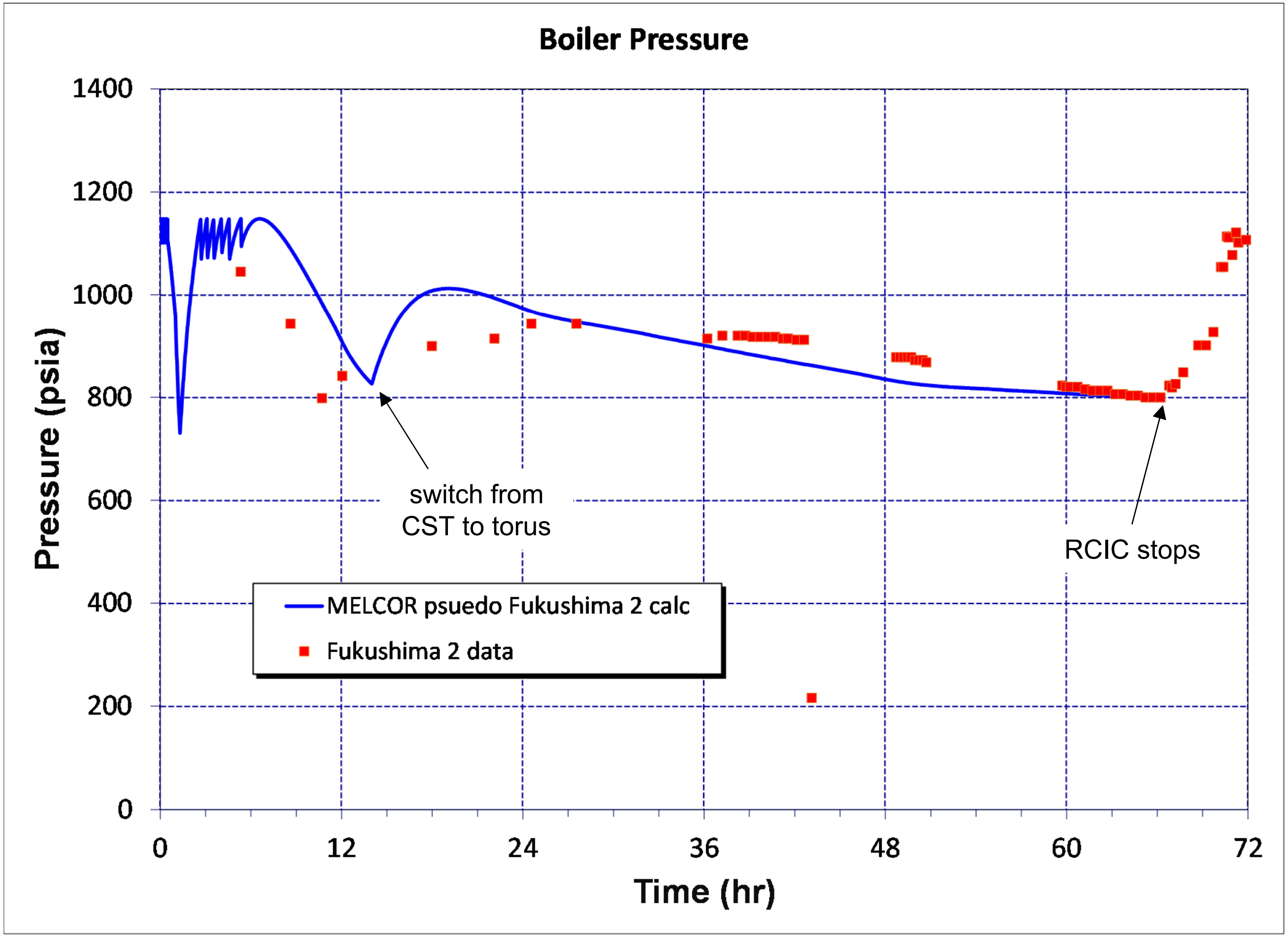


Fukushima Unit 2 RCIC Speed to 18 hours

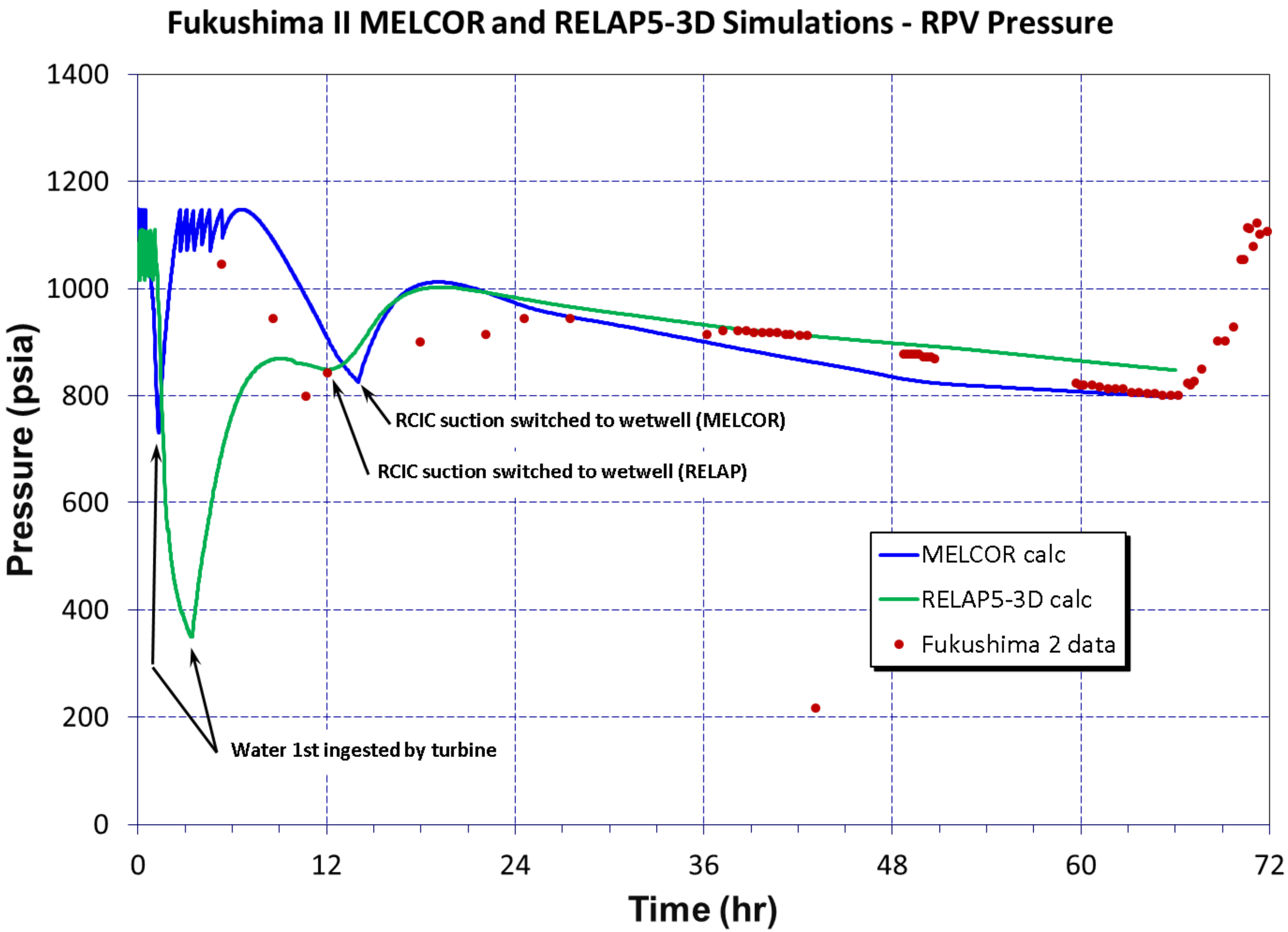


RCIC Flow to the RPV and RPV Level Recorded Early in Fukushima Unit 2 Accident

Fukushima 2 MELCOR Model



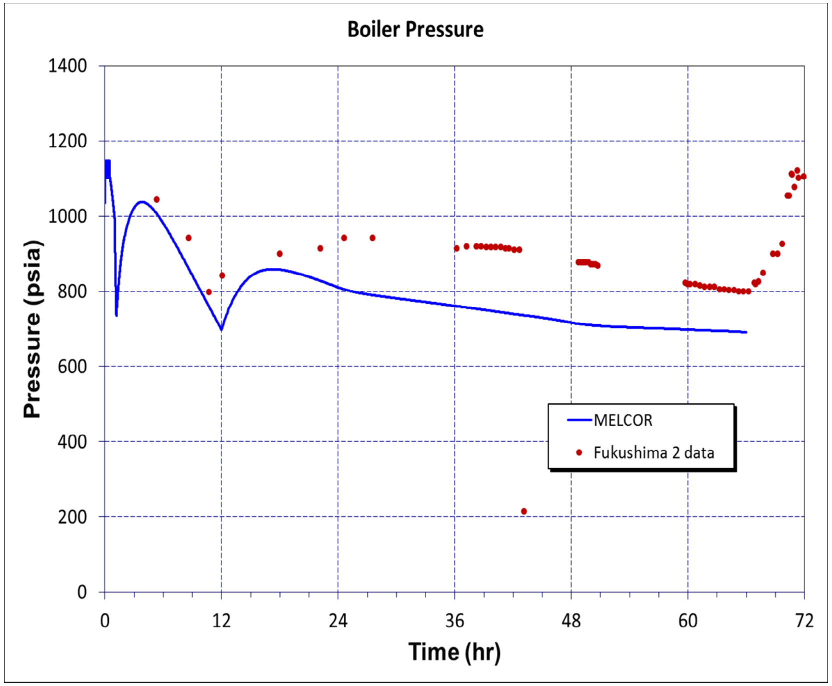
RELAP5-3D Modeling



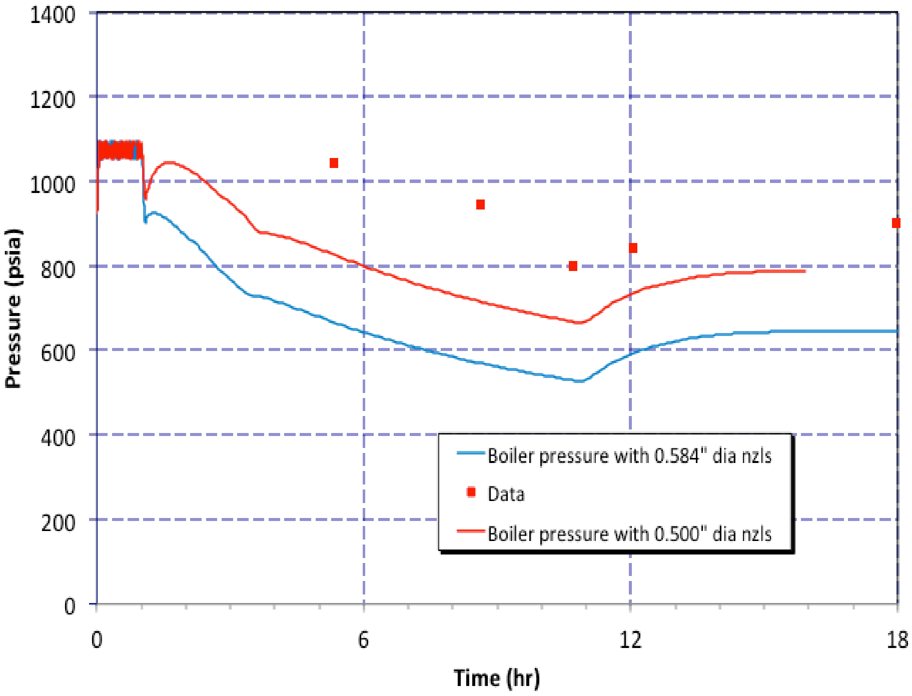
Similar results – a wide open governor & nozzle size seem critical

Homologous Pump Curve Result

- Number of Nozzles & Nozzle Size are first-order effects
- Iterative modeling process to obtain proper flow rates prior to loss of power

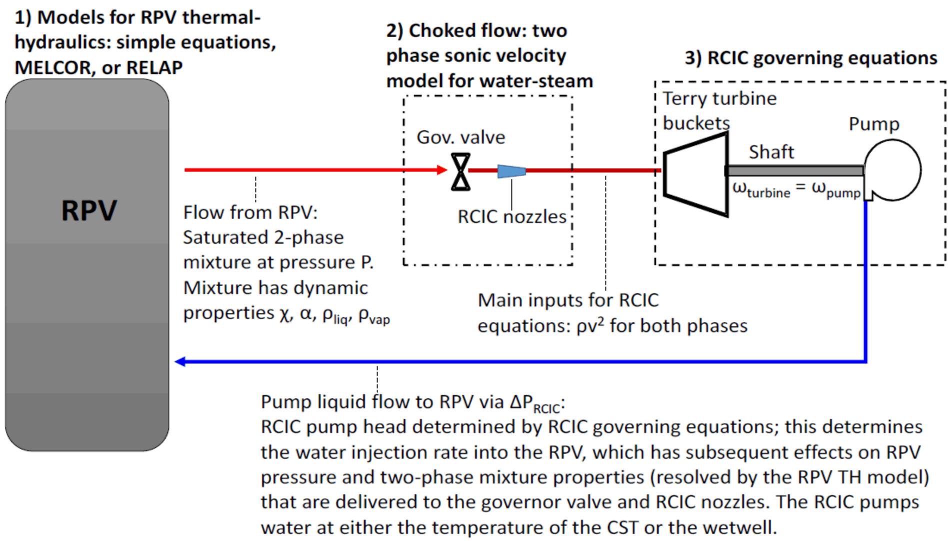


FY16 Effort

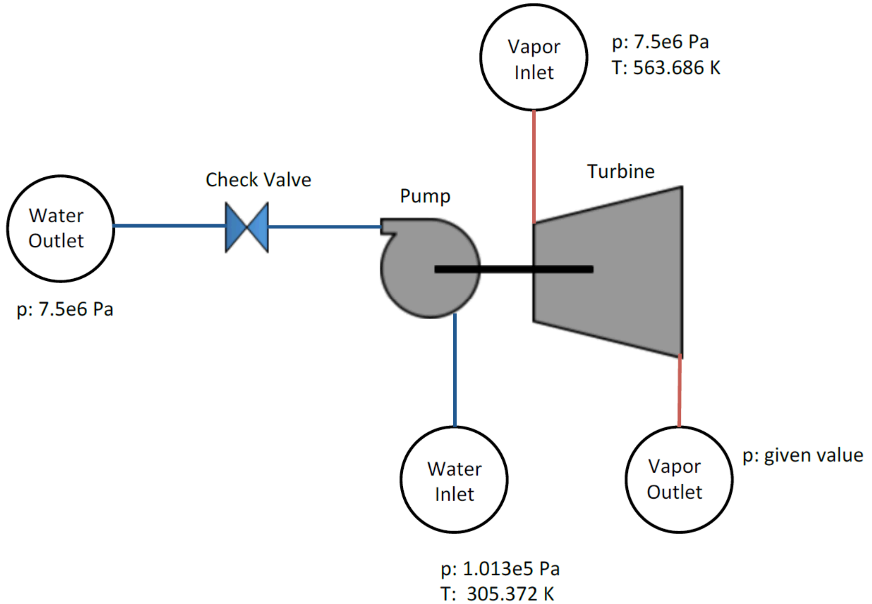


FY17 Effort

Questions



Simplified representation of physical coupling in MELCOR test model



RELAP-7 Terry turbine RCIC system test model