SAND2019-0565C

Terry Turbine Expanded Operating Band

PRESENTED BY

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Overview

Motivation/Background

Current Experiments

Current Modeling

Future Efforts

Additional Thoughts

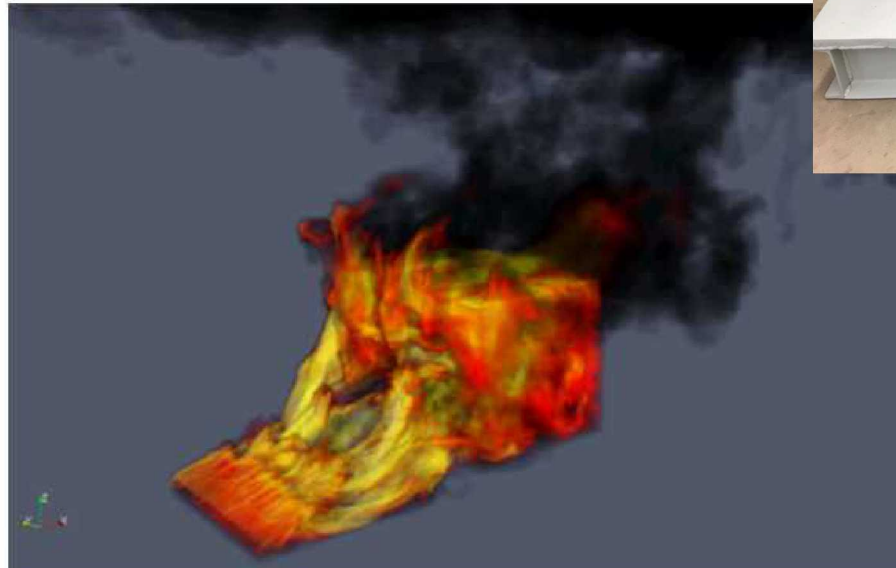# Risk-Informed Systems Analysis Pathway in DOE-NE LWRS Program

RISA Pathway Lead: Curtis Smith – INL

Applies risk-informed technology to assist operating nuclear power plants to reduce costs and support their adaptation to the changing economic and generating environment

- Enhanced resilient plant concept (include ATF)

- Cost reduction and risk categorization

- Margin recovery and operating cost reduction

- Market economics (wholesale pricing, energy policy, etc.)

Use case applications for RISA include;

- Fire PRA

- 24-month PWR fuel cycle

- Terry turbine expanded operating band

- Digital I&C

- Plant & System health management

- Risk-informed asset management

Motivation

NRC State-of-the-Art Reactor Consequence Analyses included BWR station blackout scenarios (SBO) performed *before* Fukushima accidents
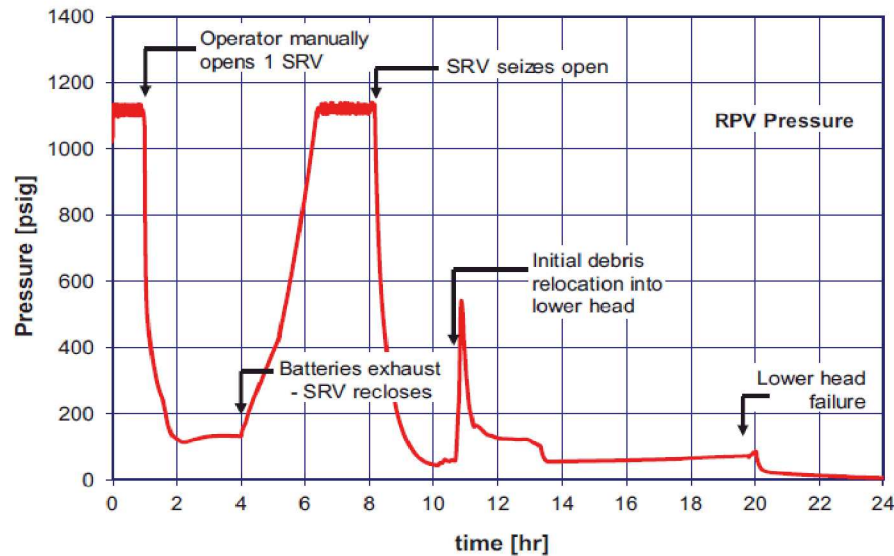- Sequences observed at Fukushima
  - *Striking similar trends*
- Accidents are classic and 'usual suspects' for analysis

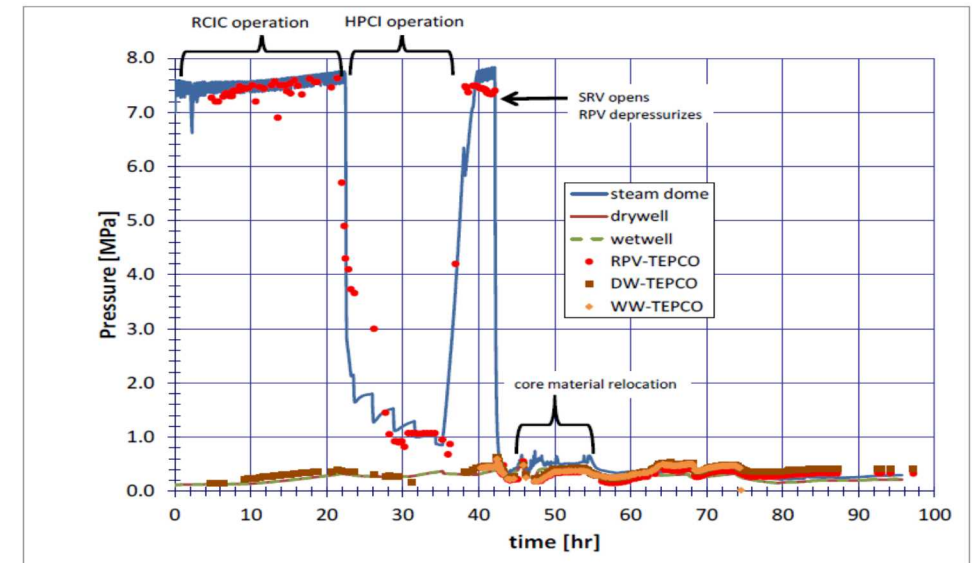Fukushima critical equipment performance brought new insights
- Understanding of real-world operations can delay or prevent severe accidents

More information will come from decommissioning activities
- Main steam line failure, safety relief valve seizure, and containment liner failure
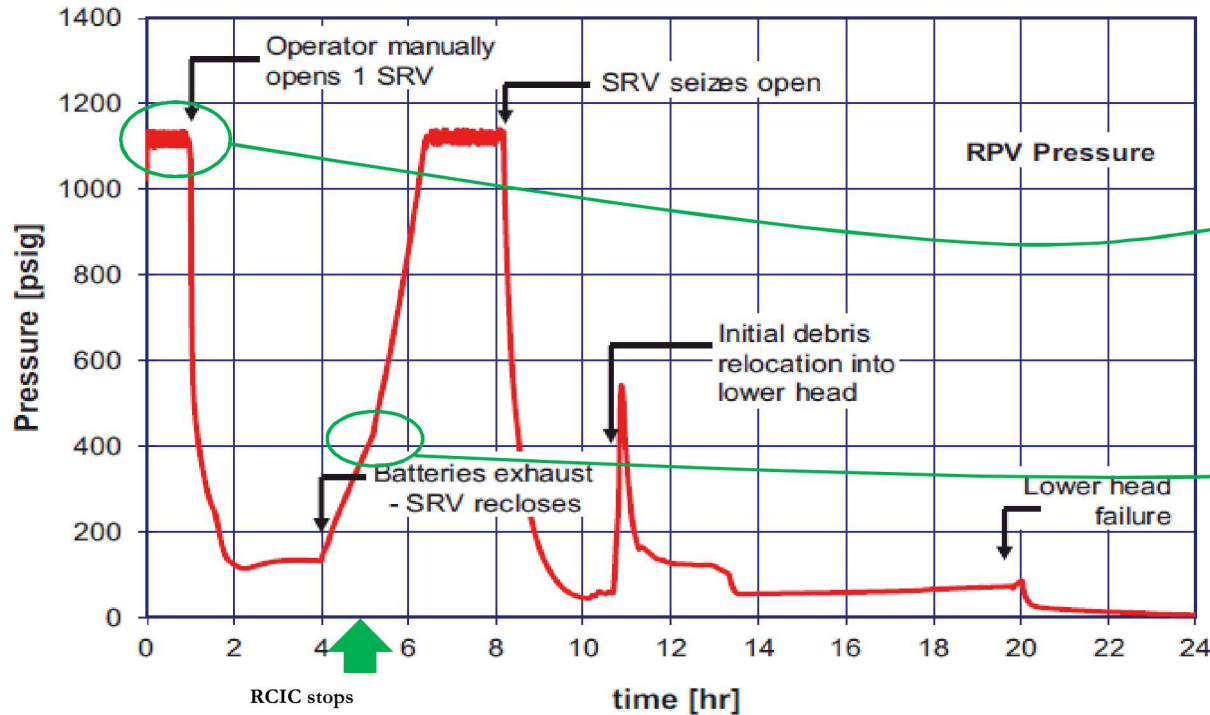

SOARCA BWR LTSBO

Fukushima Unit 3

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

Pre-Fukushima Understanding (NRC SOARCA)

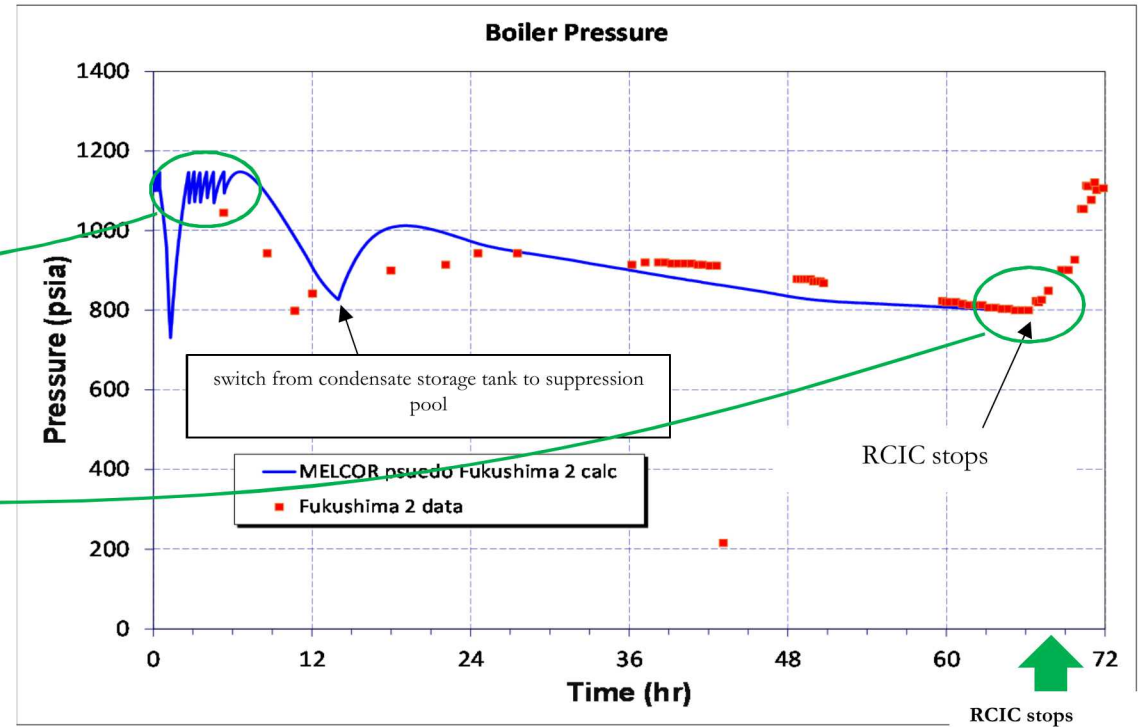

Fukushima Unit 2 Real World Response

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

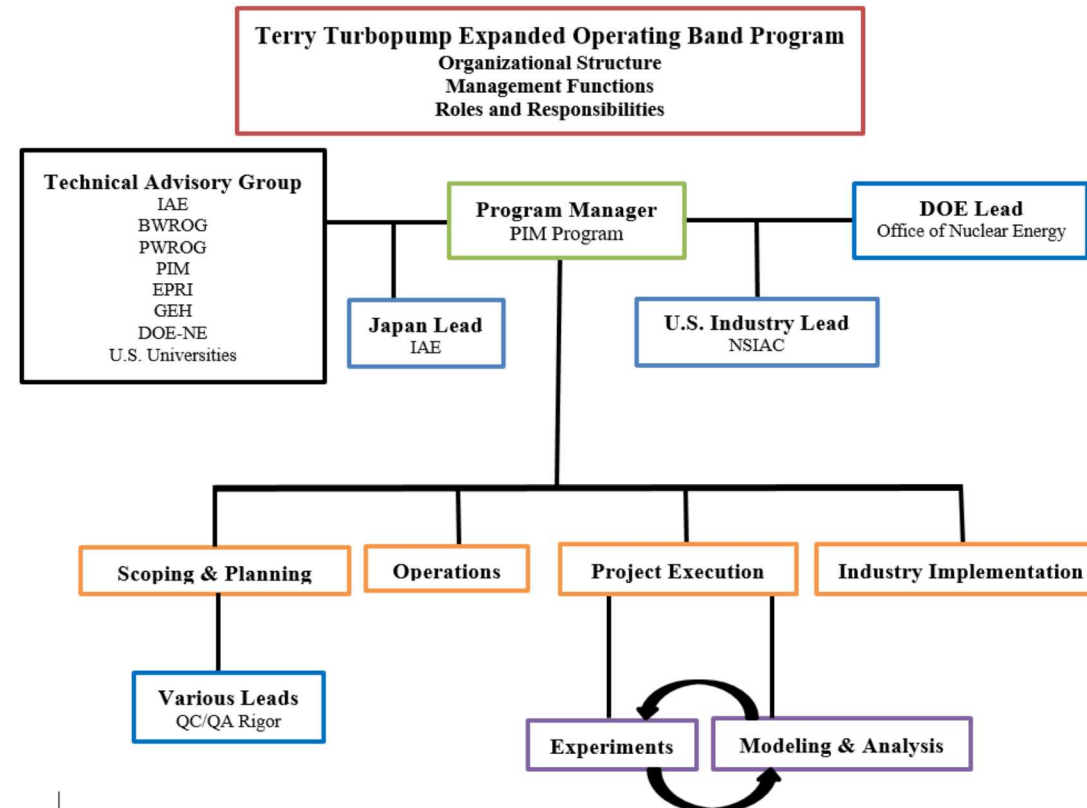Batteries fail @ 45 minutes from tsunami flooding
- *RPV overfills, MSL floods, water enters RCIC turbine, but RCIC turbine does not fail*
- *RCIC self-regulates RPV water level in cyclic mode*

Core damage avoided for nearly 3 days

Initiative Mission Statement & Participants

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.

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

Value of Extended Performance
(beyond design basis conditions)

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

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

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

The overall experimental program in particular:
- Protects utility assets by using the Terry turbopump under a broader range of conditions,
- Delays or prevents the need to use the less preferred "non-reactor grade water" sources required during FLEX events,
- Extends the interval between preventive maintenance actions,
- Provides an avenue for qualification of obsolescent parts,
  - RCIC/TDAFW control panel
- Provides a potential for regulatory avoidance, and
- Specifically, for boiling water reactors (BWRs):
  - Extends the time to get residual heat removal (RHR) system back online,
  - Extend the time for reactor pressure vessel (RPV) depressurization, and
  - Reduces outage time.

Terry Turbopump Planning

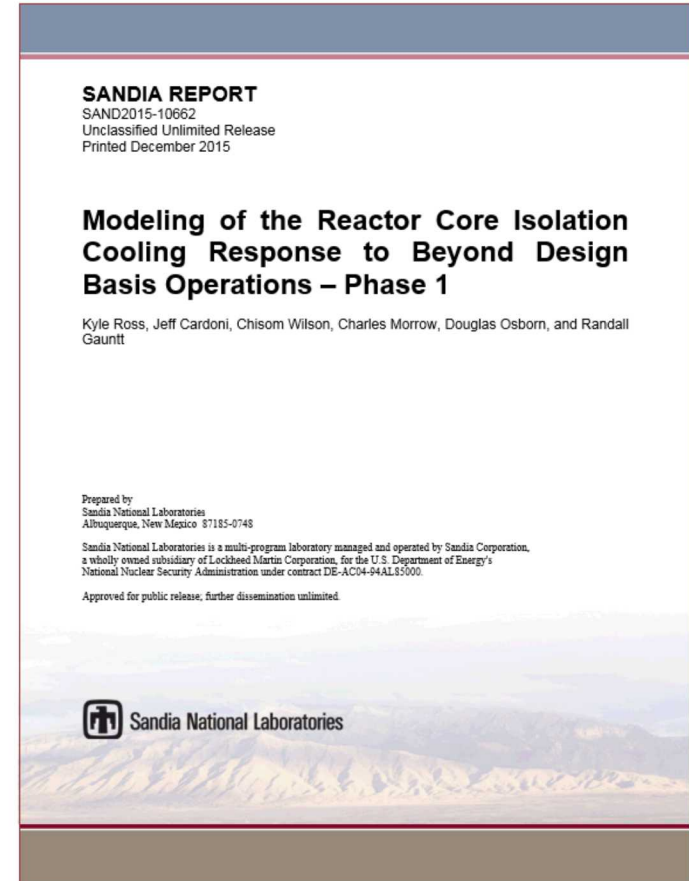## Milestones: Model development report issued in FY15
- First Principle model indicates what occurred at 1F2 is real and potentially something that could be used to preclude severe accidents

Milestone: Phased Testing Program
- Milestone 2 – Principles & Phenomenology
- Milestone 3 – Full-Scale Separate-Effect Component Experiments
- Milestone 4 – Terry Turbopump Basic Science Experiments
- Milestone 5 – Full-Scale Integral Experiments for Long-Term Low-Pressure Operations
- Milestone 6 – Scaled Experiments Replicating 1F2 Self-Regulating Feedback
- Milestone 7 is an integration of the Milestone 3-6 modeling efforts

The generic technical approach for Milestone 3 (and Milestones 4, 5, and 6) will be:
1. Model the planned tests
2. Test performance for specified test requirements
3. Analyze tests across the test requirements range
4. Compare model analyses to test results
5. Report differences and possible technical reasons
6. Extrapolate to full-scale BDBE conditions
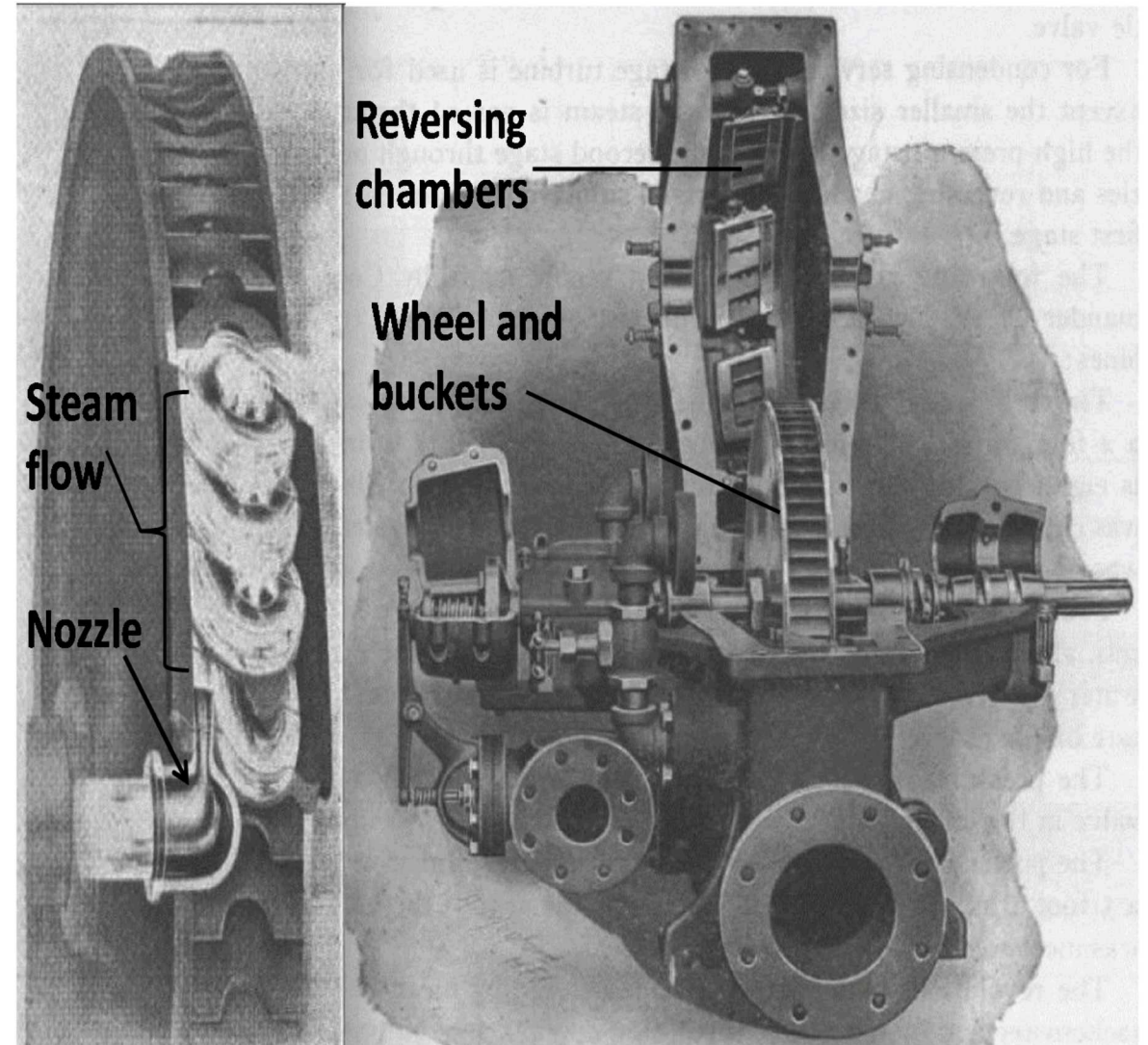7. TTExOB Advisory Committee evaluation of expectations and '*adequate confidence*'

SANDIA REPORT
SAND2015-10662
Unclassified Unlimited Release
Printed December 2015

Modeling of the Reactor Core Isolation Cooling Response to Beyond Design Basis Operations – Phase 1

Kyle Ross, Jeff Cardoni, Chisom Wilson, Charles Morrow, Douglas Osborn, and Randall Gauntt

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Approved for public release; further dissemination unlimited.

Sandia National Laboratories

Terry Turbopump Modeling

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.

Steam flow

Nozzle

Reversing chambers

Wheel and buckets

Journal of the American Society of Naval Engineers

Modeling RCIC Performance in Beyond Design Basis Conditions
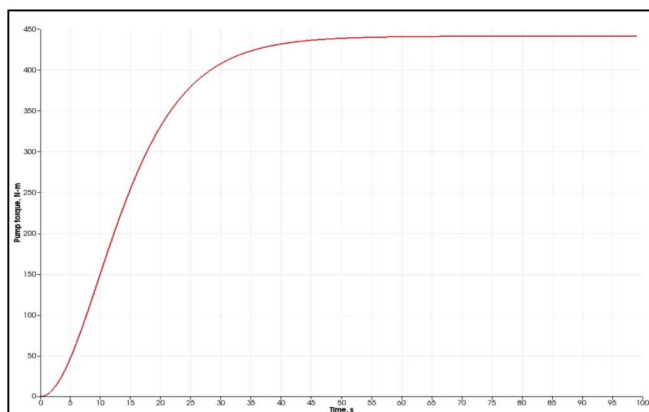
Governing equations for Terry Turbopump Model
- First principles derivation for an impulse turbine
- Quasi-steady state and differential equation schemes
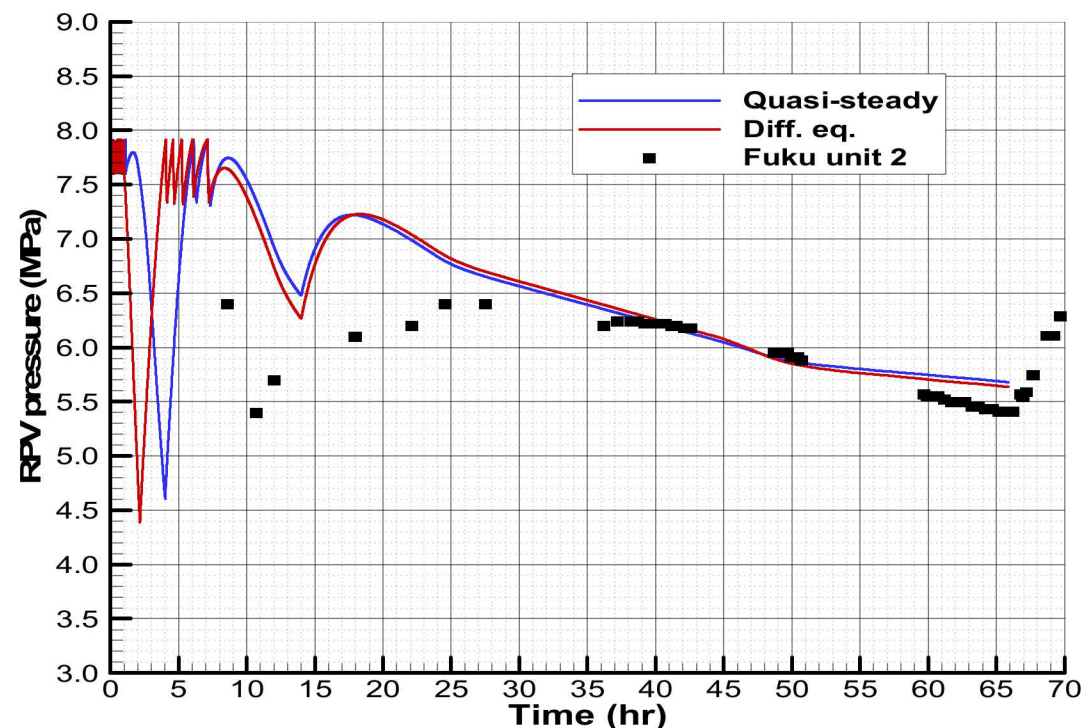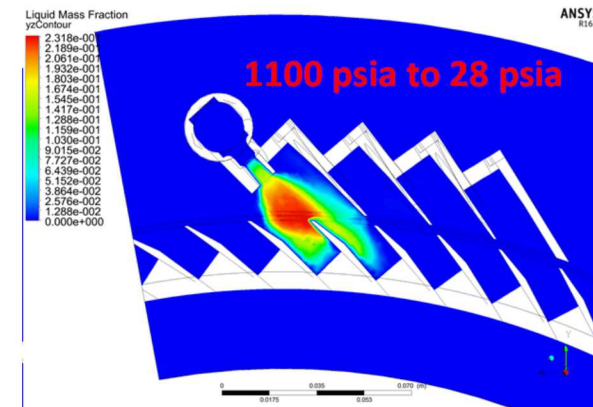
Complex Fluid Dynamics (CFD) analyses
- Provides information to system-level modeling on nozzle

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

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

MELCOR Model

Milestone 3 Tests from the Detailed Test Plan

Free Jet Tests
- Flow visualization
- In-depth flow study of Terry nozzles

Governor and Trip/Throttle valve tests
- Valve profiling (C_v, x_T, F_L) in Turbomachinery Lab
- ANSI/ISA 75.02.01 (IEC 60534-2-3) testing

Oil Tests in NHTS Lab
- Degradation
- High-temperature characteristics

Terry Turbine Bearing Tests in NHTS Lab
- Use degraded oil
- Damage/high temperature limits

Importance:
- Bearing and oil testing will provide actual measured data indicating true thermal limits for turbine utility
- Jet testing will provide data on how the particular Terry jets behave under single and two-phase flow, and how this might affect turbine performance
- Valve data is needed for code inputs AND will provide known metrics to assist with blackstart and manual turbine operations

A 480-mil throat ID Terry nozzle and elbow connector. The outlet is a rounded square of 9/16 inch

The IEC 60534 Test Loop

Milestone 4 Work

Scaled turbine profiling with ZS-1

- Single-phase (air) and two-phase (air+water) flow injected into turbine
  - Steam and steam-water testing will be performed in the near future
  - An exploratory uncontrolled feedback (Fukushima Daiichi Unit 2) scenario will be attempted as a prelude to Milestone 6
- Produce relationships between torque (via dynamometer), RPM, inlet pressure, and liquid fraction

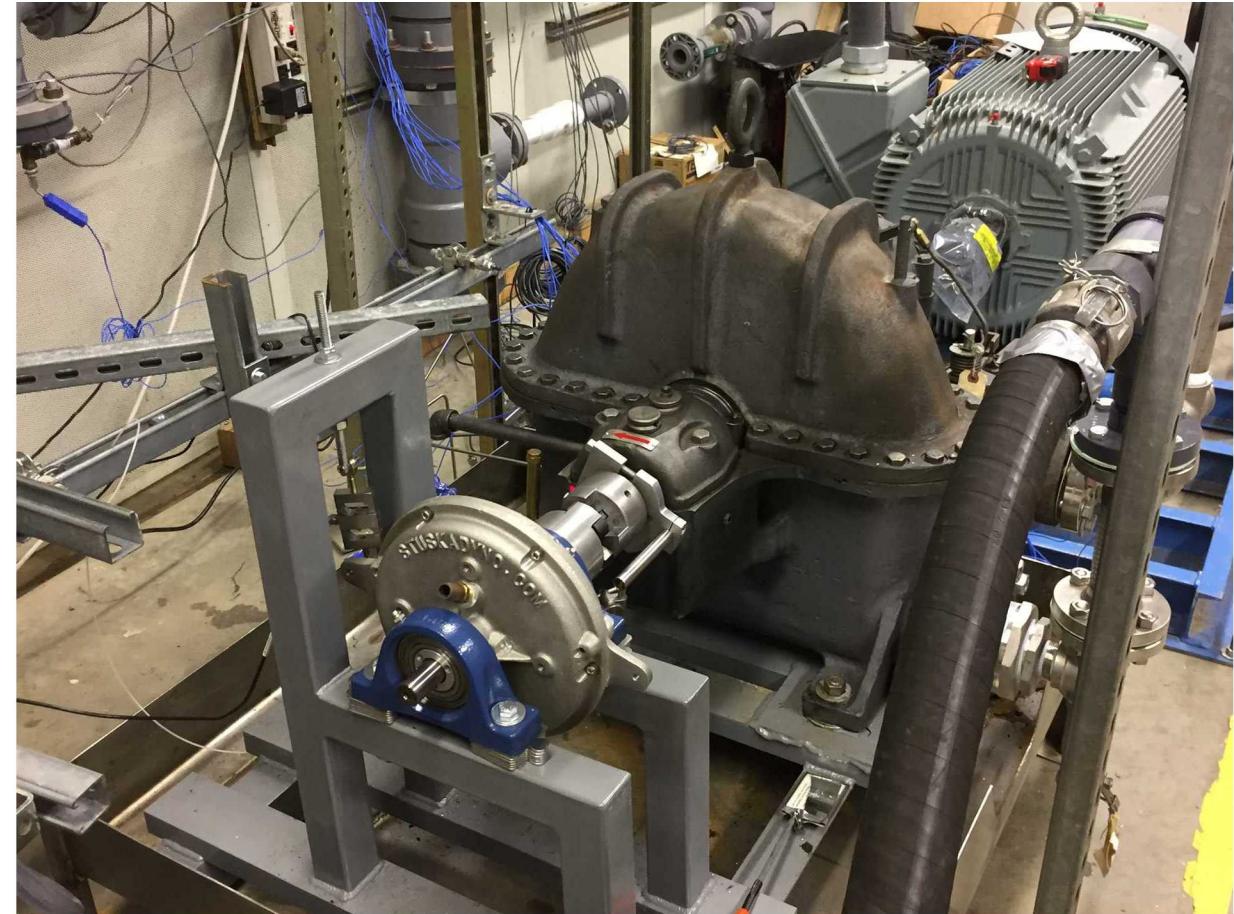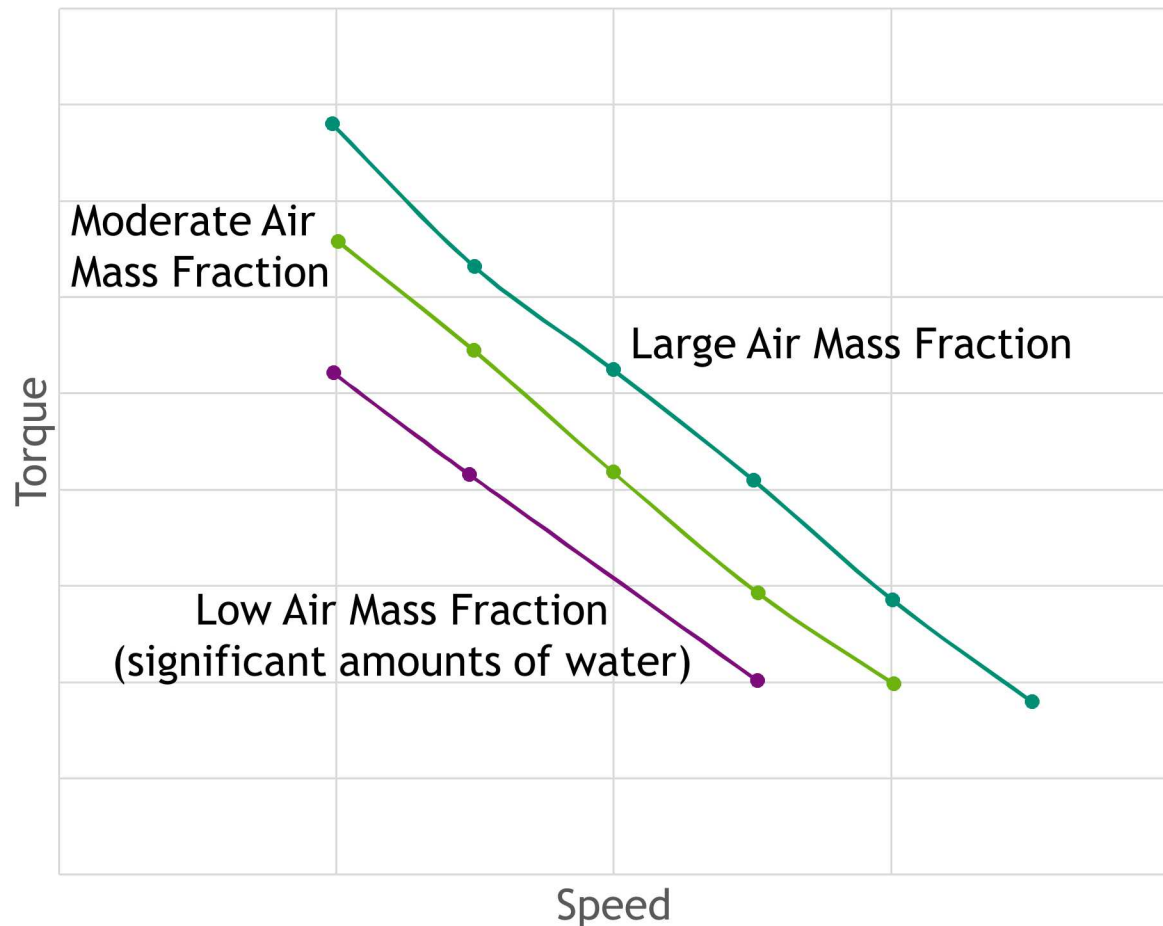## Limited Full-Scale GS-2 turbine profiling

- Will only be performed with air and air/water flow
- A GS-2 skid has been sent from Crystal River 3 to Keene Turbomachinery in the Houston area for inspection and servicing, and will be sent from there to TAMU
- Produce the same sort of torque, RPM, pressure, liquid fraction curves as for the scaled turbine, but only for the low-pressure end of the GS-2's capabilities
  - THIS WILL PRODUCE SCALING FACTORS TO ENABLE BROAD TRANSLATION BETWEEN THE SMALLER AND FULL-SCALE TURBINES

Why this is important:

- Produces a database of known, quantifiable behavior across normal and off-normal conditions
- Provides data for systems codes to be enable accurate prediction of turbine behavior

Scaled ZS-1 Profiling

Example Profile for One Pressure

Torque

Moderate Air Mass Fraction

Large Air Mass Fraction

Low Air Mass Fraction (significant amounts of water)

Speed

ZS-1 Air Test Rig at TAMU
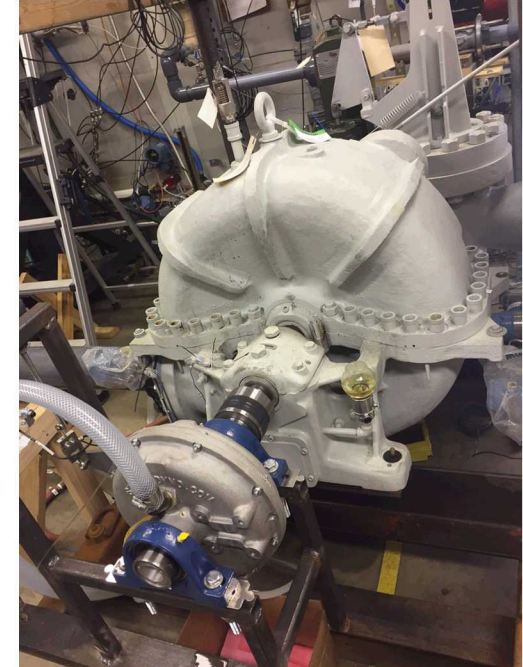
Experimental Updates

Air testing of the CR3 GS-2 has achieved a good performance map.
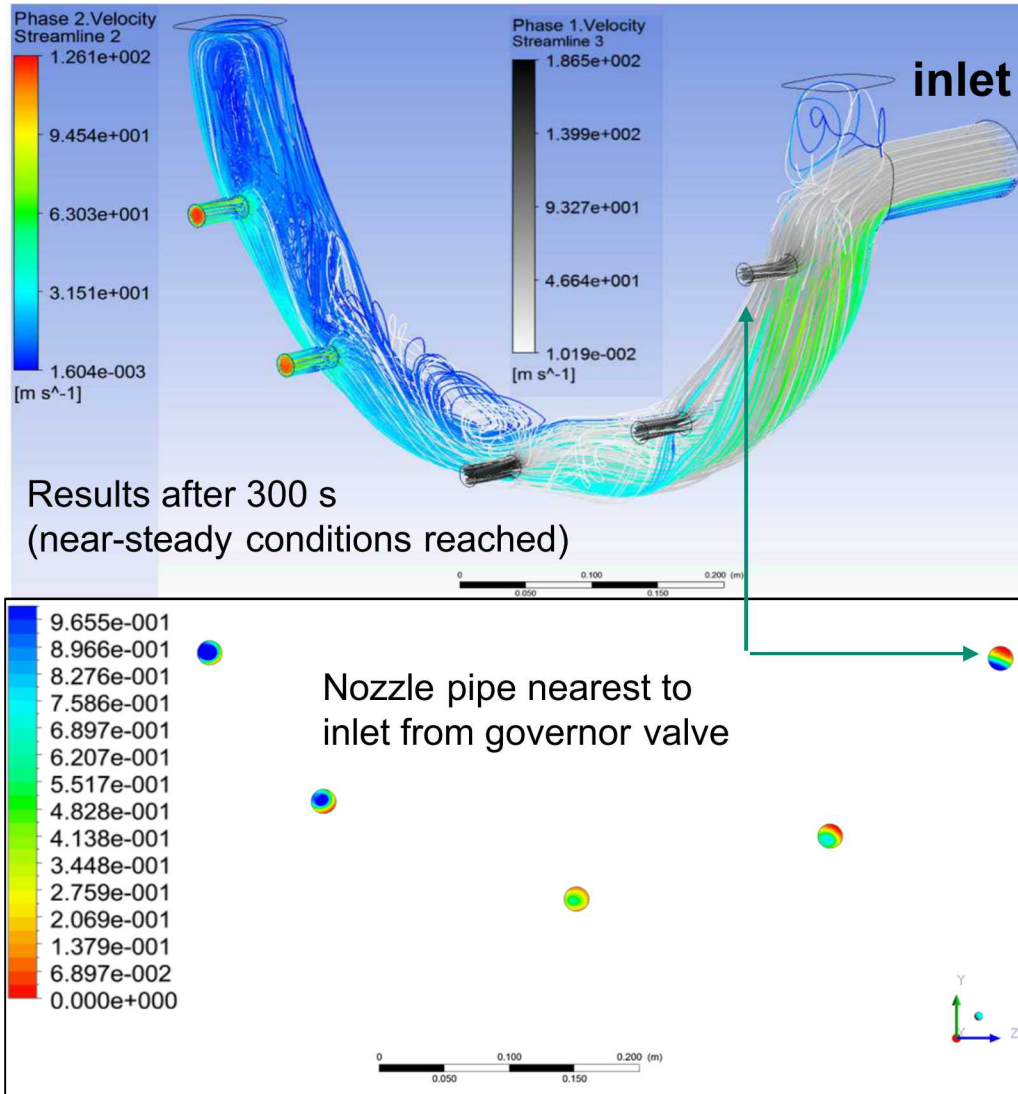- It consumes a lot of air, but can get it to turn unloaded with just a few psi of pressure at the inlet.

Shakedown of the heated oil testing and data from the 72 hour heated oil test.

For the ZS-1, it looks like it needs ~200 W of mechanical power to turn it in our range of speeds
- Much of the loses in power probably goes to friction between the wheel and air in the casing rather than bearing loss.
- Still need to do some tuning of the oil tests before running actual bearing tests on the Clinton Station GS-2 turbine.
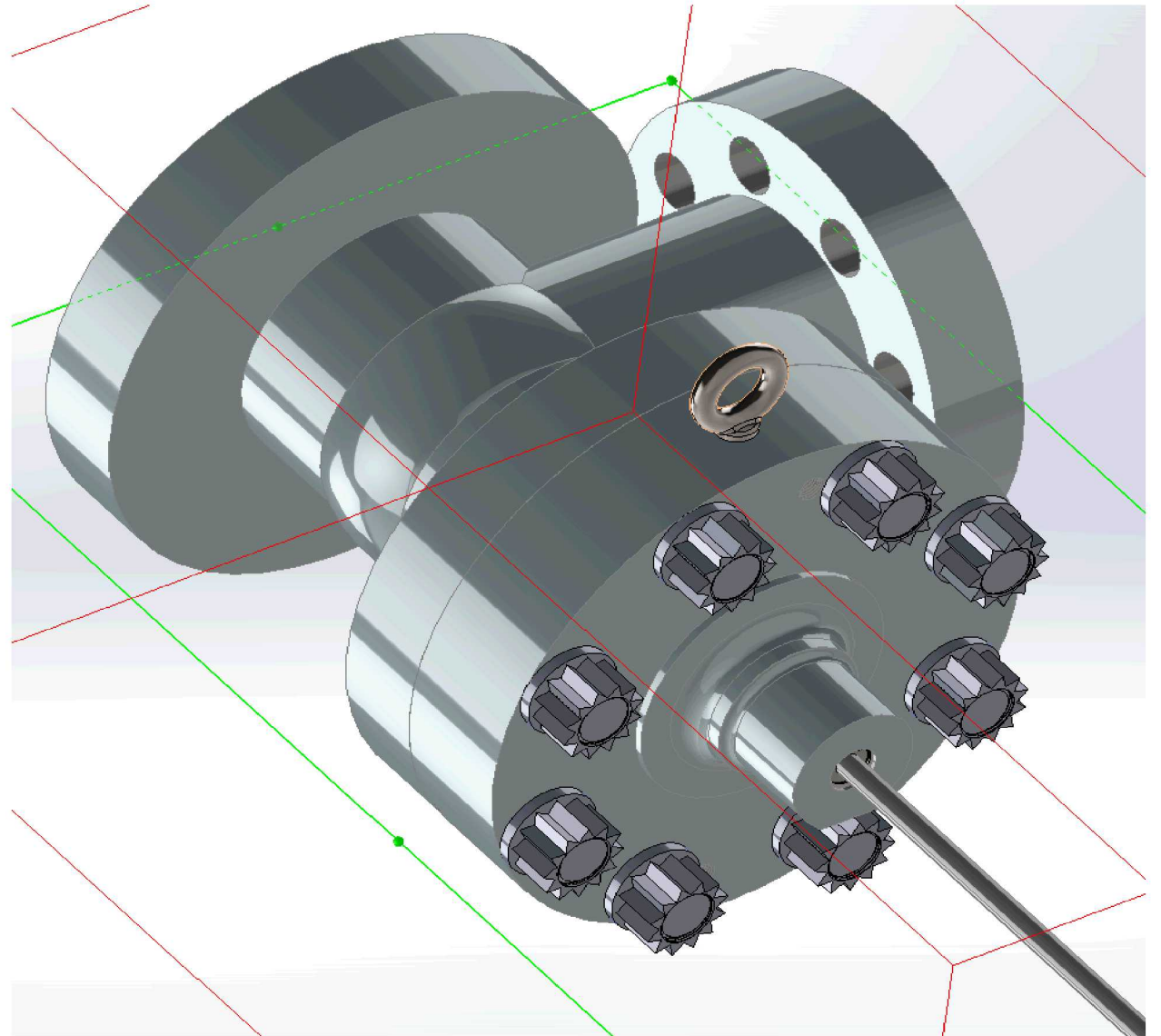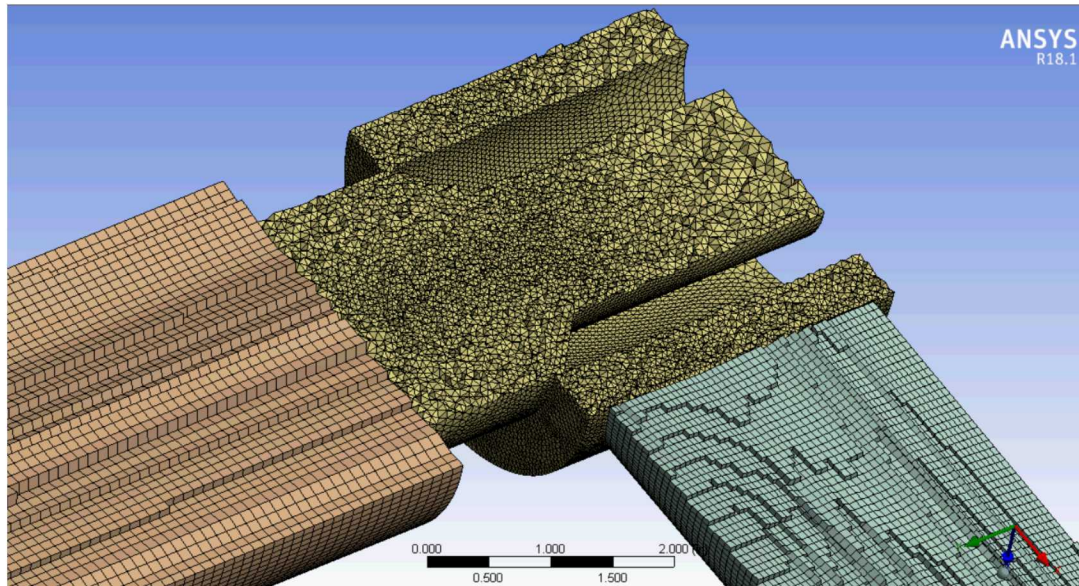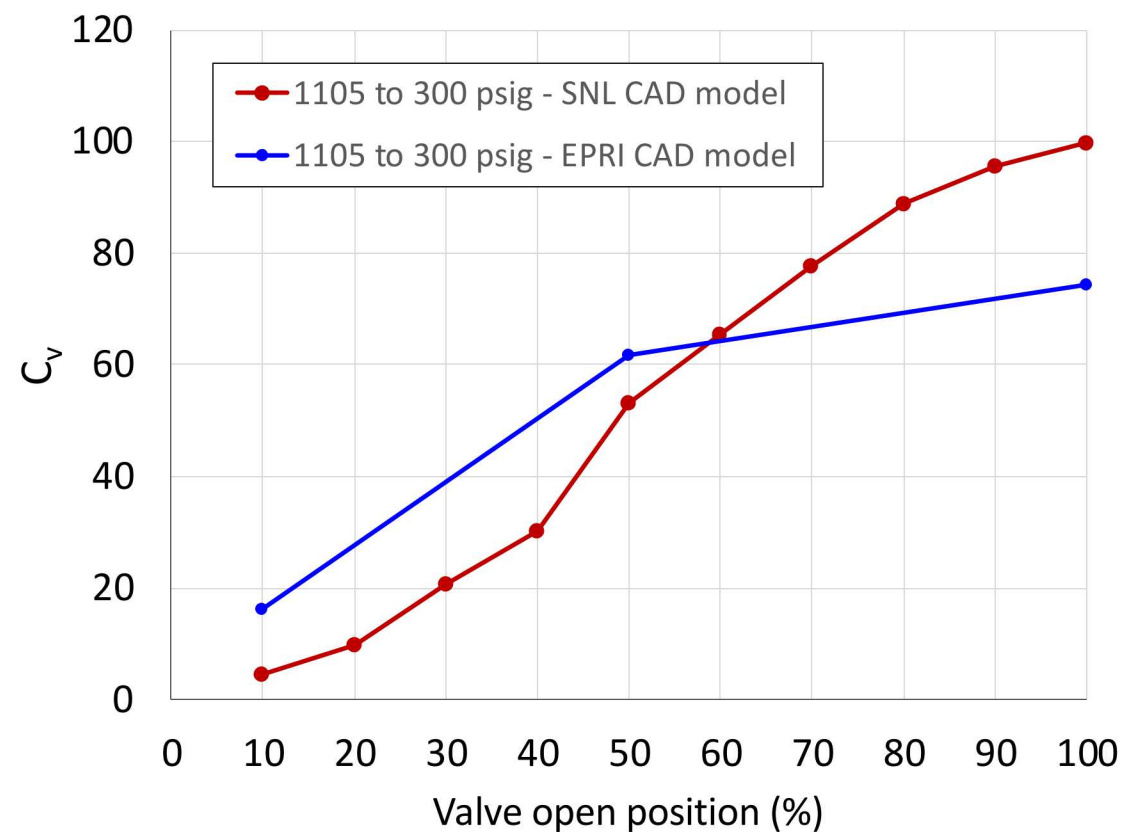
Modeling Activities

Phase 2.Velocity Streamline 2
1.261e+002
9.454e+001
6.303e+001
3.151e+001
1.604e-003
[m s^-1]

Phase 1.Velocity Streamline 3
1.865e+002
1.399e+002
9.327e+001
4.664e+001
1.019e-002
[m s^-1]

inlet

Results after 300 s
(near-steady conditions reached)

9.655e-001
8.966e-001
8.276e-001
7.586e-001
6.897e-001
6.207e-001
5.517e-001
4.828e-001
4.138e-001
3.448e-001
2.759e-001
2.069e-001
1.379e-001
6.897e-002
0.000e+000

Nozzle pipe nearest to
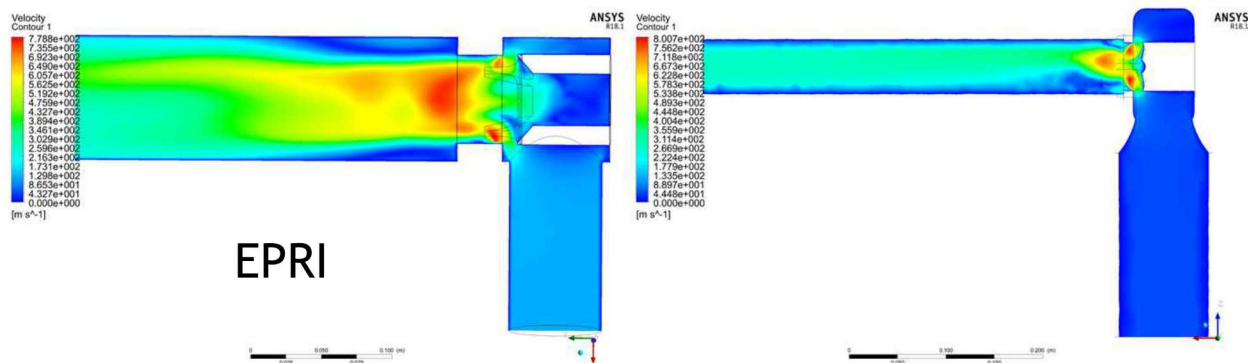inlet from governor valve

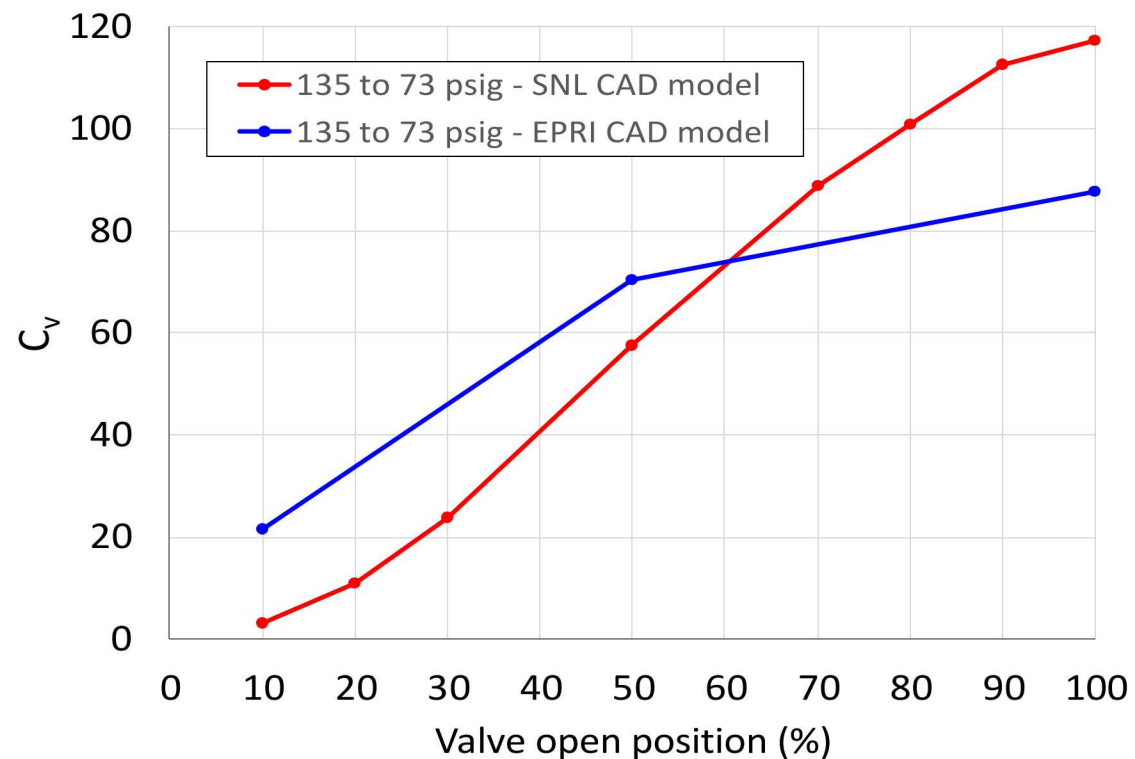Liquid vol. fraction flowing to nozzles

Sandia National Laboratories
Idaho National Laboratory
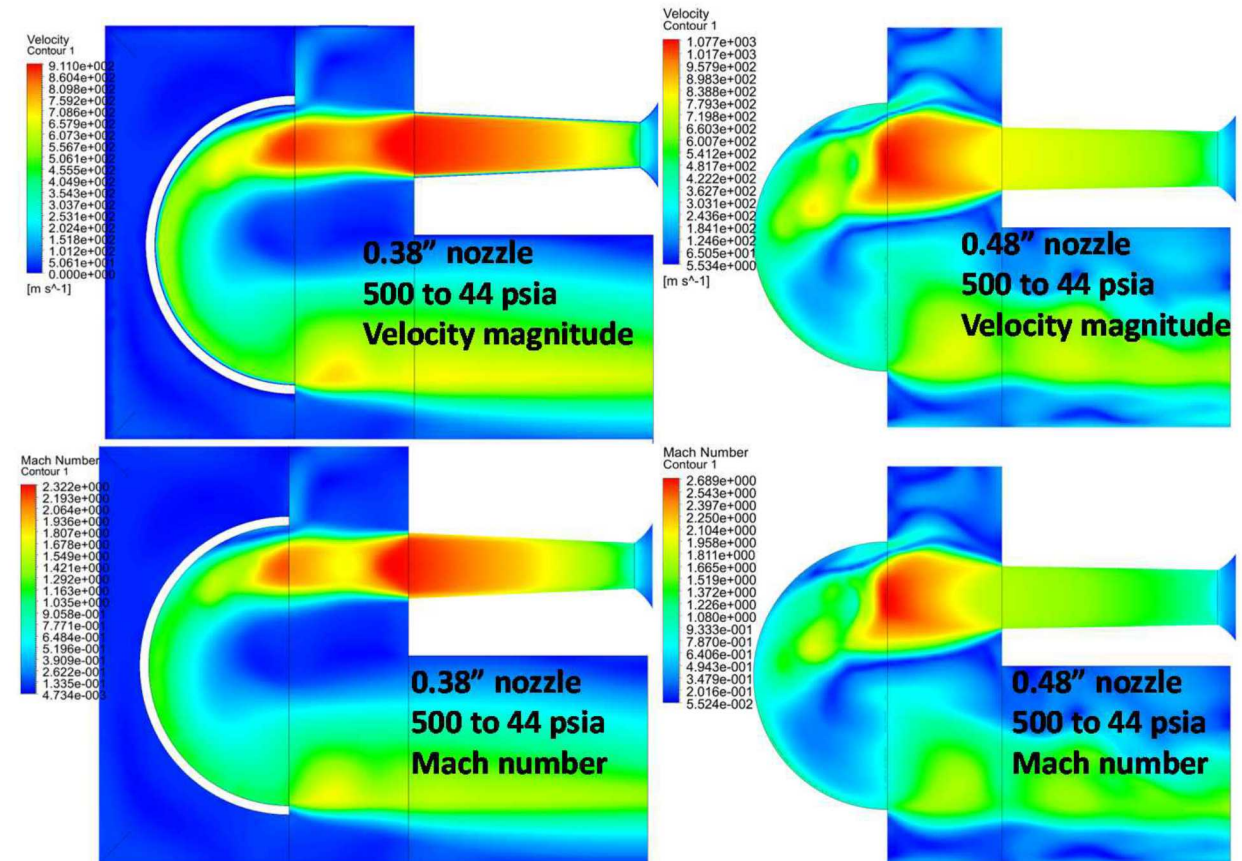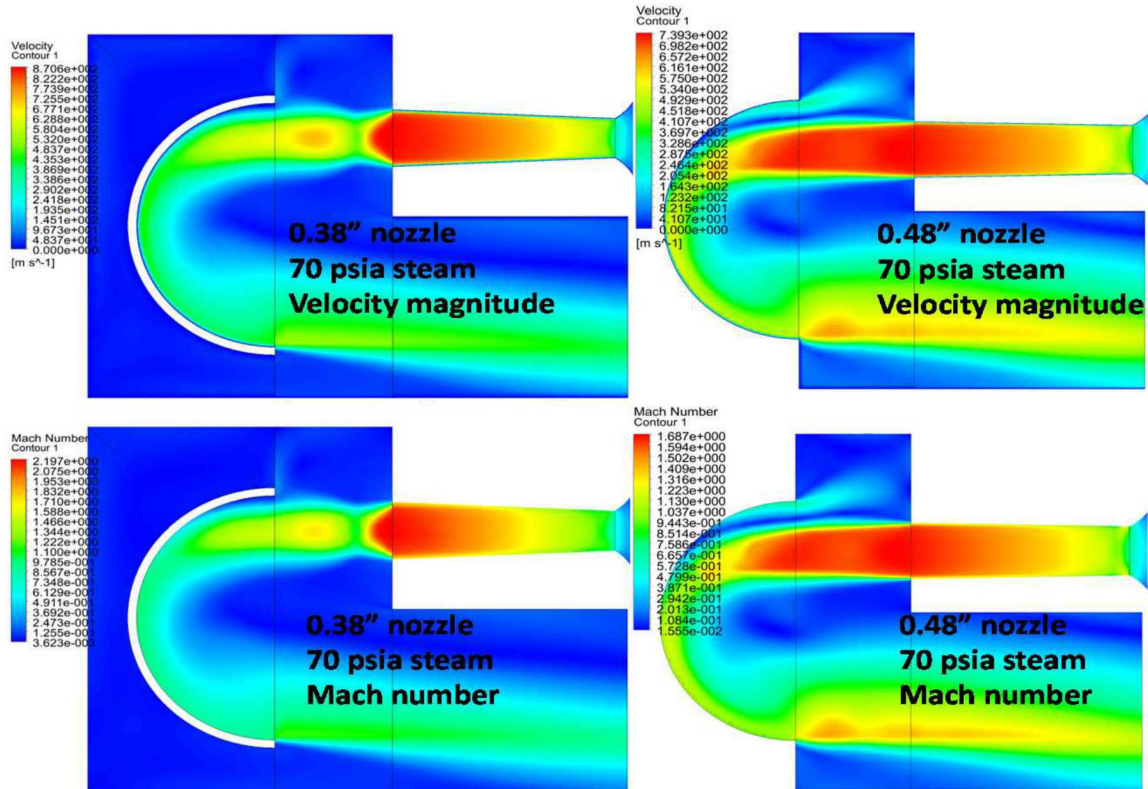Institute of Applied Energy (Japan)
Texas A&M University

CFD and system level modeling
- Pre-experimental modeling
- Identified potential areas of experimental uncertainties
- Provides justification of Milestone 3 & 4 experimental efforts
- Motivation for EPRI to provide CAD drawings of Terry turbine, trip/throttle valves, and governor valves
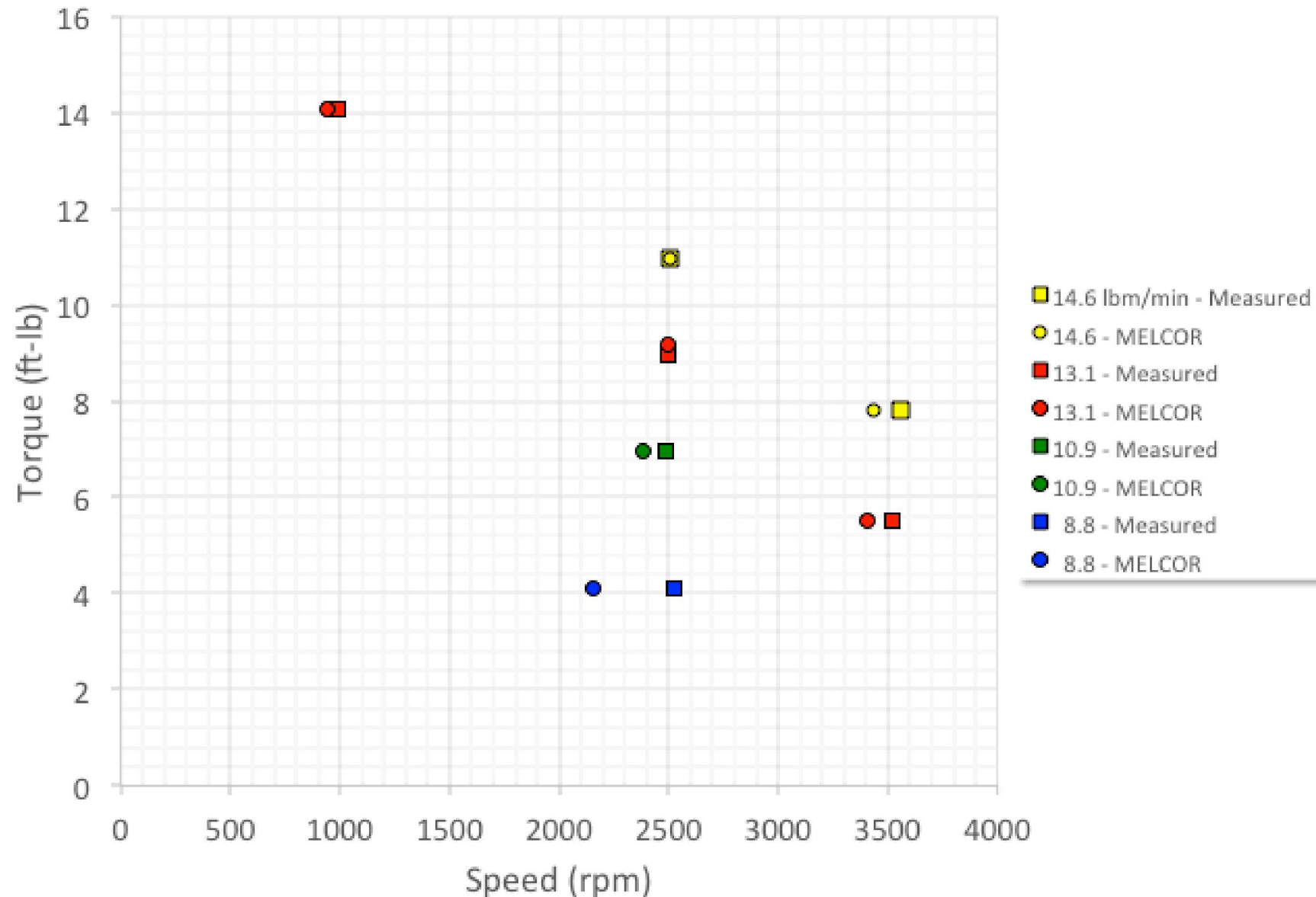
Valves

EPRI CAD models for governor valve

Valve Results

Steam Nozzle

0.38" nozzle
70 psia steam
Velocity magnitude

0.48" nozzle
70 psia steam
Velocity magnitude

0.38" nozzle
70 psia steam
Mach number

0.48" nozzle
70 psia steam
Mach number

0.38" nozzle
500 to 44 psia
Velocity magnitude

0.48" nozzle
500 to 44 psia
Velocity magnitude

0.38" nozzle
500 to 44 psia
Mach number
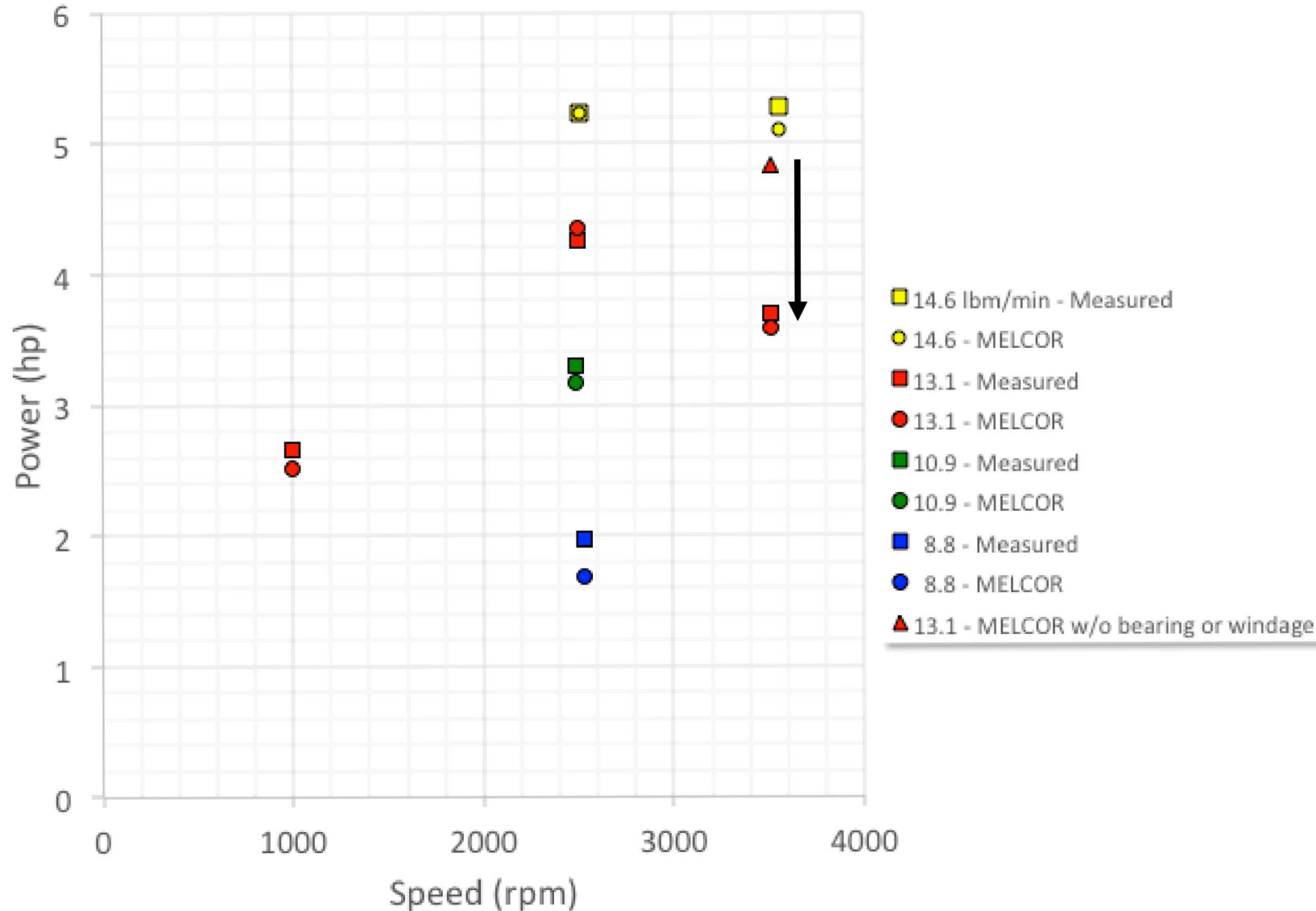
0.48" nozzle
500 to 44 psia
Mach number

System Modeling vs Experimental ZS-1 Air Tests - Torque

System Modeling vs Experimental ZS-1 Air Tests - Power

Experimental Modeling Summary

- The EPRI CAD updates to the governor valve have yielded noticeable differences in modeling and especially at near-closed positions.
  - Additional air test data from the TAMU experiments will provide further input for model refinement.
- TAMU steam nozzle experiments need to reconfigure the testing facility in order to achieve the appropriate Mach numbers for Terry turbine applications in LWRs at low pressures (~100 psia).
  - One solution is to discharge to a vacuum.
  - Another option involves replacing the nozzle with a shorter and smaller orifice that could result in drastically under-expanded flow.
  - Or a combination of these choices.
- TAMU steam nozzle experiments for assessing the validity of the wet-steam approximations will require more flexible two-phase treatments that have not yet been explored for the nozzles.
  - The use of high speed video (250K to 1M fps) and shock physics modeling will be required to properly quantify the condensation shock for applications within CFD
- TAMU turbine air testing and system-level modeling results show that a Terry turbine can develop the same power at two very different speeds.
  - This discovery has large implications with respect to understanding how a RCIC or TDAFW system would respond to a loss of electrical power for speed governing.
  - Additional testing at TAMU of a GS-2 Terry turbine (typical for RCIC/TDAFW) with air and ZS-1 Terry turbine with steam will assist in confirming this insight.
- The TAMU turbine air experiment data compared with system-level modeling suggest parasitic losses (i.e., turbine bearing friction and wheel windage) could be important.
  - Considering these losses allows the modeling of turbine performance to compare very well with measured performance in the TAMU tests.

MELCOR Model of Fukushima Daiichi Unit 2

A MELCOR model with a full representation of the Fukushima Unit 2 reactor, reactor vessel, containment, reactor building and reactor core isolation cooling (RCIC) turbine/pump system is being used to simulate the Unit 2 accident.

Uncertainties exist in the modeling of the RCIC turbine. The uncertainties, steam nozzle size for instance, are being investigated by running multiple simulations.

Striking in these uncertainty simulations is the cooled condition of the reactor system that persistently develops as RCIC self-regulates to balance the water delivery capacity and steam consumption demands of the RCIC system against the fission product decay power in the reactor.

In large part, resolution of the uncertainties is awaiting planned testing.

A shortcoming exists is the simulation in that boiler pressure doesn't track recorded pressure in the accident especially well.
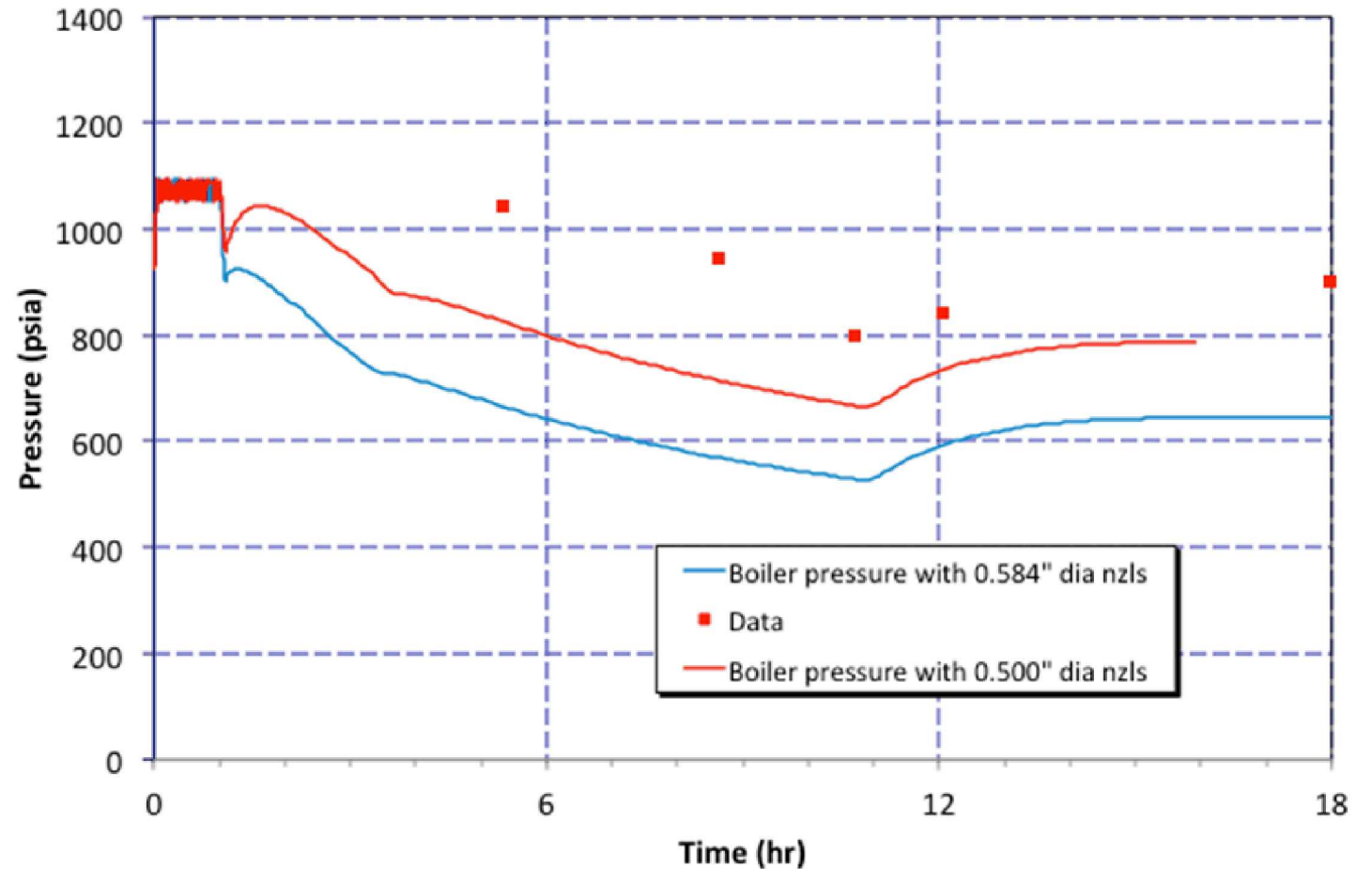
Resolution of the modeling uncertainties is expected to remedy this shortcoming.

Fukushima Daiichi Unit 2 Modeling Results – Boiler Pressure

The strong depressurization occurring when backup electrical power is lost at 1 hr results from the large increase in RCIC flow to the reactor when the power loss causes the RCIC turbine control valve to open fully

The strong inflection at 1+ hr results from the RCIC turbine ingesting water once the RPV overfills to the MSL nozzles and spills into the MSLs
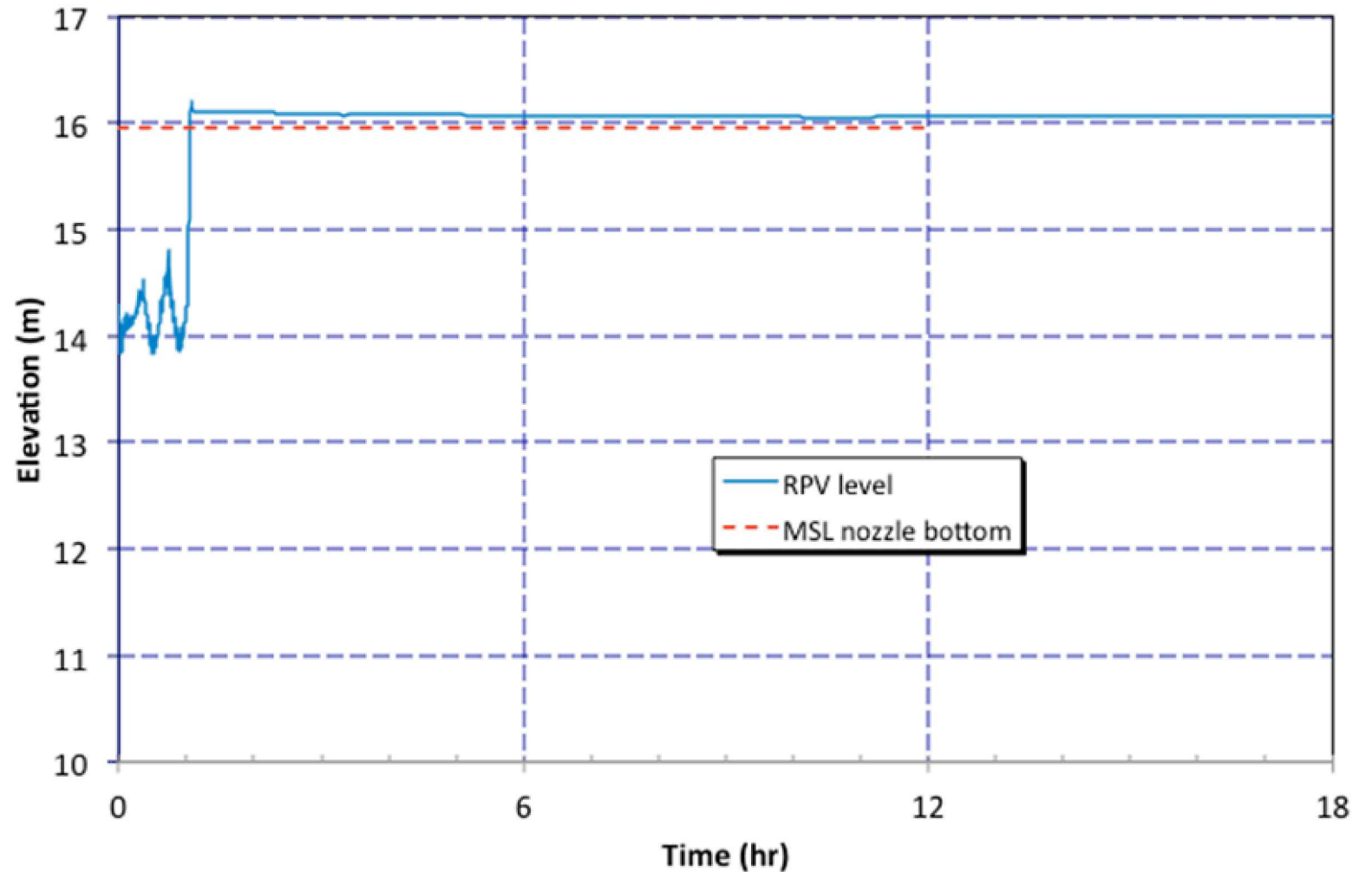
The inflection at ~11 hr is RCIC self-regulating to a higher pressure in response to the operators switching RCIC suction from the relatively cold CST to the hotter wetwell

Fukushima Daiichi Unit 2 Modeling Results – RPV Water Level

RCIC tripping twice on high level before electrical power loss at 1 hr is reflected

Level climbs rapidly when the RCIC turbine governor valve opens fully on loss of electrical power and overfills the RPV to the MSLs
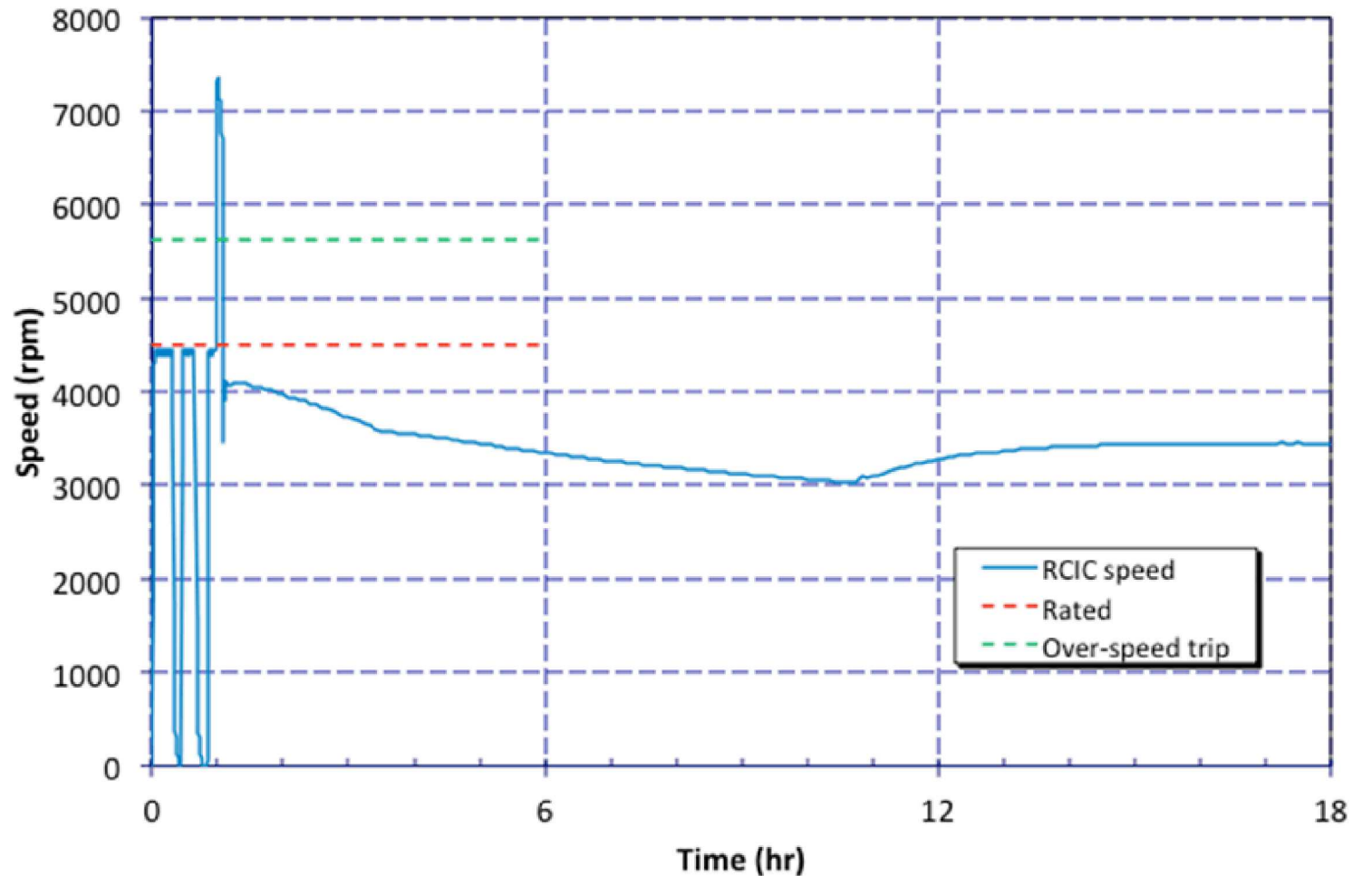
Fukushima Daiichi Unit 2 Modeling Results – RCIC Speed

The RCIC turbine governor valve opening fully on loss of electrical power sends RCIC speed screaming higher

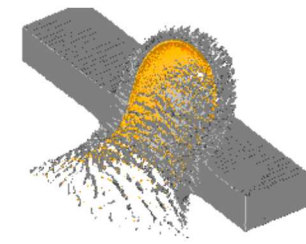The indicated over-speed trip was ignored, i.e., RCIC was allowed to continue running

Water ingestion by the RCIC turbine at 1+ hr brings RCIC speed back down

The inflection at ~11 hr is RCIC's self-regulating response to the operators switching RCIC suction from the CST to the wetwell.

Future Efforts – Steam Nozzles

- High speed video and data fusion for two-phase flow across a steam nozzle
  - TAMU has insufficient camera speeds (20,000 fps)
  - Current estimate to capture phenomena is 250,000 fps
    - Potential use of IR camera (1,000 fps) for thermal effects

- Applications beyond nuclear energy
  - Various steam system applications for power generation

- Shock Physics Modeling
  - CTH Shock code will need steam and water algorithms

- Meets modeling needs for Milestone 5 & 6 efforts
  - Precautionary modeling in the event of two-phase flow at low power levels for Milestone 5
  - Could preclude the need to do Milestone 6 (*major cost savings*)
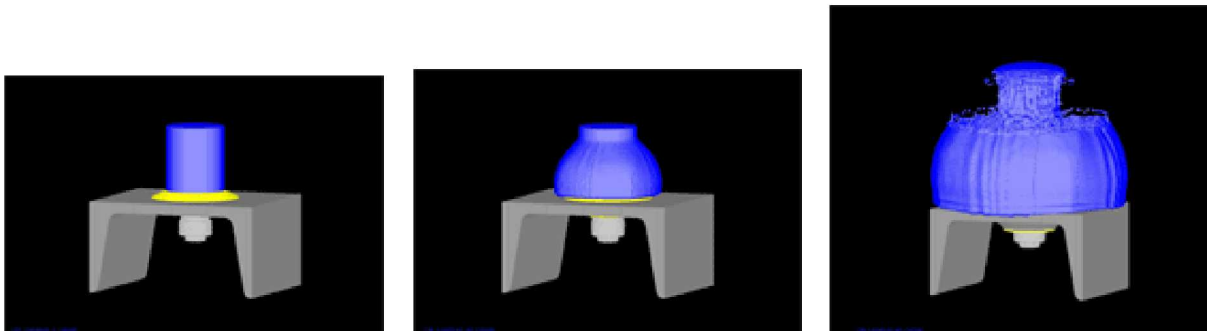
Shock Physics Modeling

CTH is a multi-material, Eulerian, large deformation, strong shock wave, solid mechanics code developed at Sandia National Laboratories.
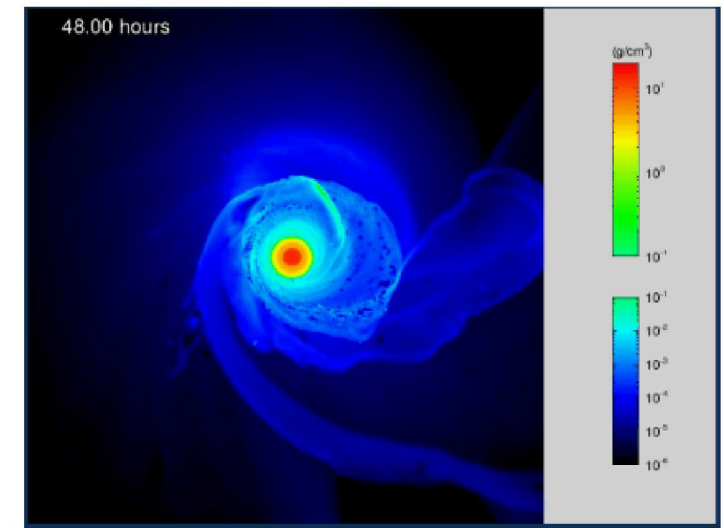
Models multi-phase, elastic viscoplastic, porous, and explosive materials.

3-D rectangular meshes, 2-D rectangular, and cylindrical meshes, and 1-D rectilinear, cylindrical, and spherical meshes are available.

Adaptive mesh refinement and uses second-order accurate numerical methods to reduce dispersion and dissipation and produce accurate, efficient results.

A 1-inch cylinder of explosive is detonated on the bottom by a booster pellet. From left to right the images show the initial geometry, the explosive partly detonated, and the expanded products after detonation is complete.

Formation of Moon by Giant Impact (Crawford & Kipp)
54-hour, AMR-CTH simulation with self-gravity, 40 million zones, equivalent to 20 billion zones without AMR (2011)
500x memory gain, 200-300x performance gain

Milestones 5 & 6

Milestone 5 – Full-Scale Integral Experiments for Long-Term Low-Pressure Operations

Milestone 6 – Scaled Experiments Replicating 1F2 Self-Regulating Feedback

Reevaluation of Physical Security

Analyze the existing physical security regime with at least one pilot plant, and compare/contrast insights with alternative methods which leverage advanced modeling and simulation, modern technologies, and novel techniques.

DOE Office of Nuclear Energy Cyber Efforts