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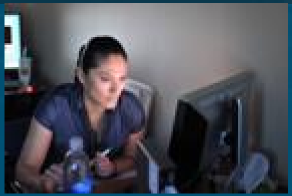
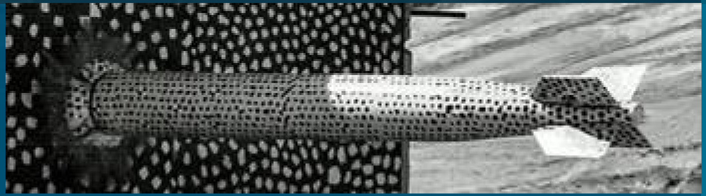
Sandia National Laboratories

MELCOR Modeling Of Uncontrolled RCIC Operation Under Beyond Design Basis Event Conditions





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Background

Reactor core isolation cooling (RCIC) is a system that provides emergency cooling to RPV (reactor pressure vessel) after an initial loss of power.

- RCIC performance during beyond design basis event conditions is not well characterized.

It is assumed that battery loss or depletion results in RCIC failure.

Fukushima Daiichi Unit 2 is an example of a real world RCIC response:

- RCIC started after initial loss of onsite power.
- Batteries lost/failed at ~1 hour.
- RCIC overflowed but did NOT fail until ~3 days into accident.

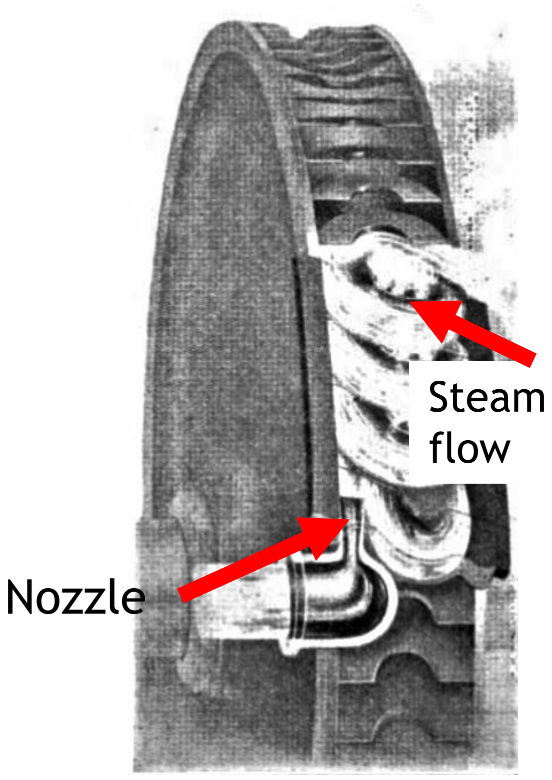
The RCIC system is a steam-driven pumping system which utilizes a Terry turbine.

- Terry turbines are not a new design but are also not well characterized.

Conservative assumptions about Terry turbines limit the mitigation options considered for normal and emergency operations.

Goal: Better understand Terry turbine behavior through a combined effort of modeling and full-scale experimental testing funded by the Terry Turbine Expanded Operating Band (TTEXOB) program. This includes:

- MELCOR modeling Texas A&M (TAMU) experimentation of ZS-1 and GS-2 Terry turbines
- MELCOR modeling a "generic" boiling water reactor (BWR) experiencing self-regulating behavior



Unknown Author, 1918. "The Terry turbine-driven fans". *Journal of the American Society of Naval Engineers*, ***30***(1), pp. 598-599.

MELCOR Modeling – TAMU ZS-1 Experiments Description

Experiments:

ZS-1 turbine flowing air with dynamometer loading used to control turbine speed

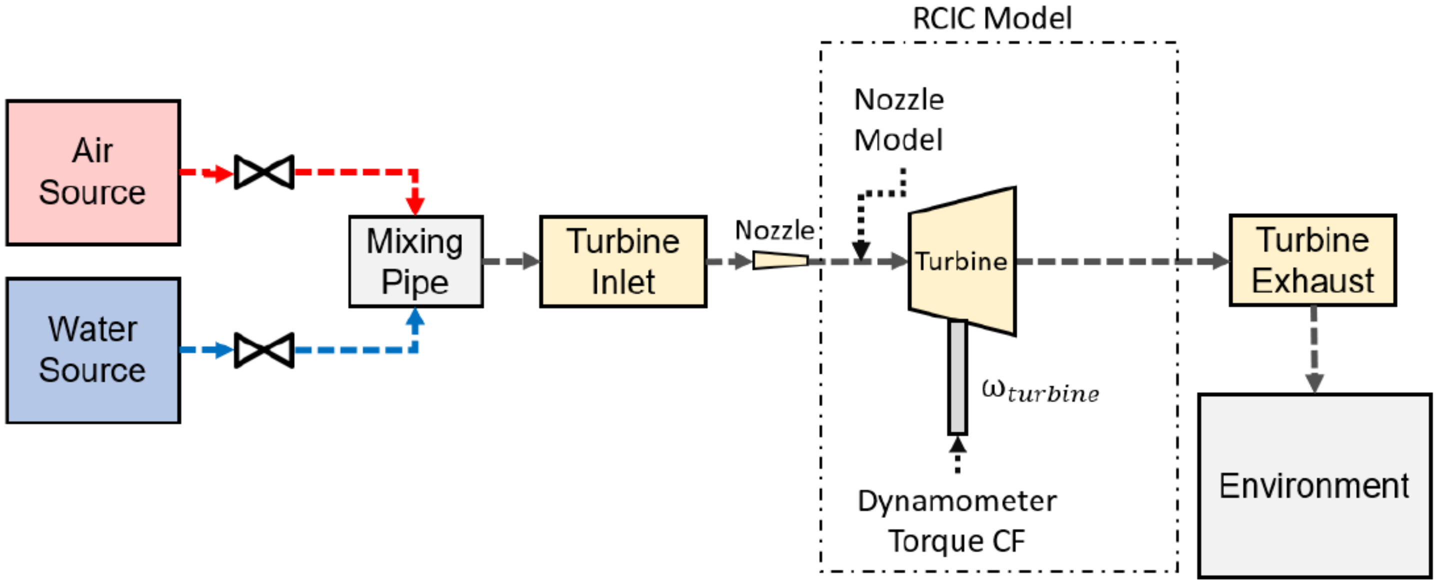
- ZS-1: 457 mm (18 in) diameter and 1 nozzle
- A range of pressures, mass flow rates, and speeds
- Data collected: mass flow rate, dynamometer loading, torque, power

MELCOR Modeling:

Mass flow rate and pressure from experiment matched

Dynamometer/resistive torque as input to Terry turbine model

ZS-1 MELCOR Nodalization



TAMU ZS-1 and GS-2 experiment publications:

A. Patil et al., "Two-phase operation of a Terry steam turbine using air and water mixtures as working fluids," Applied Thermal Engineering, 165, pp. 114567 (2020)

J. Vandervort et al., "Performance evaluation of a Terry GS-2 steam impulse turbine with air-water mixtures," Applied Thermal Engineering, 191, pp. 116636 (2021)

MELCOR Modeling – TAMU ZS-1 Calibration

Loss form for ZS-1 was provided by TAMU:

$$\tau_{loss} = c_{windage}\omega^2 + c_{linear}\omega + constant$$

$$\tau_{net} = c_{torque} \times \tau_T - \tau_{loss}$$

$\omega = speed$

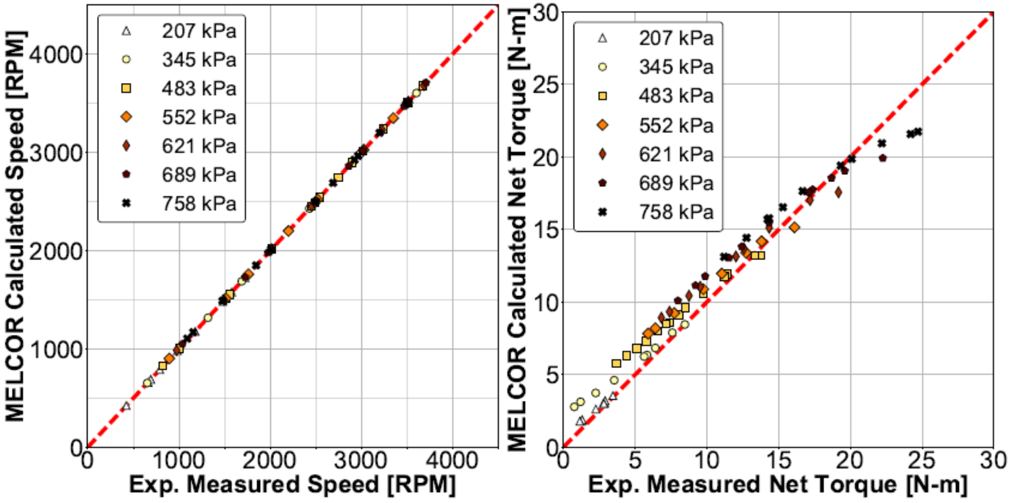
$\tau = turbine\ torque$

- $c_{linear} = 1.39 \times 10^{-7}$ and $c_{windage} = 2.3 \times 10^{-4}$ approximated from data
- c_{torque} needs to be determined through calibration.

Two calibration exercises:

1. Calibrate a c_{torque} value for every TAMU test.
   - NOT predictive, but can be used to verify model is working properly
2. Calibrate a global c_{torque} value for all TAMU tests

Results of Calibrating c_{torque} Individually to Each Test

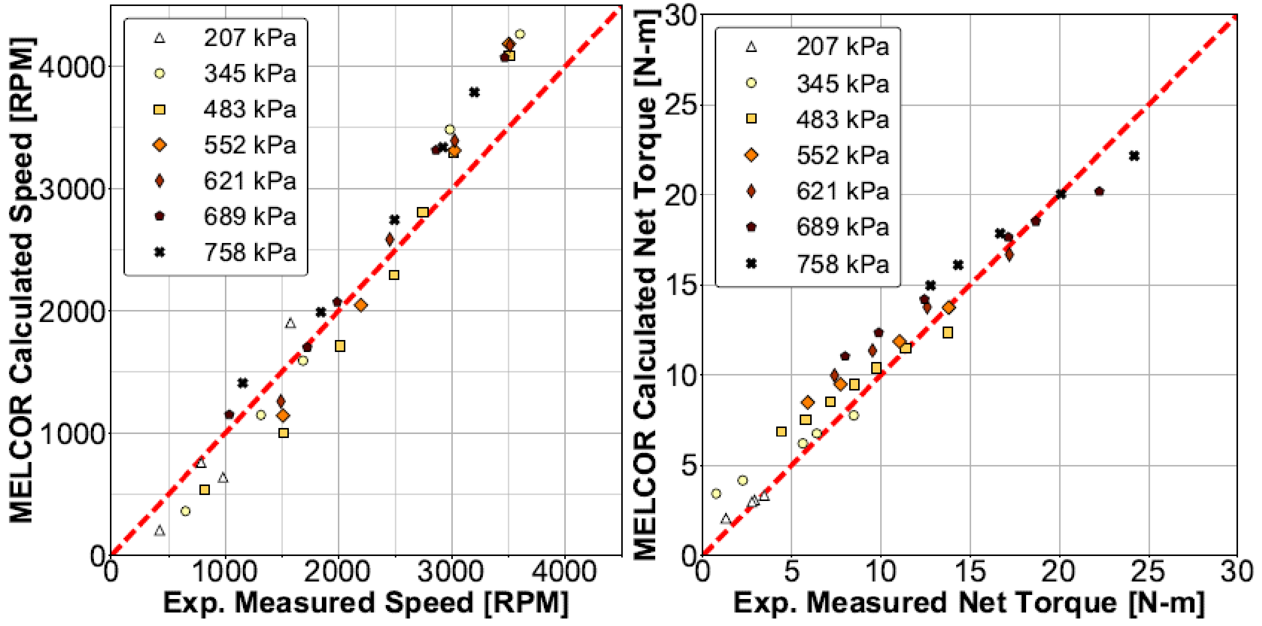


MELCOR Modeling – TAMU ZS-1 Global Calibration

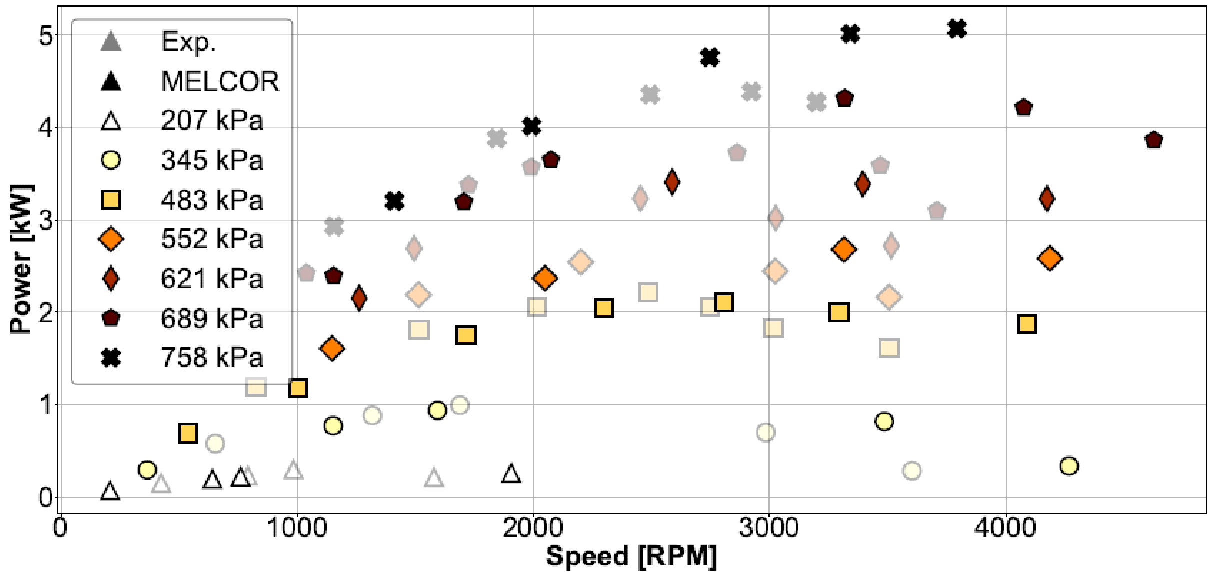
Results of calibrating single c_{torque} value for all experiments

- Overall good match to speed/torque can be obtained from calibrating global c_{torque} value.
- Power curve is a product of both quantities.

ZS-1 Experiment vs MELCOR Speed & Torque



ZS-1 Experiment vs MELCOR Power



Transparent symbols are experimental points, solid symbols are MELCOR points

MELCOR Modeling – TAMU GS-2 Comparison

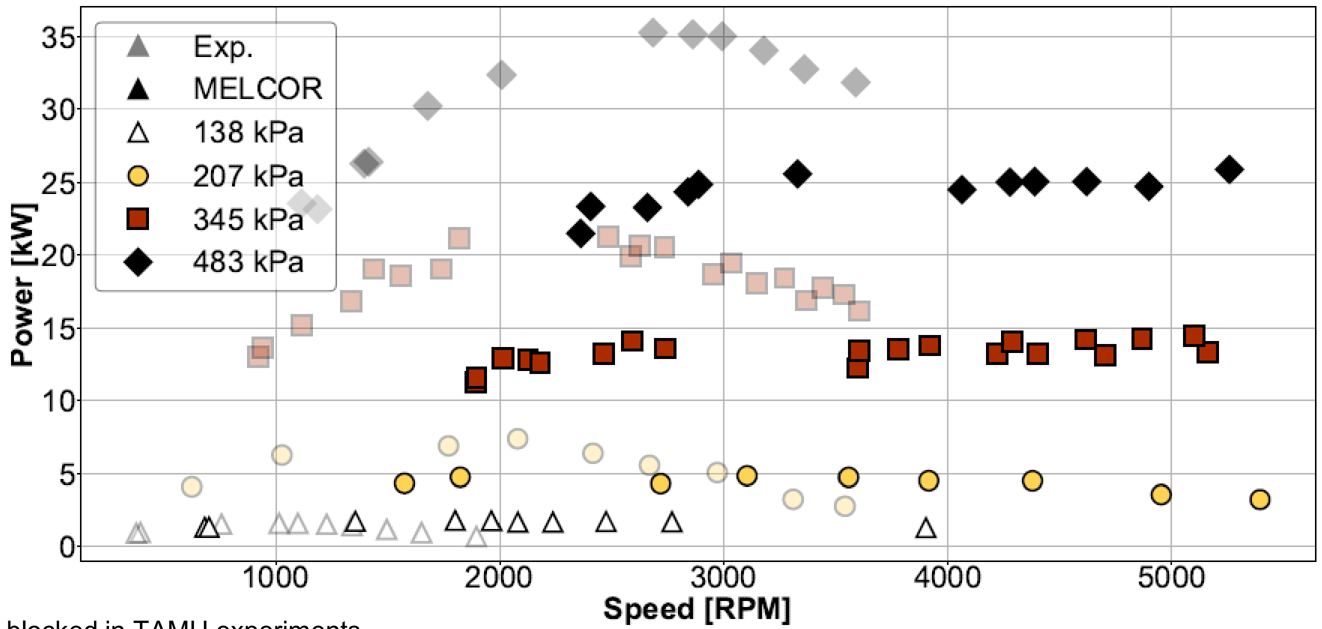
TAMU also performed GS-2 air experiments.

- GS-2: 610 mm (24 in) diameter and 5 nozzles**
  - GS-2 was included for comparison, but not the focus of this modeling exercise

A new global coefficient would need to be determined for the GS-2.

- Loss data will need to be provided to perform a similar exercise

GS-2 Experiment vs MELCOR Power using ZS-1 Global c_{torque} Value and ZS-1 loss form



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**GS-2 Terry turbines have 10 nozzles, but 5 were blocked in TAMU experiments

MELCOR Modeling – Generic BWR with Uncontrolled RCIC

A MELCOR input deck was developed with emphasis on capturing self-regulating RCIC turbopump behavior of a GS-1 turbine

Self-regulating feedback mechanism:

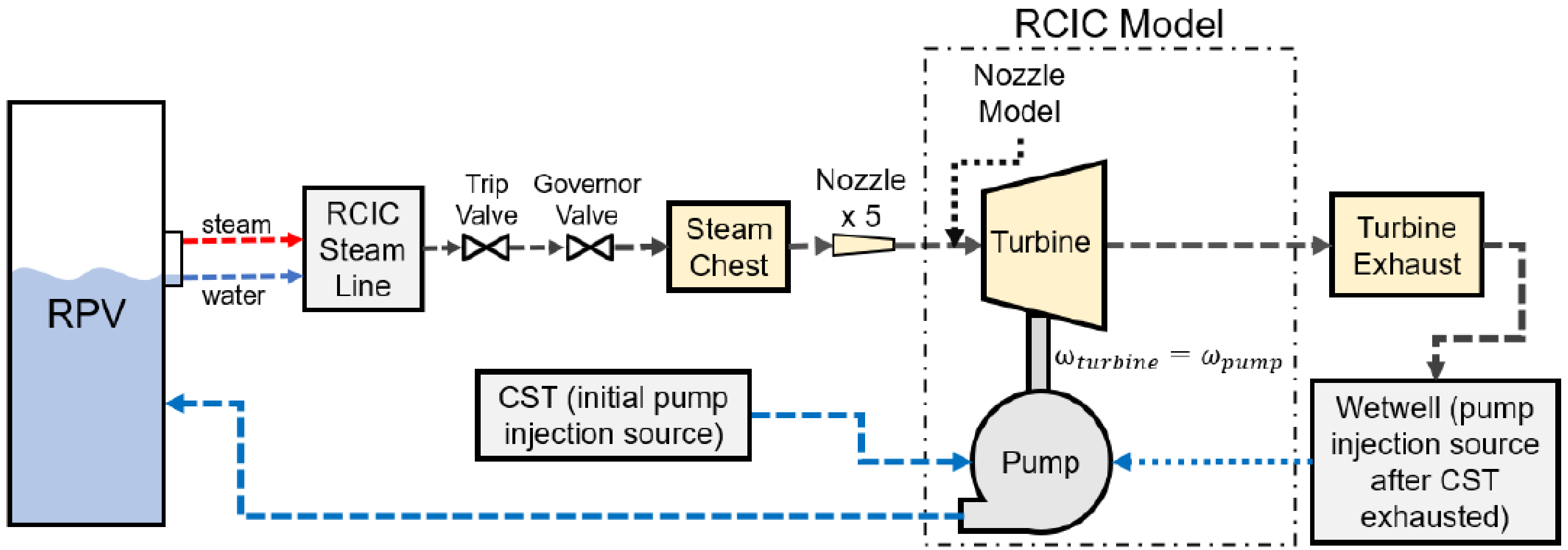
- Loss of power leads to trip/governor valves opening
- Increased steam admittance ⇒ increased turbine speed/pump injection ⇒ water overflowing the RPV into RCIC steam line
- Water enters turbine ⇒ turbine slows down ⇒ decreased pump injection ⇒ RPV water level drops
- Increased steam admittance ⇒ increased turbine speed/pump injection ⇒ … And so on

MELCOR Modeling – Generic BWR with Uncontrolled RCIC

Accident being modeled:

- SCRAM at t = 0
- RCIC starts at t=60 seconds
- Battery power lost at t=2 hours
  - Trip/governor valves open
- RCIC operates uncontrolled

Generic BWR MELCOR Nodalization



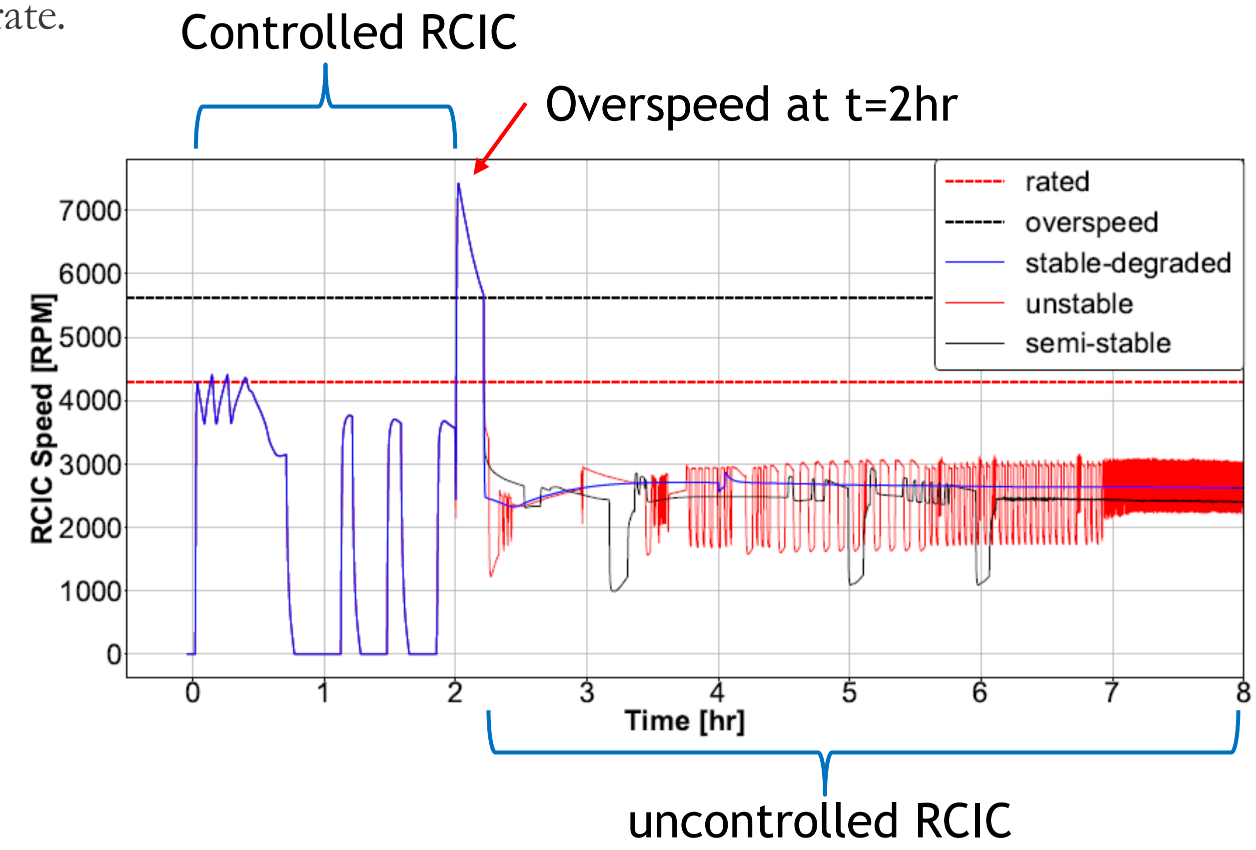
MELCOR Modeling –Uncontrolled RCIC Modes

Three Uncontrolled RCIC Modes:

- **Stable-degraded self-regulation:** Constant turbine speed and degraded pump injection.
- **Unstable self-regulation:** Unstable turbine speed and pump injection.
- **Semi-stable degraded self-regulation:** Constant turbine speed and degraded pump injection with significant fluctuations of turbine speed and pump injection rate.

Difference in modeling:

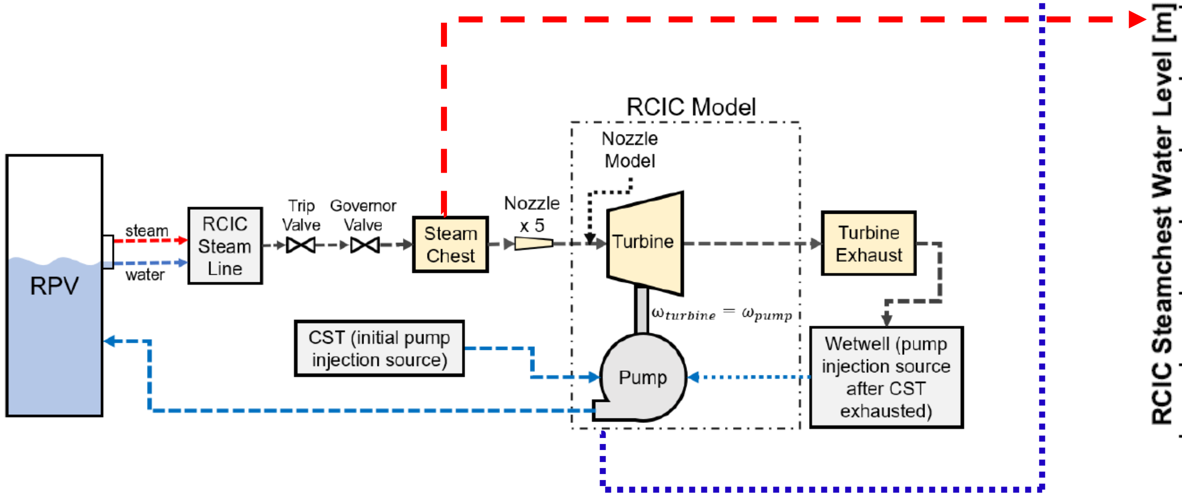
- 5 nozzle flow paths
- Varied elevation of nozzles relative to each other
  - Nozzle elevation affects nozzle void fraction
  - **Stable-degraded:** Evenly spaced in elevation
  - **Unstable**: 3 high, 2 low
  - **Semi-stable:** 2 high, 3 low

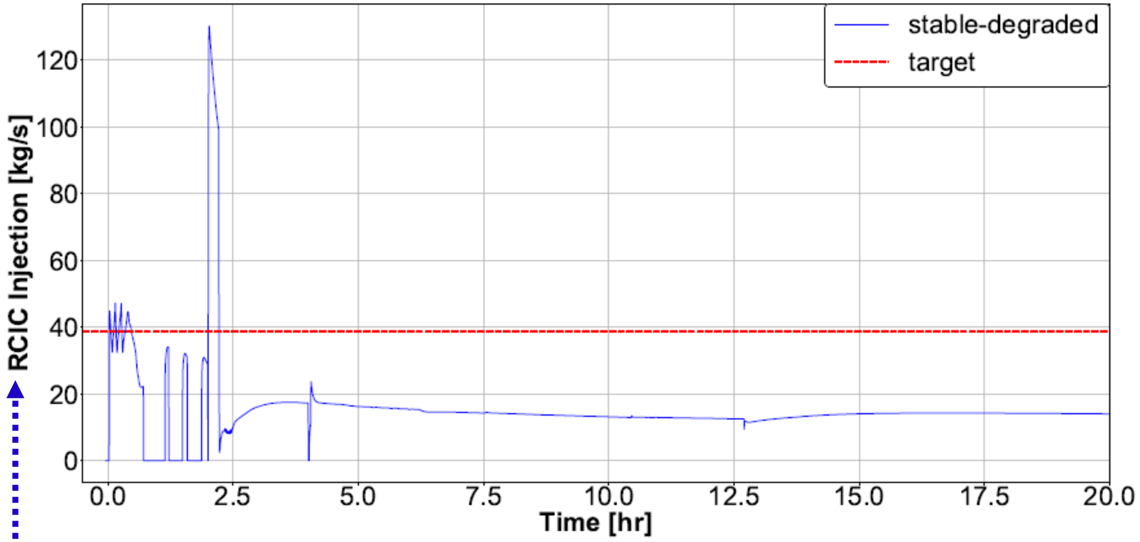


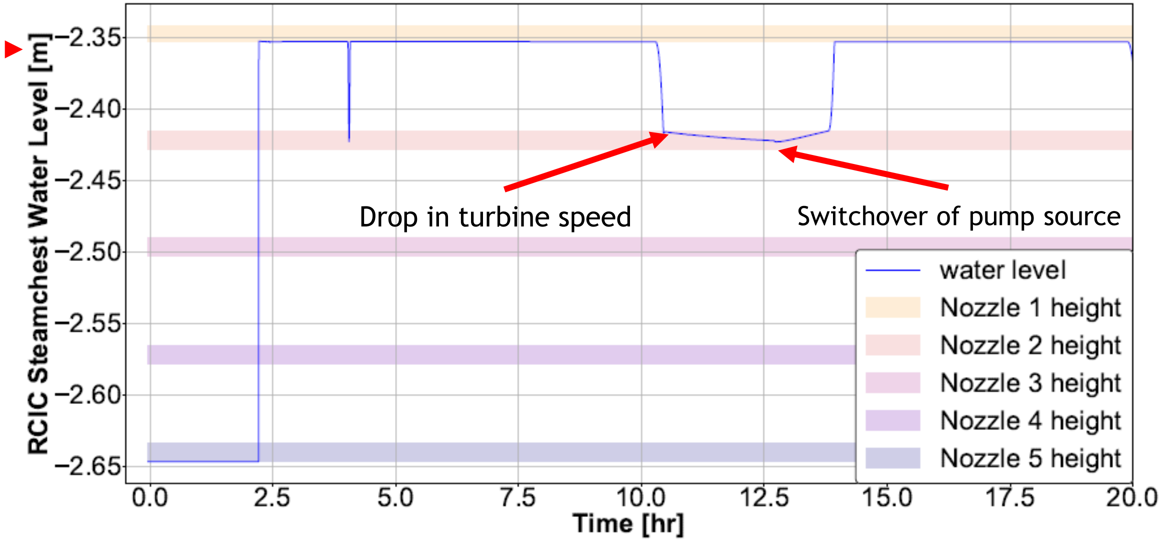
MELCOR Modeling – Stable-Degraded Self-Regulation

Stable-degraded self-regulation: Constant turbine speed and degraded pump injection.

- 13 and 18 kg/s injection produced by the pump during self-regulating mode, which is degraded from the standard rated injection of ~39 kg/s.
- Steady injection leads to a relatively steady RPV/steamchest water level
- Nozzles evenly spaced in elevation ⇒ Bottom 4 nozzles submerged, top 1 nozzle is uncovered through nearly entire simulation



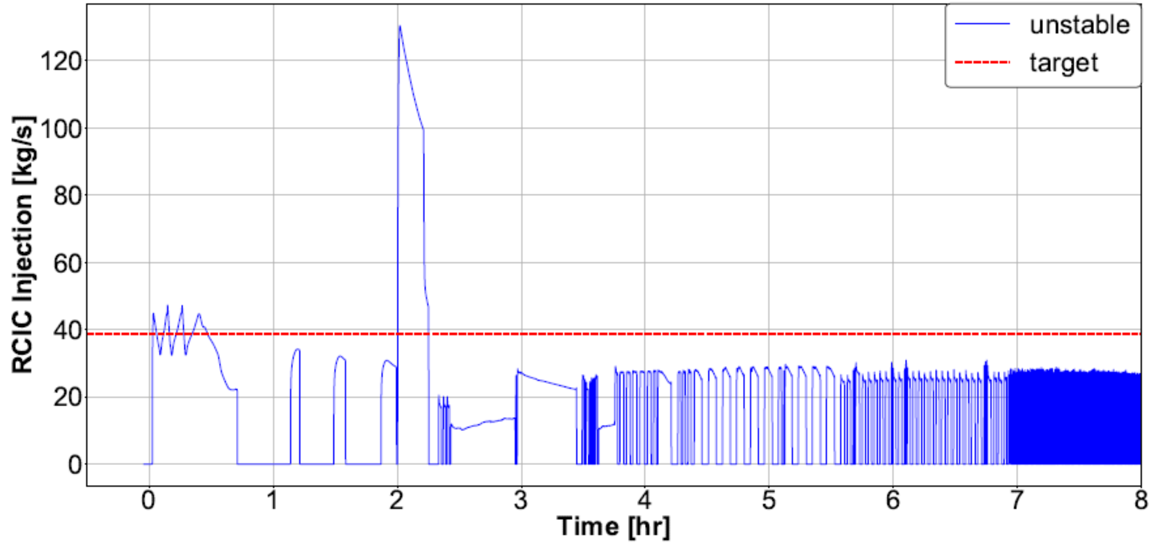


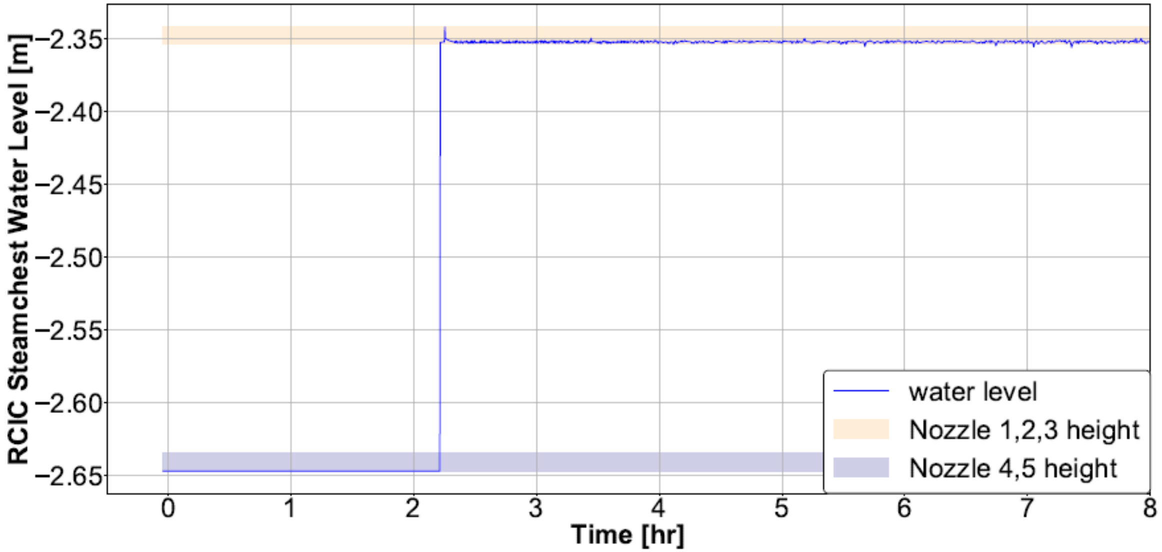


MELCOR Modeling – Unstable Self-Regulation

Unstable self-regulation: Unstable turbine speed and pump injection.

- Fluctuating pump injection leads to a fluctuating RPV/steamchest water level
- Three nozzles at top of steamchest, two at bottom



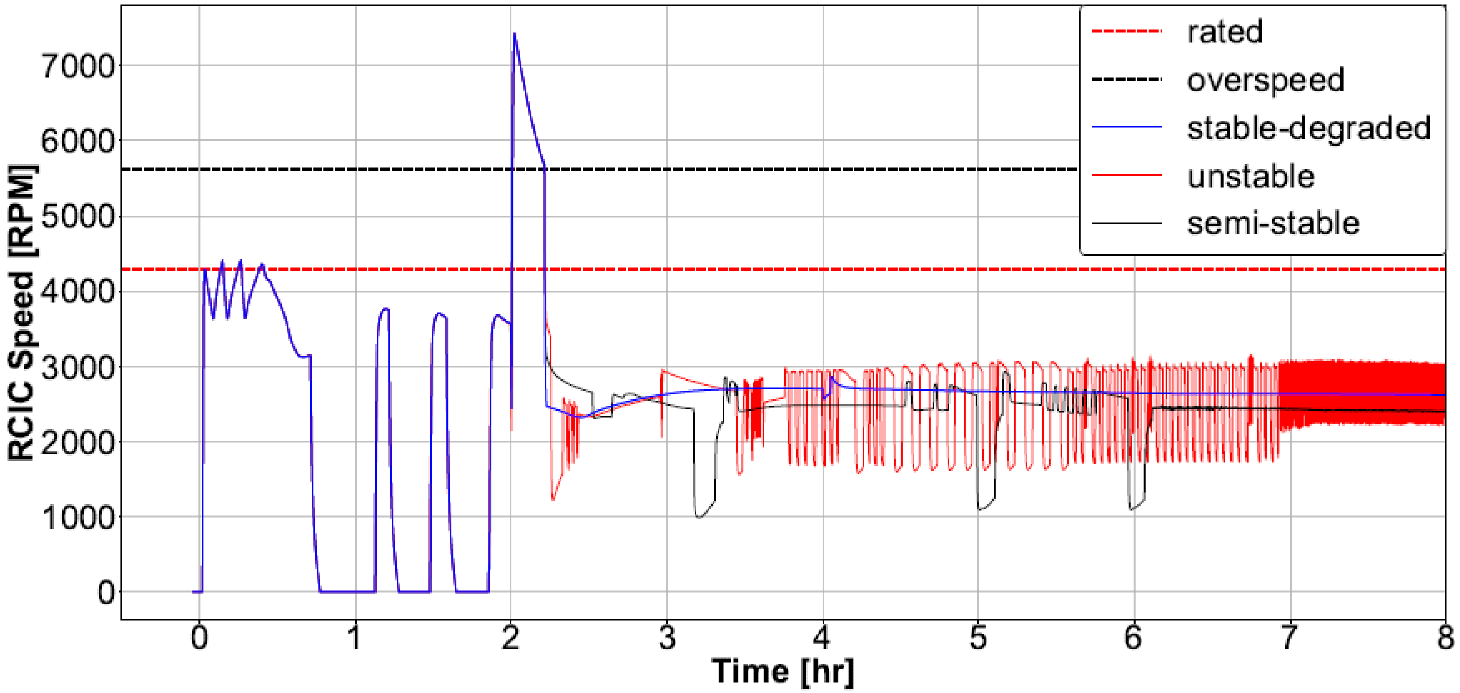


MELCOR Modeling – Semi-Stable Degraded Self-Regulation

Semi-stable degraded self-regulation: Constant turbine speed and degraded pump injection with significant fluctuations of turbine speed and pump injection rate.

Has characteristics of both stable and unstable self-regulation.

- Two nozzles at top of steamchest, three at bottom
  - Addition of 1 "bottom" (i.e., primarily flowing water nozzle) enough to prevent the frequent turbine speed spikes seen in unstable modeling



MELCOR Modeling –Uncontrolled RCIC Modes Summary

What determined the self-regulating mode: how the nozzles were represented.

- 5 nozzle flow paths
- Varied elevation of nozzles relative to each other
  - **Stable-degraded:** Evenly spaced in elevation
  - **Unstable**: 3 high, 2 low
  - **Semi-stable:** 2 high, 3 low
- How to best represent the nozzles is an uncertain parameter and it is unknown how a steam and water mixture will behave once the mixture enters the steam chest and the nozzles

RCIC behavior is *highly* sensitive to uncertain model inputs.

- Some of these behavior modes will be inherently more stressful mechanically, and severe oscillations could potentially take the system offline.
- Uncertain if this sensitivity extends to the real life RCIC turbopump system

Overall Conclusions

Modeling RCIC behavior is complicated due to the coupled feedback mechanisms that drives the system behavior.

ZS-1 modeling:

- We were provided loss data that allows us to characterize the loss form. To perform the same analysis for the GS-2, we would need GS-2 loss data.
- Improving the ZS-1 and GS-2 TAMU Terry turbine models will support and inform modeling efforts pertaining to the full-scale plant analysis.

Generic BWR modeling:

- Highly sensitive to uncertain model inputs.
- Unknown parameters need to be addressed by additional experimentation, data collection, and modeling to gain insights into RCIC behavior

Thank you!

Backups

Background Cont. - Terry Turbine Overview

Terry turbines are not a new design but are also not well characterized.

Terry Turbines:

1. Solid, robust one-piece wheel,
2. Low maintenance requirements,
3. Can operate in degraded steam conditions,
4. Can operate at low pressures, and
5. Quick start from cold shutdown.

Typical Turbine:

1. Complex construction,
2. Requires regular maintenance, and
3. Operates at high pressures and high efficiencies.

MELCOR Modeling – General RCIC Model Description

Ongoing effort to develop MELCOR models to express components of RCIC turbopump system.

Homologous Pump Model:

- Flow path package
- Determines pressure head of pump as a function of pump speed and capacity
  - Pump torque, friction losses, inertia, energy dissipation.
  - User can supply pump performance curves

Pressure Stage Model (Terry Turbine):

- Steam through converging/diverging nozzles
- Flow and jet velocities used as inputs to velocity stage model

Velocity Stage Model (Terry Turbine):

- $\tau_T = r \times \dot{m} \times const \times [(V_{in} - V_{out}) cos\alpha - 2r\omega]$
- τ_T = turbine torque
- r = turbine radius
- $\dot{m}$ = jet mass flow rate
- V = velocity of jet entering/leaving bucket
- α = angle of incidence of the jet
- ω = turbine speed

Shaft speed of coupled turbine-pump system:

- $(I_T + I_P)\frac{\partial \omega}{\partial t} = \tau_T - \tau_P - \tau_{fr,T} - \tau_{fr,P}$
- I = Moment of inertia
- τ = torque
- ω = speed
- t = time
- Subscripts T, P, fr = turbine, pump, and friction

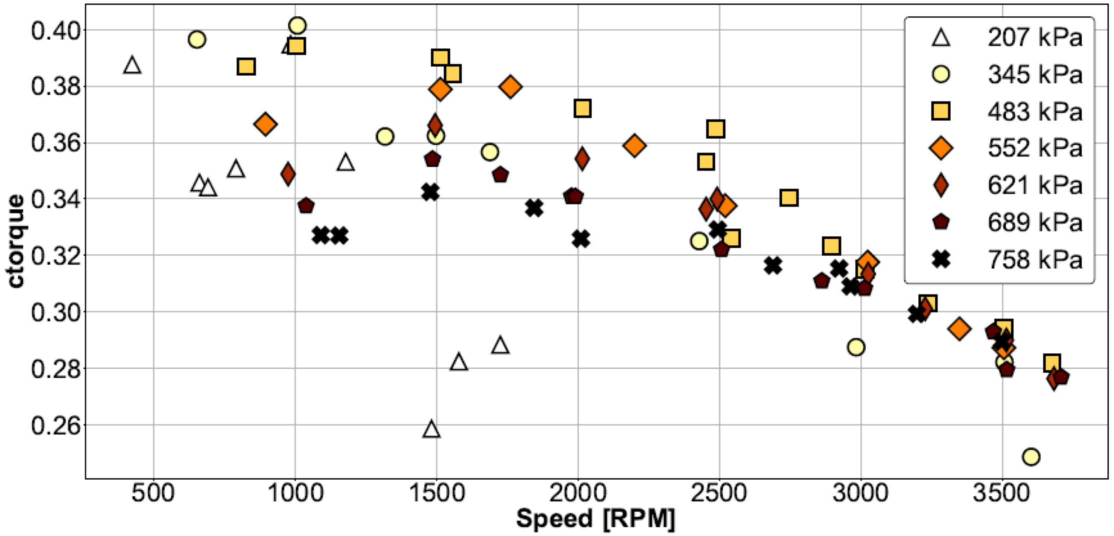
MELCOR Modeling – TAMU ZS-1 Calibrated to Each Test

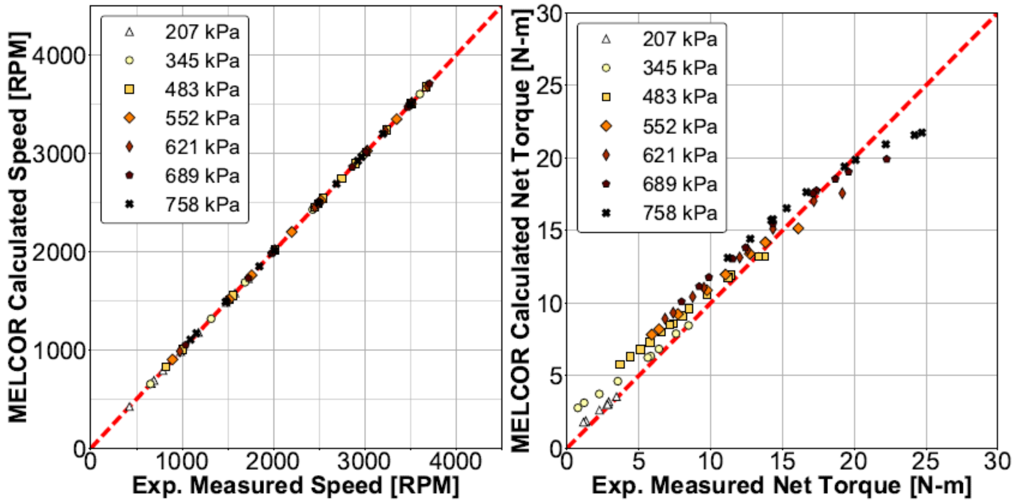
Relationship in c_{torque} and turbine speed.

- Lower speed tests generally have higher c_{torque} values
- High pressure tests have lower c_{torque} values
- Low inlet pressure tests display different behavior

Possible to get a near exact match to speed, and close match to experimental torque

Good match to speed/torque can be obtained from adjusting c_{torque} value





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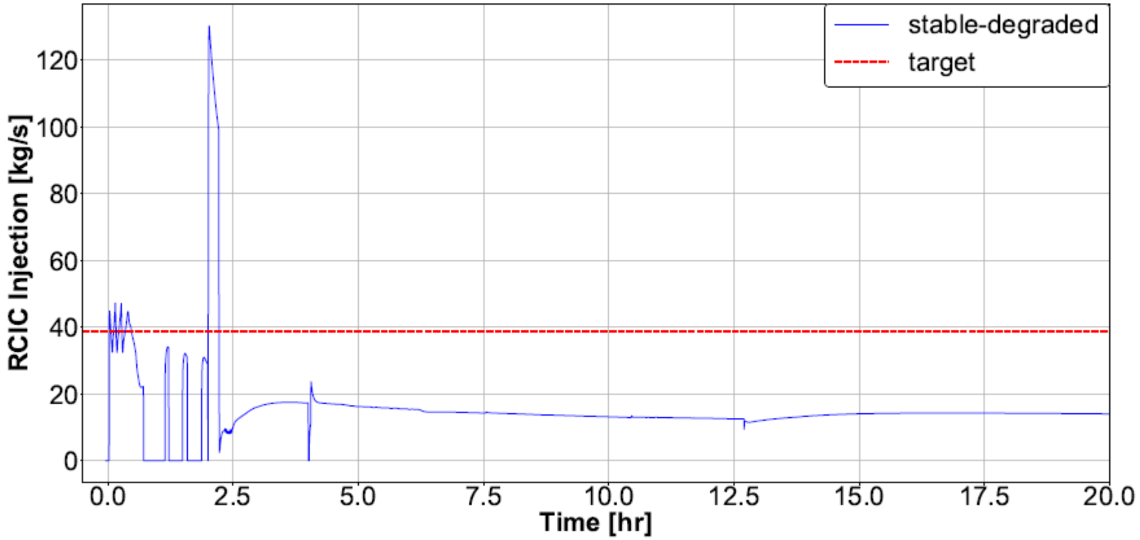

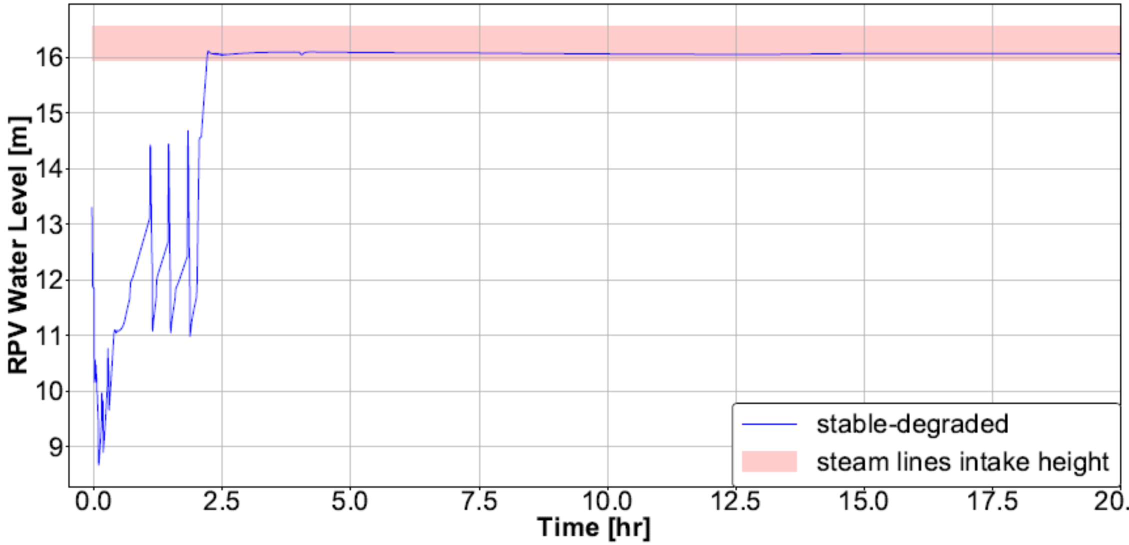

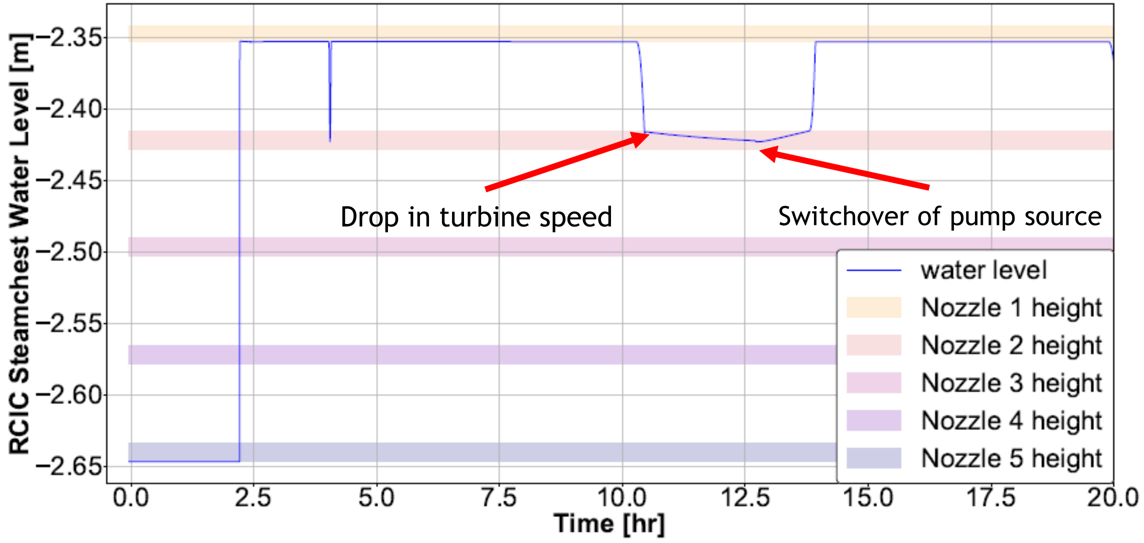

MELCOR Modeling – An Different Unstable Self-Regulation Mode

Unstable self-regulation: Unstable turbine speed and pump injection.

- Different input deck used than the other results shown previously.
  - Higher c_{torque} value $\Rightarrow$ turbine produces more torque overall