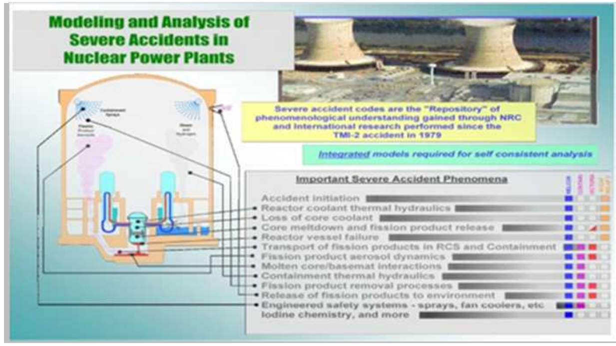
SAND2015-6995C

Exceptional service in the national interest

Sandia National Laboratories

Used by permission from TEPCO

Used by permission from TEPCO



RCIC Governing Equation Scoping Studies

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Overview

1. Purpose of work
2. Quick historic/literature review
3. Model development and test results

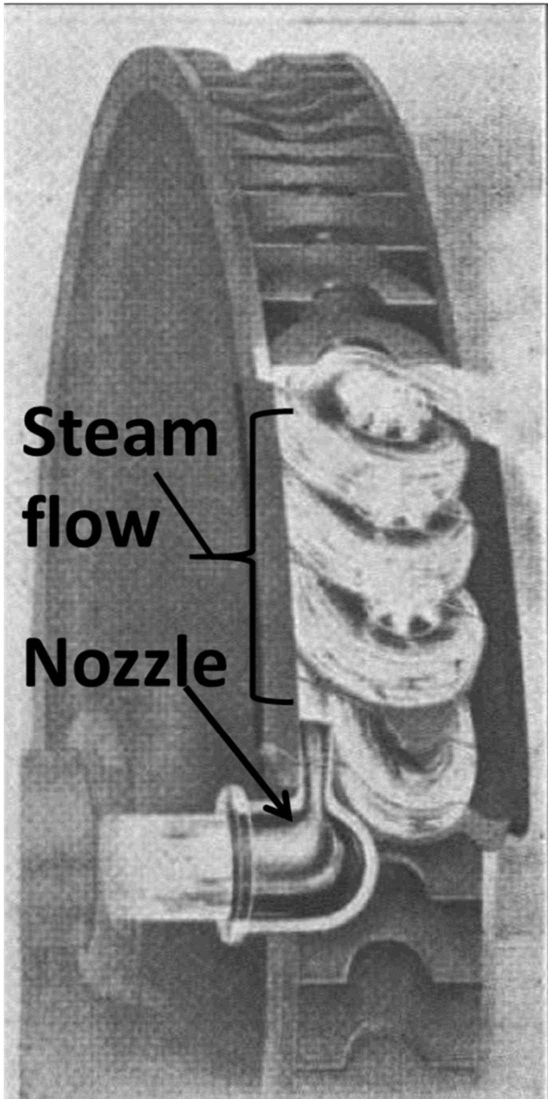
Purpose of work

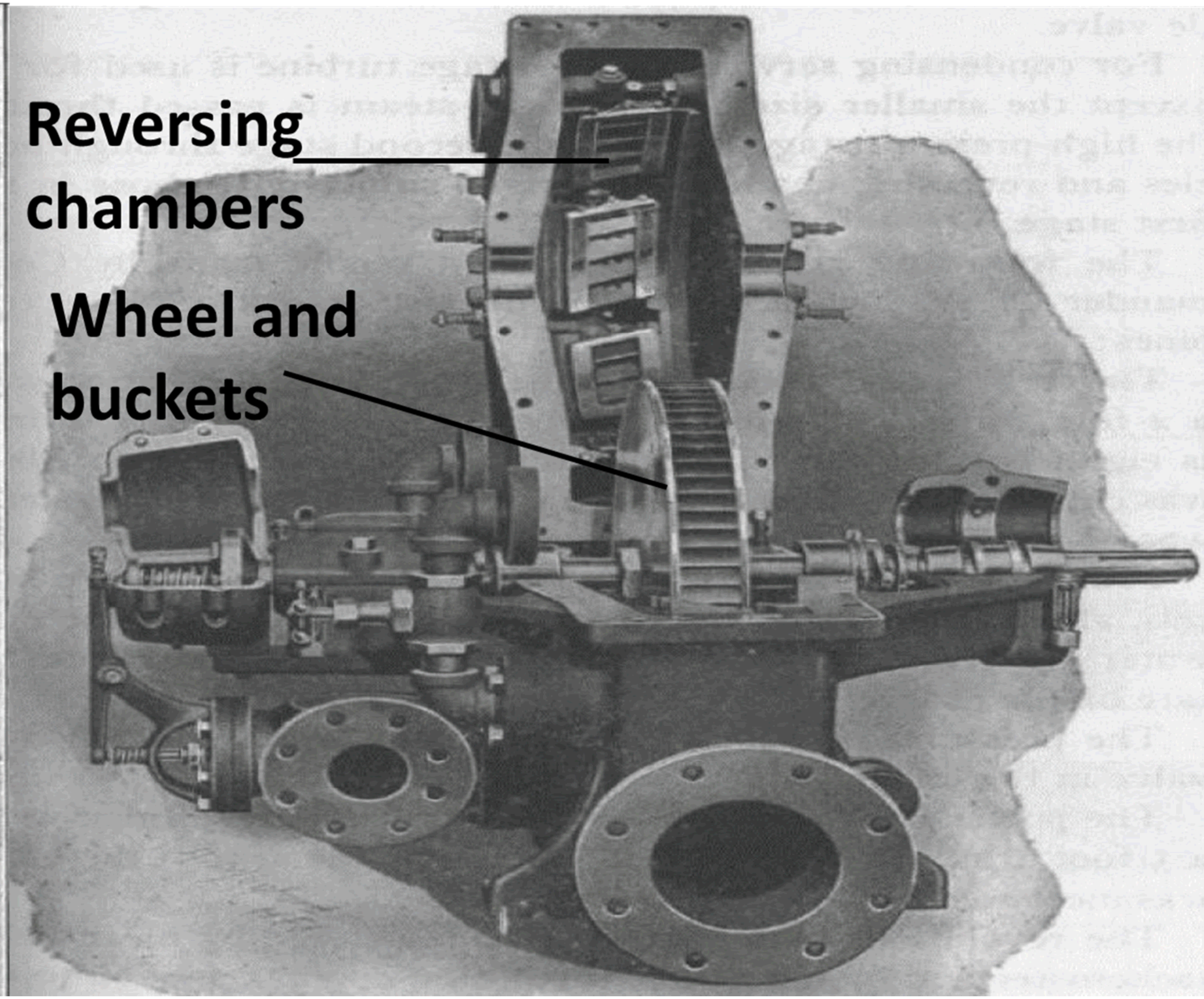
- Events at Fukushima unit 2 suggest that RCIC is a resilient and quasi-passive system
  - Historical PRAs credited a few hours of RCIC, and assumed instant system failure following water ingestion into the turbine
- It is therefore prudent to develop a deeper understanding of the RCIC system and how it behaves during severe accidents
  - This entails experimental and analytical research to develop **mechanistic** and **predictive** models
- This permits:
  - Improved knowledge of the Fukushima accident that may facilitate mitigation of future severe accidents
  - Taking credit of RCIC resilience for US FLEX and SAMGs: establish **technical confidence** that RCIC can operate for 24 hours without operator intervention (after initial system startup)

Terry turbine historical review

- All US RCIC (BWR) and TD-AFW (PWR) systems use Terry turbines
  - Different sized applications (e.g. HPCI): number of nozzles; HPCI may use two adjacent wheels; pressure control (gov. valve) before nozzles
- The Terry turbine is a small steam turbine that was principally designed for waste-steam applications where:
  - Reliability and low-maintenance are of primary importance
  - Rapid start up (< 60 s) is required
  - Efficiency is of secondary importance
  - Turbine casing at low or atmospheric pressure
- Designed around 1900 by the Terry Turbine Steam company
  - Turbine is a 24" (61 cm) cylindrical wheel with many small semi-circular 'buckets' shaped into the body of the wheel
  - Turbine wheel is surrounded by **fixed** nozzles and reversing chambers

Terry depictions from ~1900-1910





Terry turbine design: key theoretical aspects

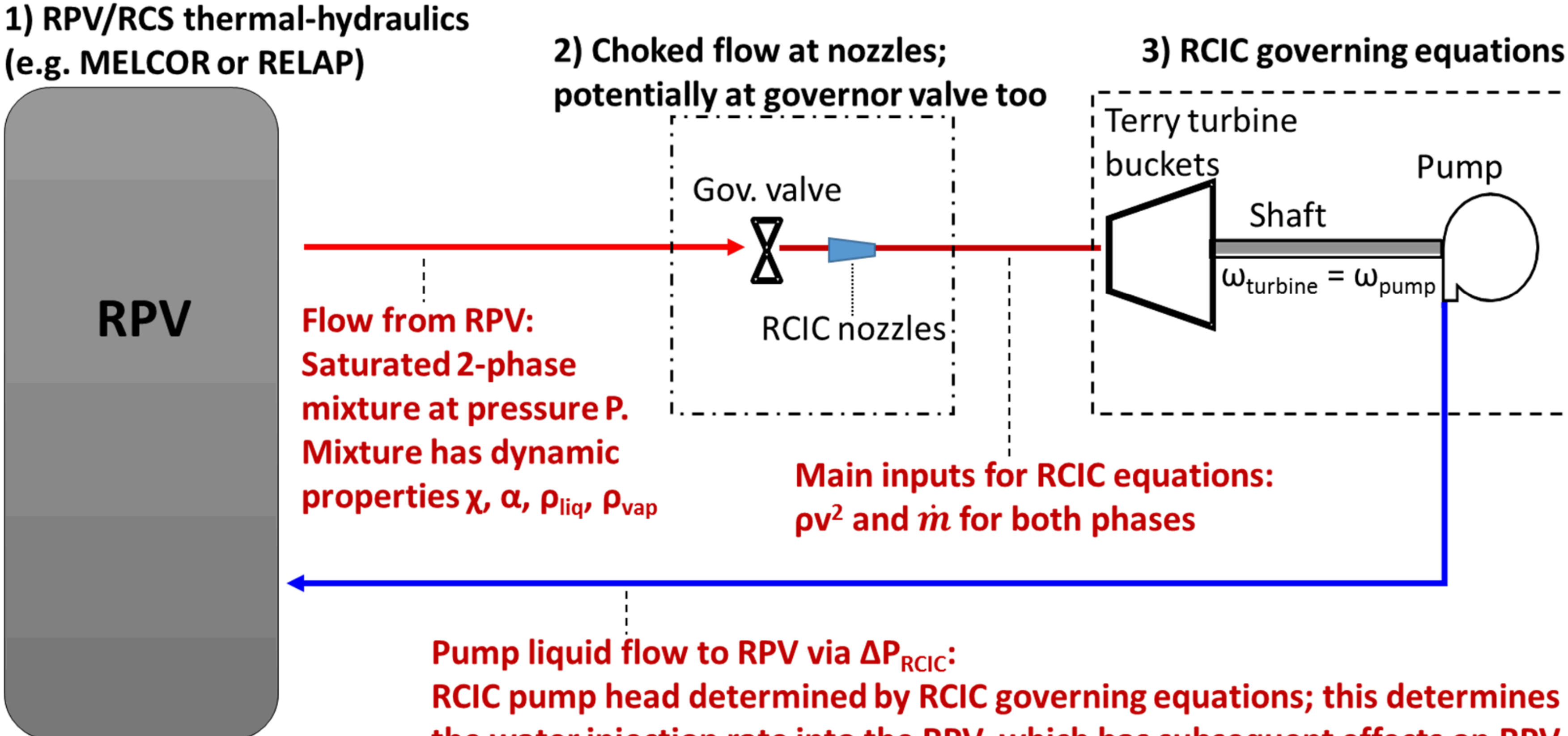
Sandia National Laboratories

- **Terry turbine is a "pure-impulse" turbine**
  - Reaction vs. impulse: turbine designs generally differ more by degree than type
  - i.e. many turbines have both reaction and impulse stages
  - Terry is a ***single-stage, pure-impulse*** turbine: steam enters a bucket and reverses direction
  - 'Compound velocity' feature refers to the reversing chambers
- **Steam is <u>totally</u> expanded after the nozzles**
  - Nozzle converts enthalpy energy to kinetic energy
- **No expansion 'reaction' occurs in the turbine blades**
  - Terry buckets are too small anyway – reaction blades are much longer, more area
  - Nozzles are stationary and detached from the turbine wheel
- **Turbine motion is induced by means of steam acceleration in the buckets after it has been totally expanded through the nozzles**
  - Exchange of momentum and kinetic energy
  - Reversing chamber feature intended to capture as much kinetic energy as possible

Mechanistic RCIC modeling for severe accidents

- Terry turbine is essentially an exotic water wheel
- Turbine is driven my exchange of momentum and kinetic energy
- Develop momentum-based model from the control volume formulation of angular momentum conservation
  - Simplify/abstract for lumped-parameter, system-level modeling of long transients
  - Capture the most essential aspects for mechanistic modeling
  - Simplify even more for initial scoping analyses – i.e. quickly assess the merit
- Initial implementation is via MELCOR control functions
  - Large room for improvement, but need to gauge utility of such a model before starting a highly detailed and more complex analytic approach

Principal physics coupling

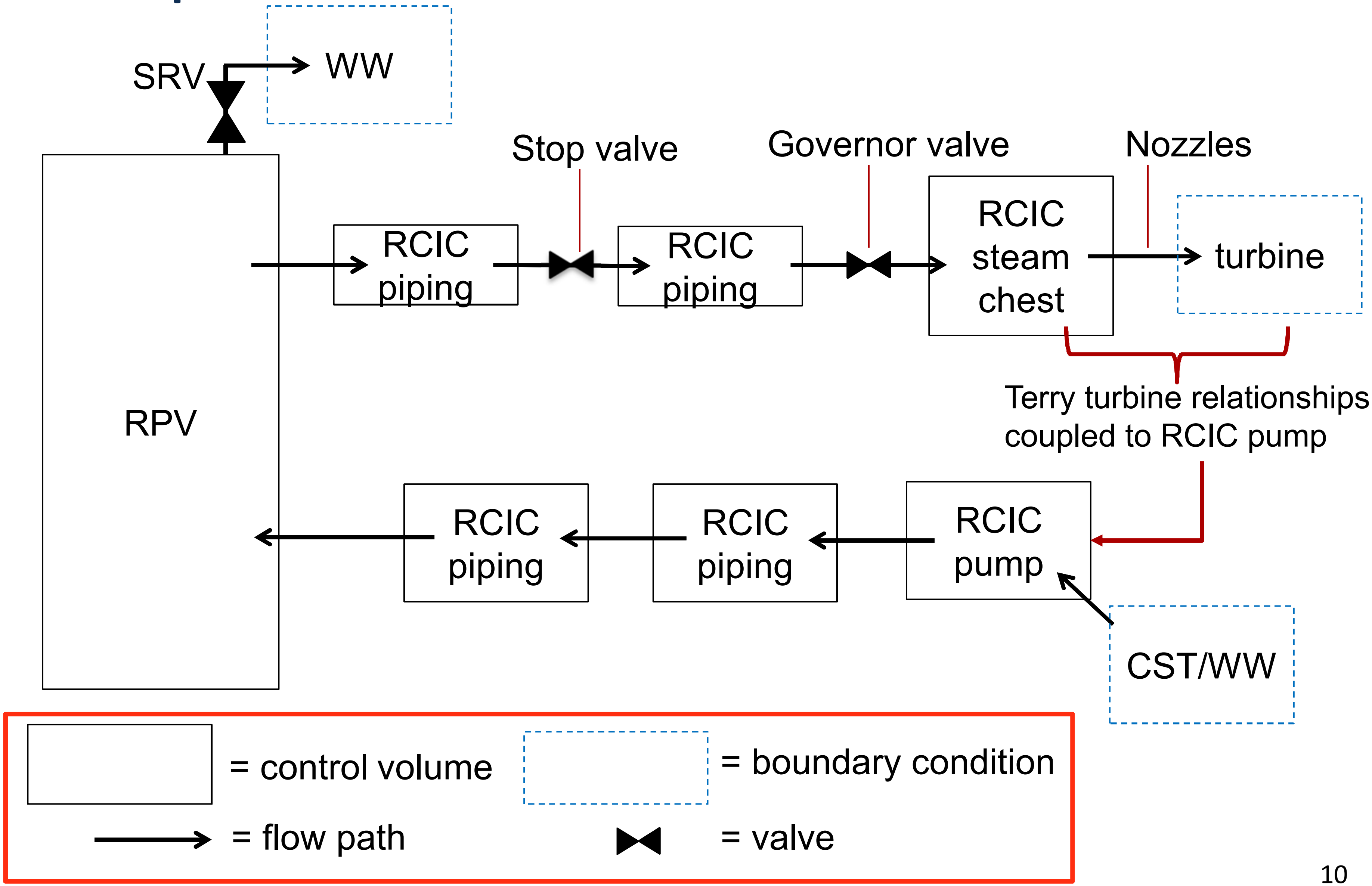


Pump liquid flow to RPV via ΔP_{RCIC}:
RCIC pump head determined by RCIC governing equations; this determines the water injection rate into the RPV, which has subsequent effects on RPV pressure and two-phase mixture properties (resolved by the RPV TH model) that are delivered to the governor valve and RCIC nozzles. The RCIC pumps water at either the temperature of the CST or the wetwell.

Testing calculations

- **Generic, simplified BWR *test* model – 2000 MW power level**
- **Boiler and SRV properties from Peach Bottom SOARCA model**
- **Just 7 active control volumes; 3 time-independent control volumes; 10 flow paths**
  - 1 volume for the RPV
  - 2 volumes for RCIC piping between RPV and governor valve
  - 1 volume for RCIC steam chest between gov. valve and nozzles
  - 3 volumes for the RCIC pump and its piping
  - MSL piping currently neglected; arbitrary RCIC piping lengths; neglect large elevation changes
- **Active MELCOR model ends at the nozzles for scoping analyses**
  - Currently neglect supersonic flow exiting nozzles
  - Take MELCOR-predicted critical mass flow rate and velocity to provide needed terms to lumped momentum equation for RCIC turbine
- **Simple and generic accounting of RCIC turbine-pump coupling and pump efficiency**
- **Test model purposefully does *<u>not</u>* closely reflect Fukushima unit 2**
  - Don't tune the model before you assess the technical utility/feasibility of the approach
  - Many unknown and uncertain model parameters (this is intrinsic to lumped-**parameter** modeling)
  - First acquire precision, then adjust model parameters for accuracy

Simple model nodalization



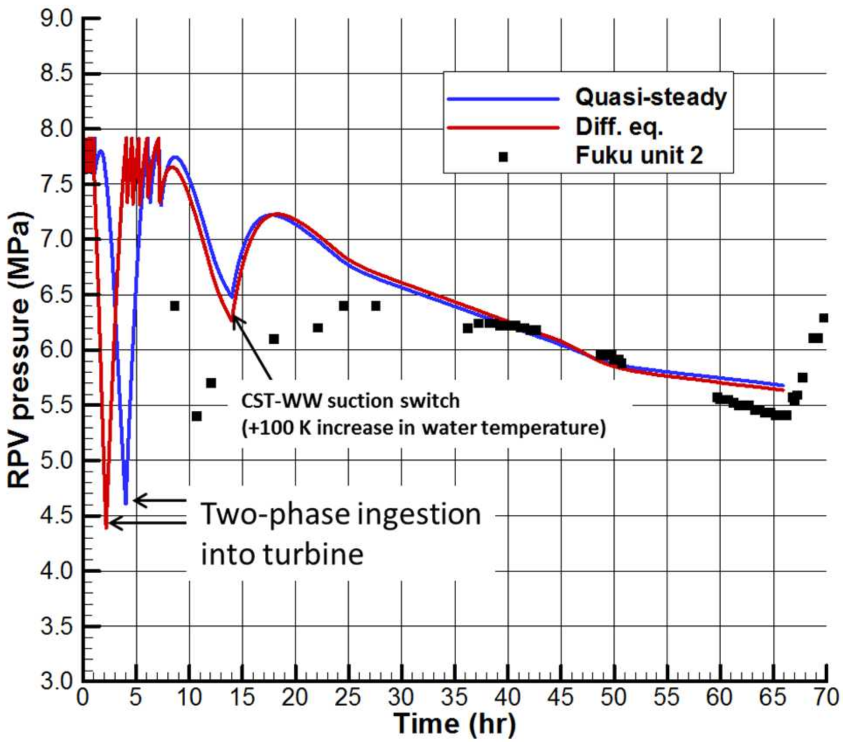
Numerical implementation

1. **Quasi-steady assumption:**
   - Time-derivative in angular momentum equation is zero
     - Severe accidents are rather slowly evolving with respect to time
   - Derive a quasi-steady formula for pump head that couples to the MELCOR model
2. **Solve differential equation for angular speed**
   - Keep time-derivative in angular momentum equation
   - Allows some consideration of turbine inertia

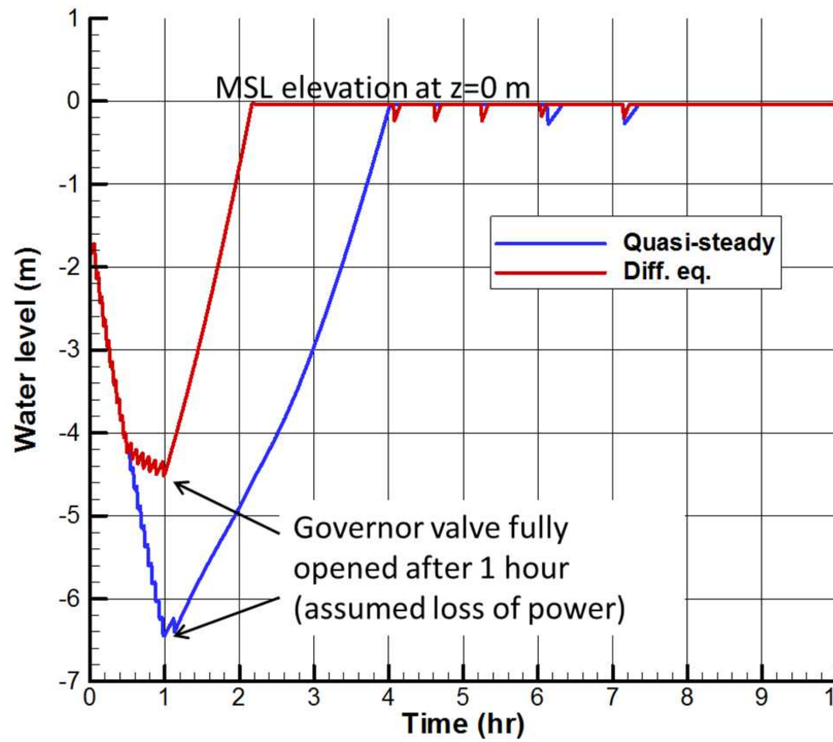
- Coupling is currently explicit for both formulations
- Formulations yield comparable results for test calculations;
- Consideration of inertia might provide additional insights into system behavior during key time periods
  - e.g. startup, initial water ingestion, CST-WW switch, and final RCIC failure and shutdown

Results

RPV pressure



RPV liquid level

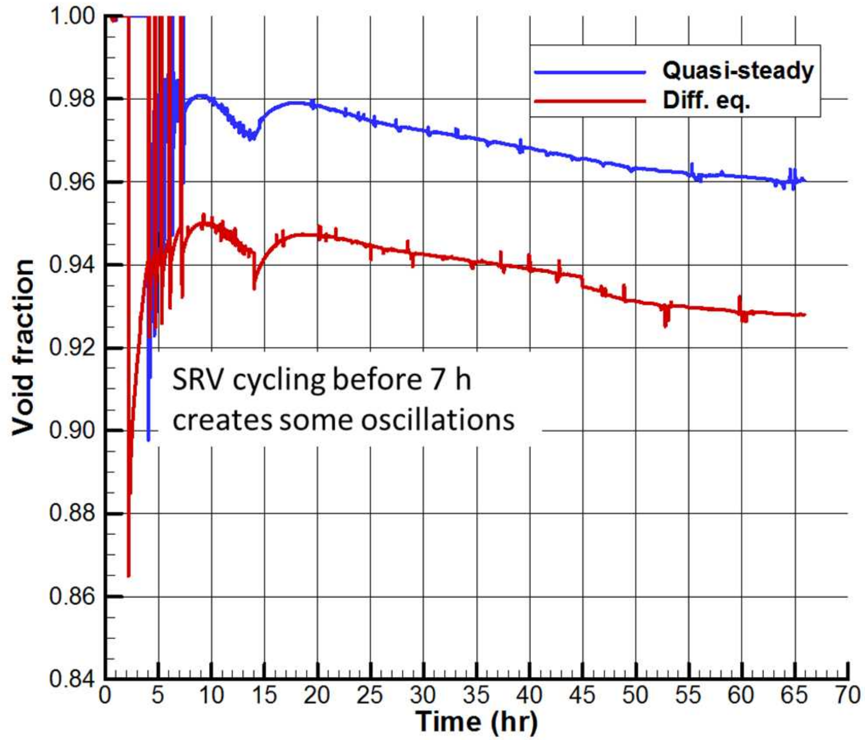


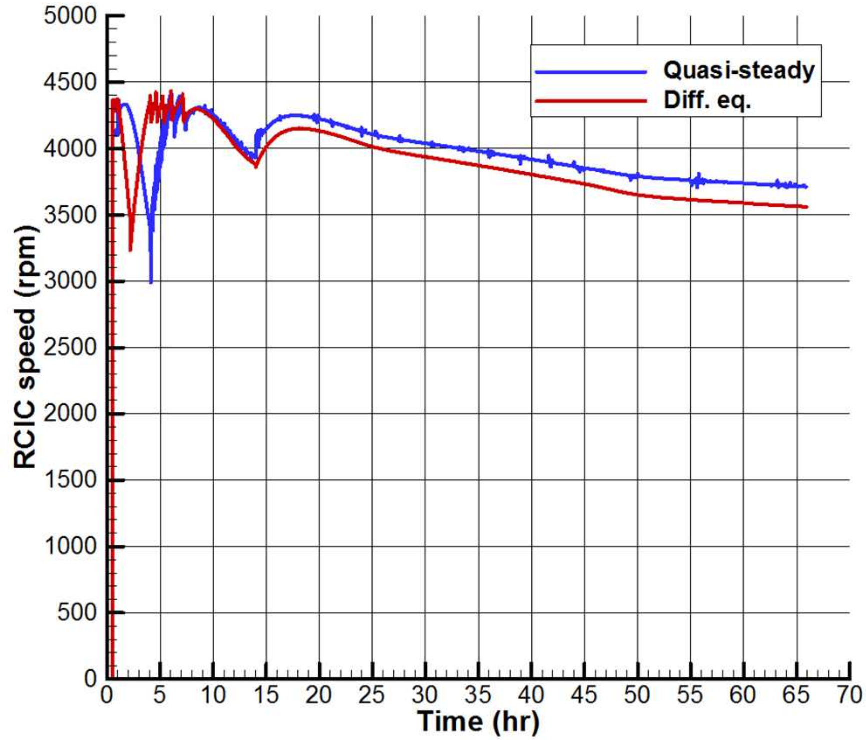
- **two RCIC equation models**
  - **ODE of turbine speed**
  - **quasi-steady algebraic turbine torque equation**
- **no operator throttling or automatic control assumed after loss of power**
- **no 'tuning' of results**
- **trends reflect MELCOR thermal-hydraulics and RCIC equations only**

Results

Void fraction at nozzles

RCIC speed

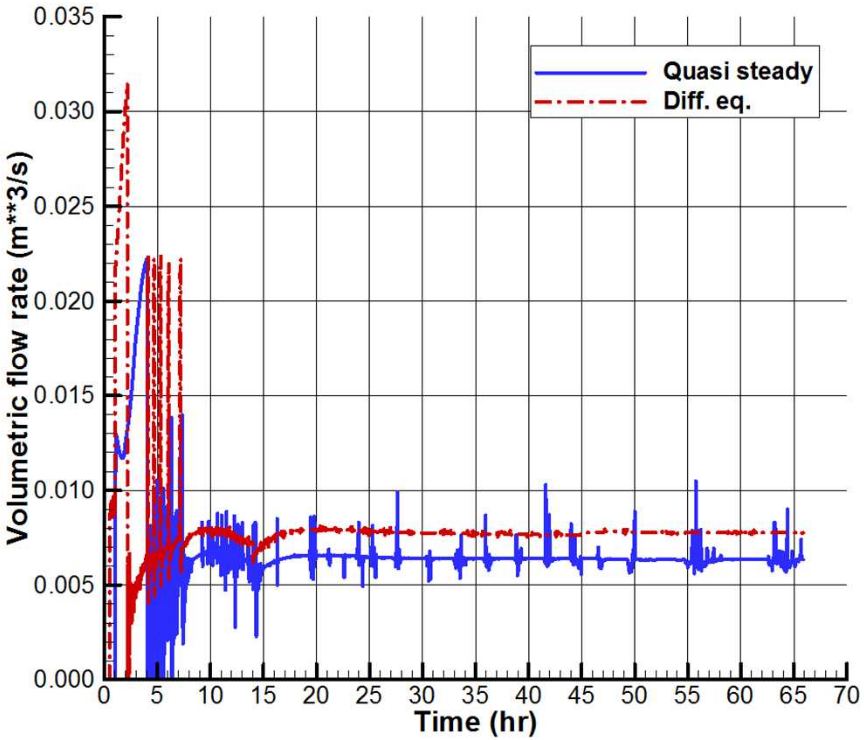




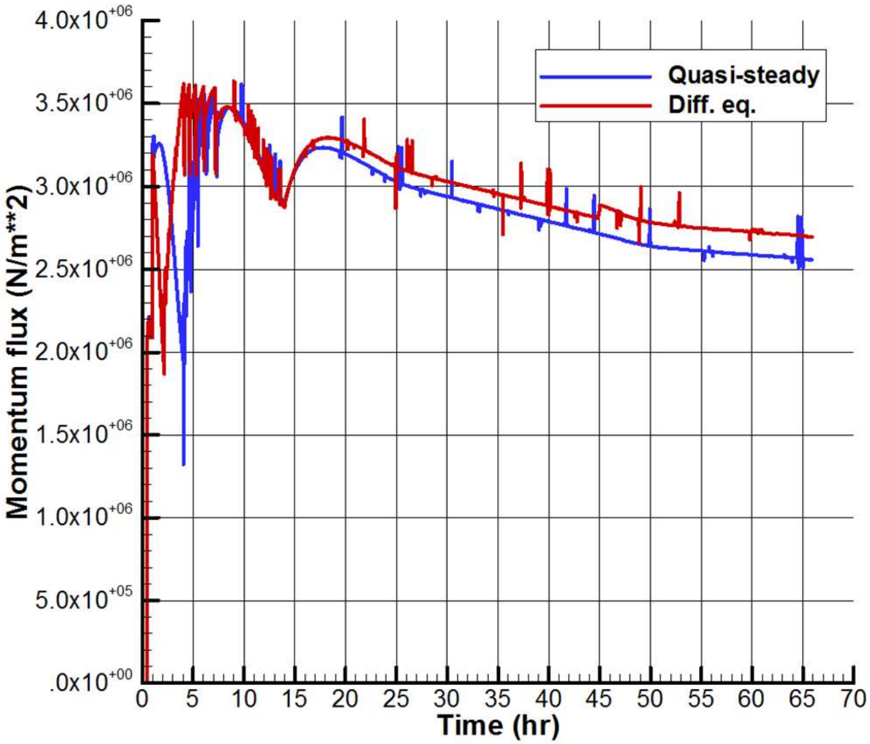
EXTRA

Results

RCIC pump volumetric flow rate



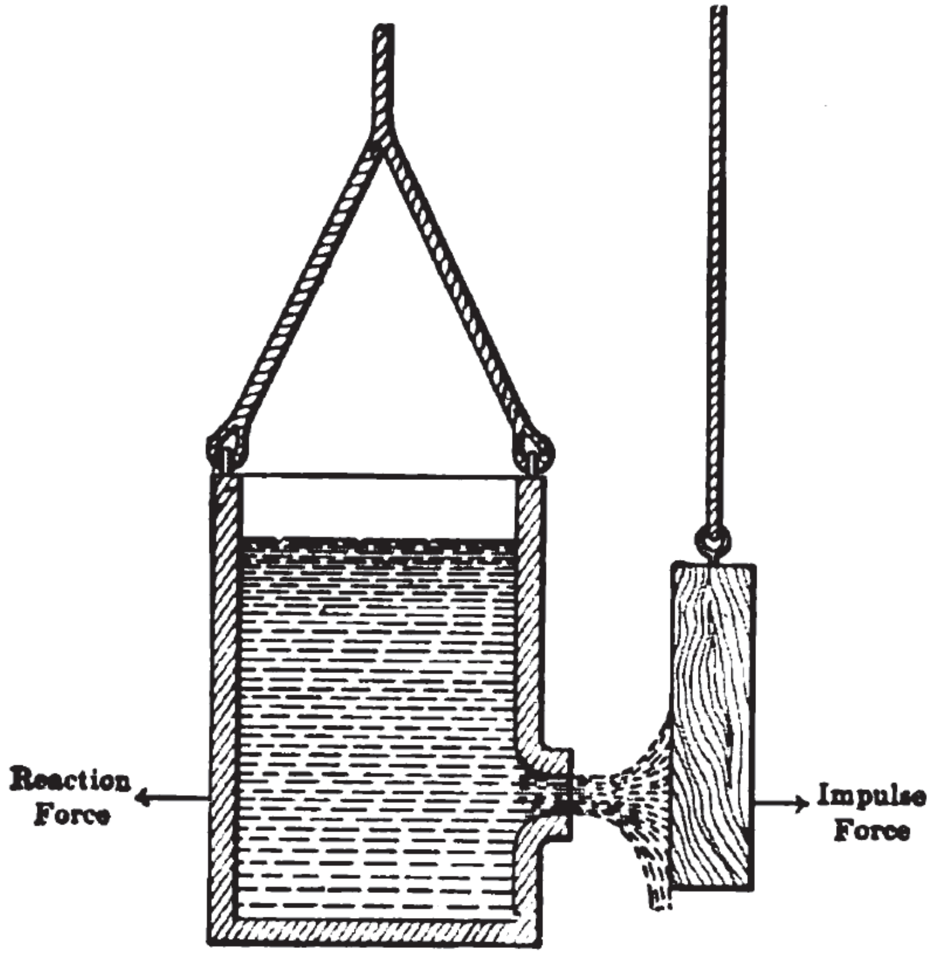
Total momentum flux to bucket



Reaction vs. impulse

Many turbines utilize both reaction and impulse forces.

Reaction stages have relatively long blades that act as nozzles



Terry turbines driven only by impulse forces

Image from:
J. A. Moyer, *Steam Turbines*, John Wiley & Sons, New York, NY, 1914. (Page 58)

Reversing chambers

- **Currently neglected in system-level model**
- Proven design feature for circa 1900 systems
- Literature review suggests that the reversing chambers are of **secondary importance** for the higher speeds and pressures involved with LWR (RCIC, HPCI, TDAFW) applications
- This is substantiated by historical Terry research
  - Dubbed the 'the most complicated problem' in small turbine work: very difficult to assess how many reversing actions the steam makes, especially at higher turbine speeds
- Corroborated by EPRI maintenance manual for Terry turbine
  - Reversing chambers are not significant above 2500 rpm (RCIC operates around 4000-4700 rpm)
- Initial CFD analyses also suggest the reversing chambers are of secondary importance

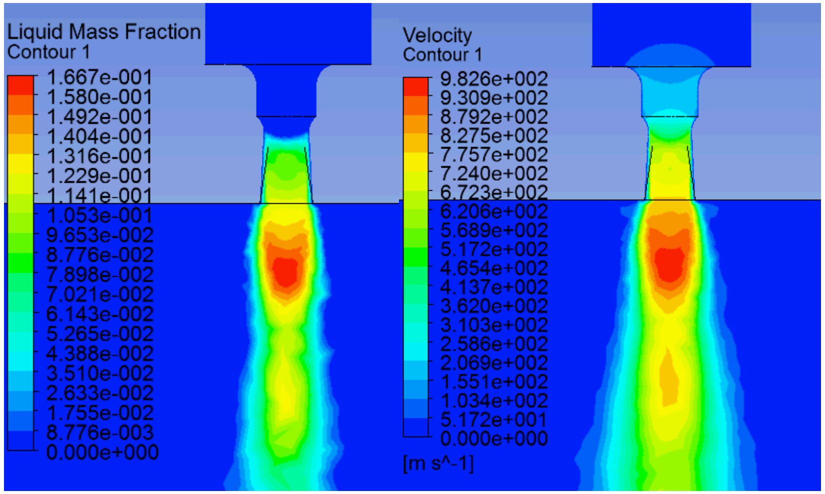
Terry nozzles

- Current system models do not account for nozzle behavior
- Terry nozzles are known to be converging-diverging nozzles
- Converging-diverging nozzles are intended to yield supersonic velocities
- Supersonic velocities have been calculated via two-phase CFD analyses using Fluent and SolidWorks Flow
  - Future system models will incorporate CFD results in the form of supersonic nozzle velocity curves (functions, tables, etc.) that are a function of the pertinent variables (e.g. pressure, void fraction, etc.)

Utility of momentum-based model; limitations of energy-only based model

$\dot{m}\mathrm{v} = \mathrm{A}(\rho \mathrm{v}^2)$ terms drive the impulse turbine in the momentum equation

- **steam is totally expanded after the nozzle.**
- **The nozzle converts enthalpy to kinetic energy.**



Neglecting friction (nozzle coefficient) and inlet velocity:

$$\dot{m}_{in} h_{in} = \dot{m}_{out}\left(h_{out} + \frac{1}{2}\mathrm{v}_{out}^2\right)$$

$\dot{m}_{in} = \dot{m}_{out}$ (choked mass rate)

- Exit velocities are 800+ m/s (according to CFD analyses); the KE component of the outlet energy flow is significant.
- Dynamic mass and energy transfer between the liquid and vapor phases as the steam expands and accelerates through the nozzle: **hence both outlet enthalpy and velocity are unknown**
- Parametric, "dynamic boundary condition" models are indeed possible and easy to implement into SA codes, i.e. $\dot{m}_{in} h_{in}$(energy going into the turbine) and prescribe a gross efficiency term
    - This is not really mechanistic – it lacks the physics
    - This approach cannot really model highly dynamic transients like severe accidents

Terry turbine overview

Historical perspective and literature review

Terry turbine

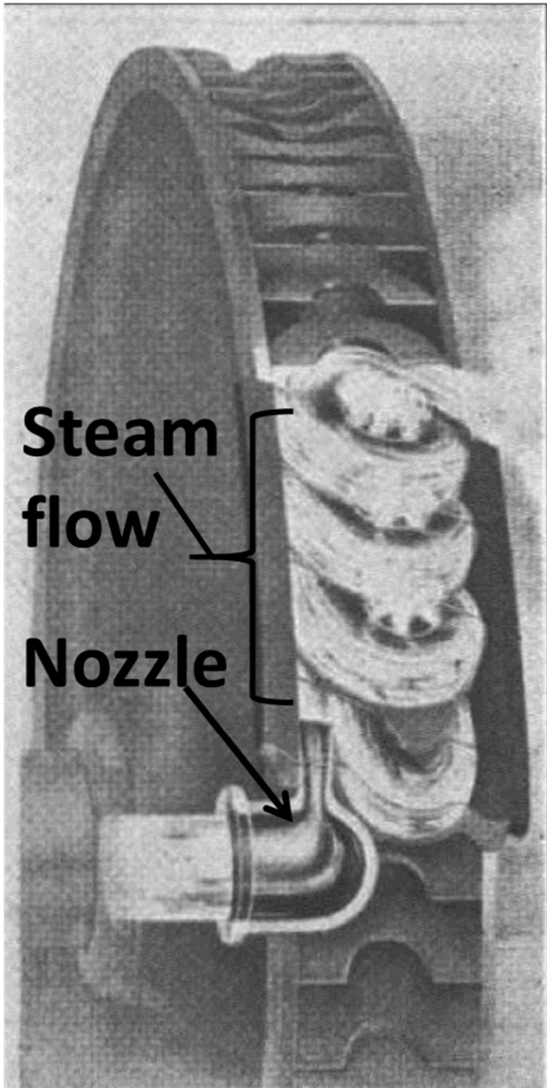
- All US RCIC (BWR) and TD-AFW (PWR) systems use Terry turbines
  - Different sizes: e.g. larger Terry turbine used in HPCI applications
    - Number of nozzles, HPCI may use two adjacent wheels

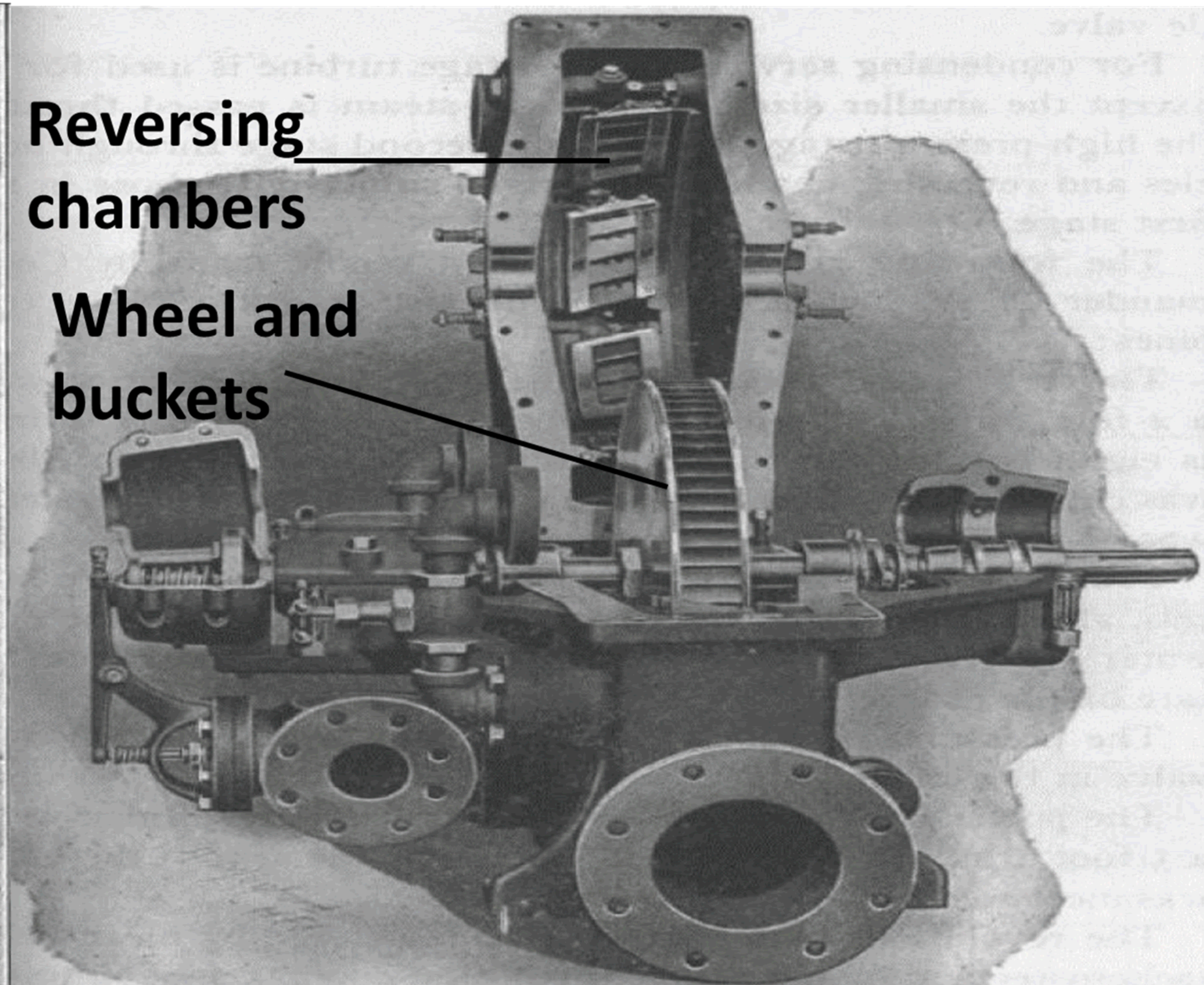
- The Terry turbine is a small steam turbine that was principally designed for waste-steam applications where:
  - Reliability and low-maintenance are of primary importance
  - Rapid start up (< 60 s) is required
  - Efficiency is of secondary importance

Terry turbine design

- Designed around 1900 by the Terry Turbine Steam company
  - ➢Purchased by Ingersoll-Rand in 1974
  - ➢currently marketed by Dresser-Rand
- Turbine is a cylindrical wheel with many small semi-circular ‘buckets’ shaped into the body of the wheel
- Wheel is surrounded by **fixed** nozzles and reversing chambers
  - ➢5-10 nozzles
  - ➢4-5 reversing chambers near each nozzle
  - ➢Turbine casing can be at low pressure (even atmospheric)
- US RCIC application use a 24” (0.61 m) diameter turbine wheel

Terry depictions from ~1900-1910





Terry turbine design: key theoretical aspects

Sandia National Laboratories

- **Terry turbine is a "pure-impulse" turbine**
  - Reaction vs. impulse: turbine designs generally differ more by degree than type
  - i.e. many turbines have both reaction and impulse stages
  - Terry is a ***single-stage, pure-impulse*** turbine: steam enters a bucket and reverses direction
  - 'Compound velocity' feature refers to the reversing chambers
- **Steam is <u>totally</u> expanded after the nozzles**
  - Nozzle converts enthalpy energy to kinetic energy
- **No expansion 'reaction' occurs in the turbine blades**
  - Terry buckets are too small anyway – reaction blades are much longer, more area
  - Nozzles are stationary and detached from the turbine wheel
- **Turbine motion is induced by means of steam acceleration in the buckets after it has been totally expanded through the nozzles**
  - Exchange of momentum and kinetic energy
  - Reversing chamber feature intended to capture as much kinetic energy as possible

Key takeaways from literature review

- RCIC uses a Terry turbine
  - Essentially an exotic water wheel that runs on high-velocity steam
- Terry turbine responds to the steam momentum/kinetic energy exiting the nozzles (pure-impulse design)
  - Does not principally operate on the enthalpy energy exiting the nozzles
- Reversing chambers are likely of secondary importance
  - Historical (~1910-1920) research dubbed it 'the most complicated problem' in small turbine work: impossible to easily assess how many reversing actions the steam makes, especially at higher turbine speeds
  - Modern literature states that the effects of the reversing chambers are minimal above 2500 rpm; RCIC operates around 4000-4700 rpm
  - These assertions make sense considering the era when the Terry turbine was designed (pre-1900) – small turbine speeds for most applications was generally less than 1300 rpm
  - Reversing chamber effects could still be significant during RCIC startup

Ongoing and future model enhancements

1. Implementation of homologous pump curves into MELCOR
2. Incorporate insights from initial CFD calculations
3. RELAP modeling
4. Future plans

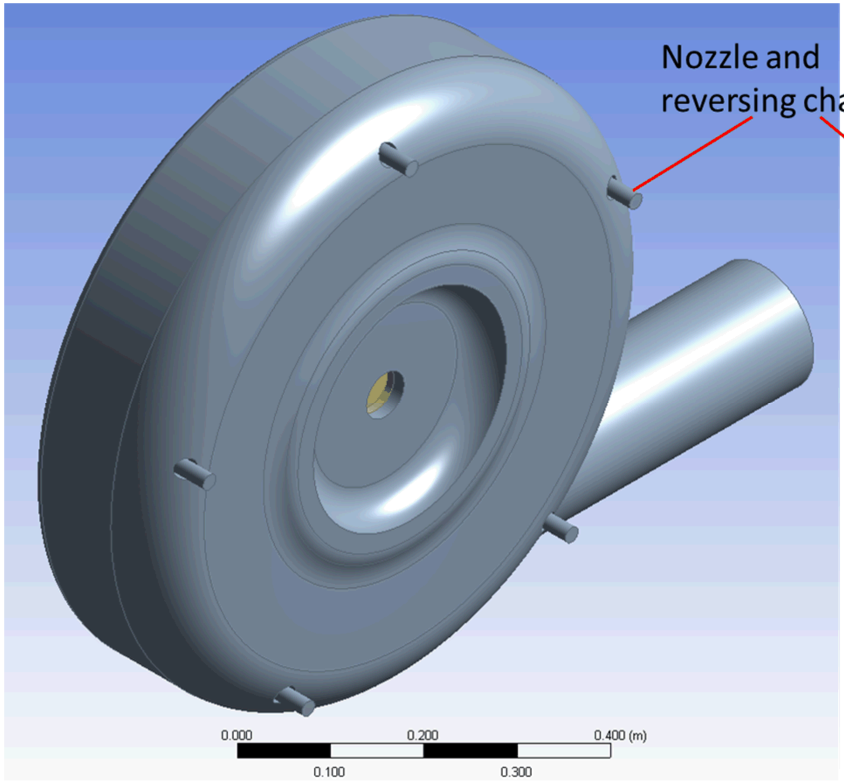
1. Homologous pump curves

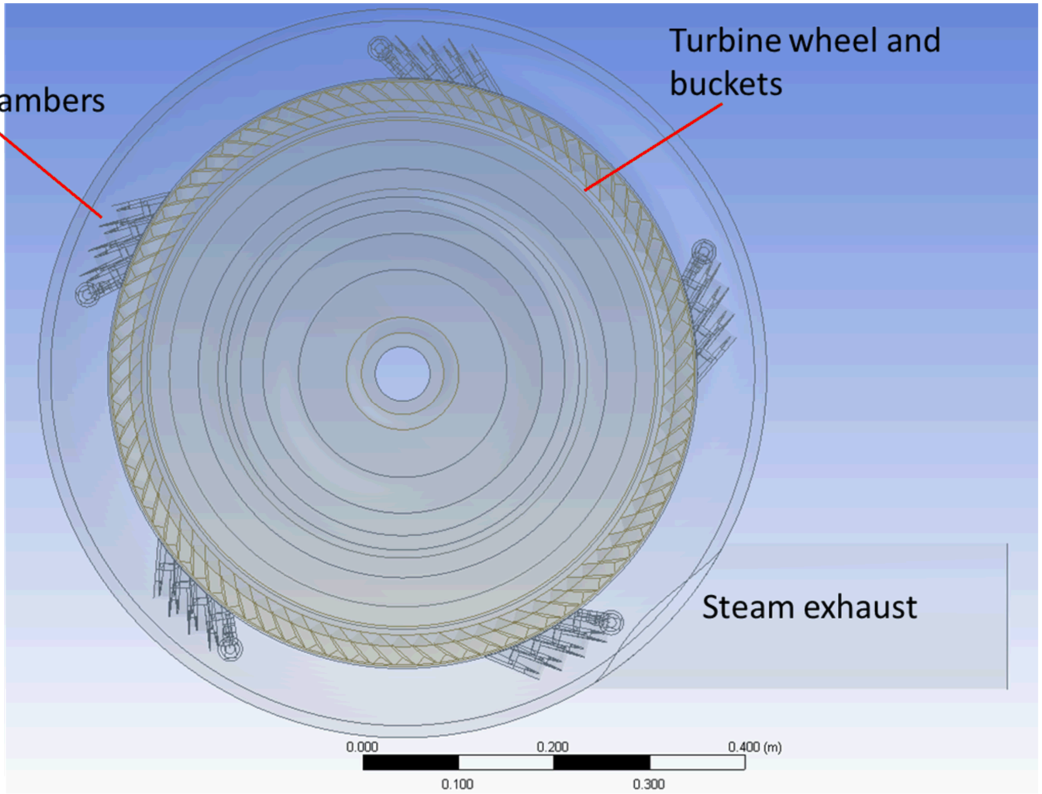
- Default MELCOR pump is numerically explicit in FL velocity/momentum equation
  - Solver iterates (several times) to ‘converge’ the velocity equation, only to have a pump ΔP term added that was based on start-of-timestep conditions
  - User lagging, artificially long FL path length, and short time steps usually necessary
- Leads to stability issues that manifest themselves as large variability in key figures of merit
  - Numerical noise/bias: answers change significantly when using slightly different time steps (or essentially any slightly different set of inputs)
  - Large changes are unexplainable by physics
  - Code can encounter convergence issues; ad-hoc schemes change the time steps to resolve the trouble, thereby changing the answer
    - Code may also just crash entirely
- Implementation of homologous pump curves and improved numerical schemes will go a long way in removing/reducing these issues

2. Initial CFD insights

- Terry turbines use converging-diverging nozzle that yield supersonic velocities
- Use SolidWorks and Fluent to investigate the flow behavior of the nozzle
- This is a rather complicated **two-phase** problem even if perfectly dry steam enters the nozzle
  - Steam rapidly expands through the nozzle, converting static pressure (enthalpy/heat energy) to kinetic energy – velocities are supersonic in the diverging section
  - Steam initially enters a metastable 'supersaturated' state (i.e. subcooled steam) upon its initial expansion; after the throat there is a 'condensation shock' and the steam spontaneously condenses **[non-equilibrium thermodynamic effects]**
  - Obvious technical utility in CFD analyses:
    - MELCOR, RELAP, and hand calculations cannot (easily) address the question of the state of the fluid exiting the nozzle – exit velocity is unknown, two-phase composition is unknown, enthalpy is unknown
    - 3D problem: the Terry nozzle has a circular to square transition from the throat to the diverging exit
    - Friction and turbulence effects in the nozzle, buckets, reversing chambers
    - Flow patterns through Terry buckets and reversing chambers; e.g. bucket exit velocity magnitude
  - **3D, compressible, two-phase (with mass/heat transfer), turbulent flow problem**

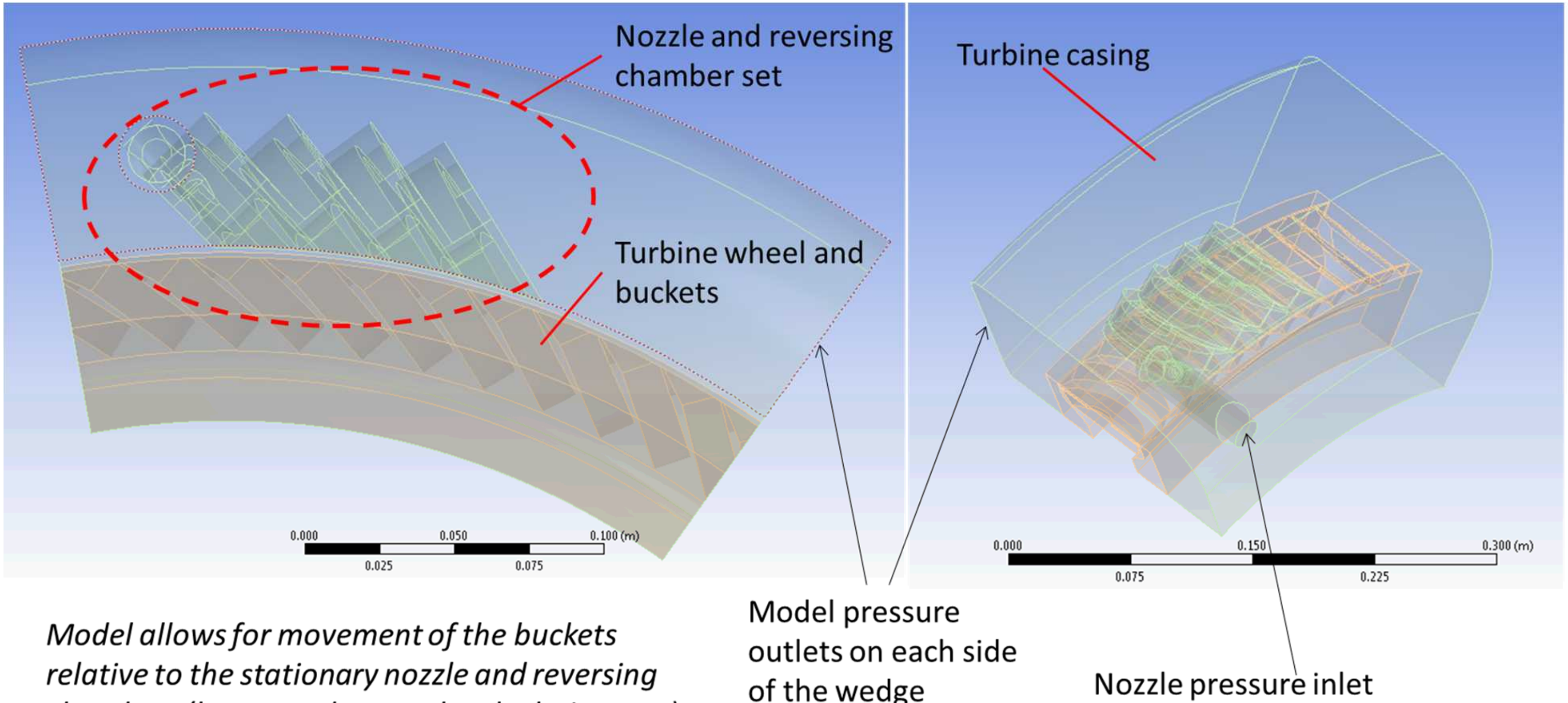
Full 3D CAD model of Terry turbine





CFD calculations are performed for subsection of the CAD model

→ minimize mesh size and reduce CPU time

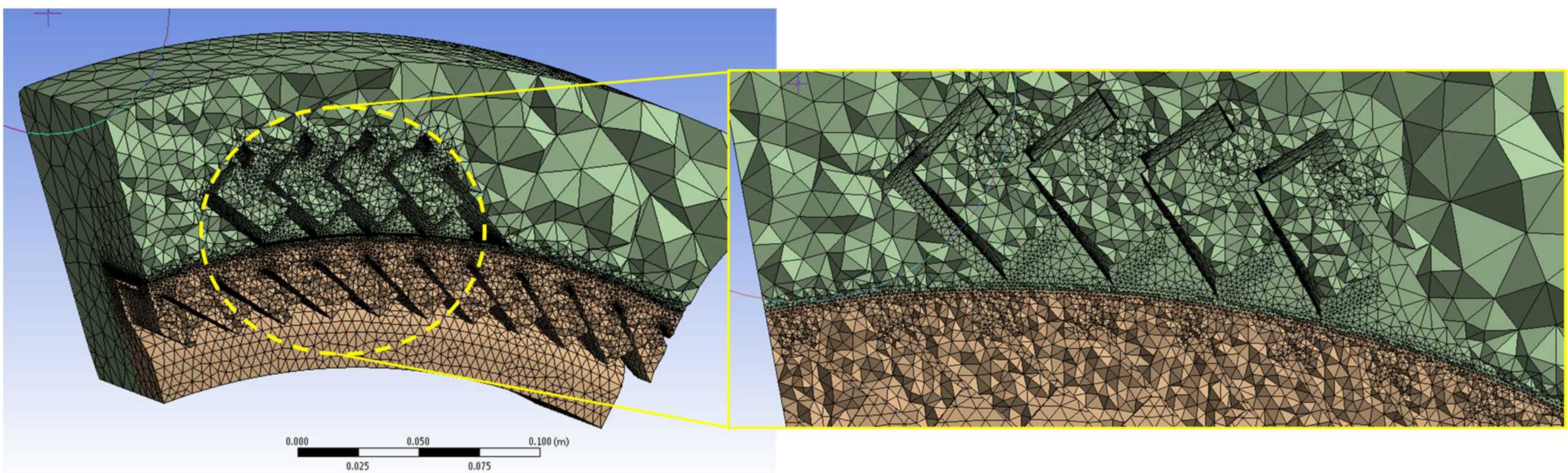


Model allows for movement of the buckets relative to the stationary nozzle and reversing chambers (have not done such calculations yet)

<u>Pressure B.C.'s</u>: CFD code predicts mass flow rate through model

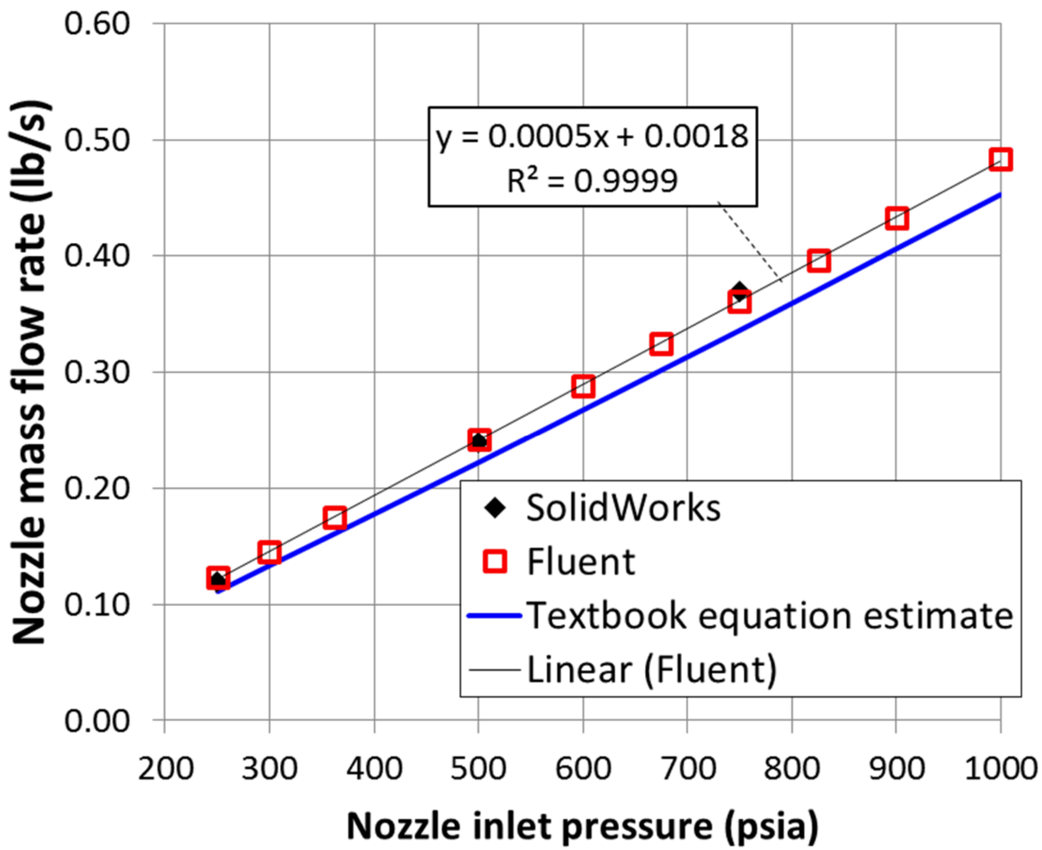
Fluent CFD mesh

- About 1 million cells, mostly tetrahedral
- High quality: 0.2 minimum orthogonal quality (> 0.1 is good)
- Model allows for rotation of the wheel and buckets relative to the nozzle, reversing chambers, and turbine casing



Choked mass flow rate test problem

- Fluent and SolidWorks predictions agree very well
- CFD predictions agree well with simplified hand calculation



Calculations with dry steam inlet

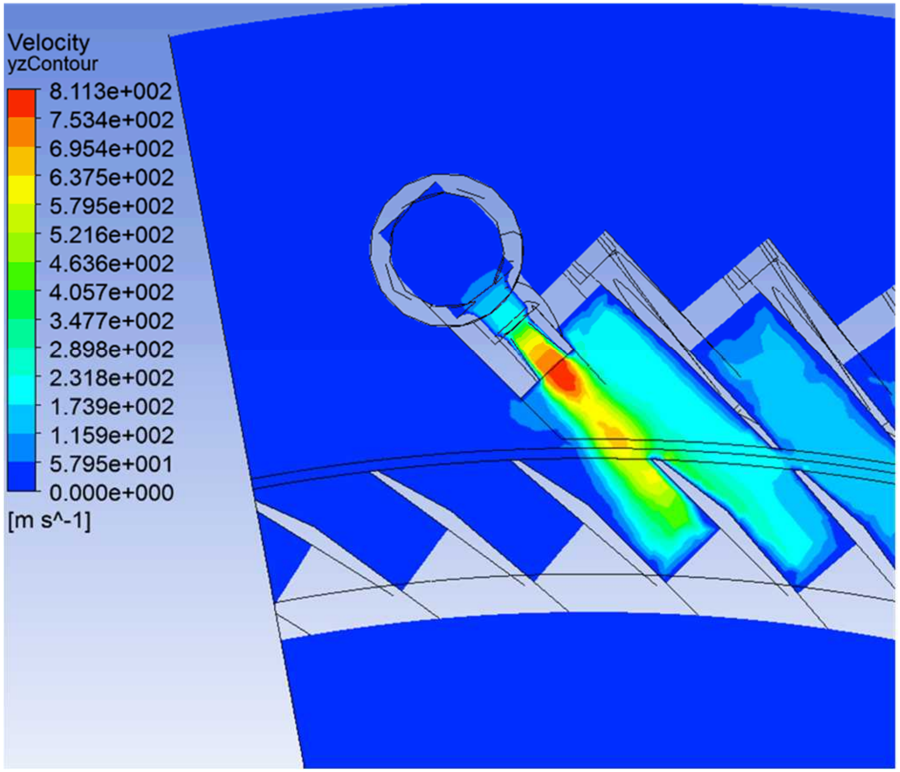
Choked mass flow rate is linear with respect to inlet pressure

Mass flow rate in CFD calculations does **not** vary (significantly) when outlet pressure is changed, as expected

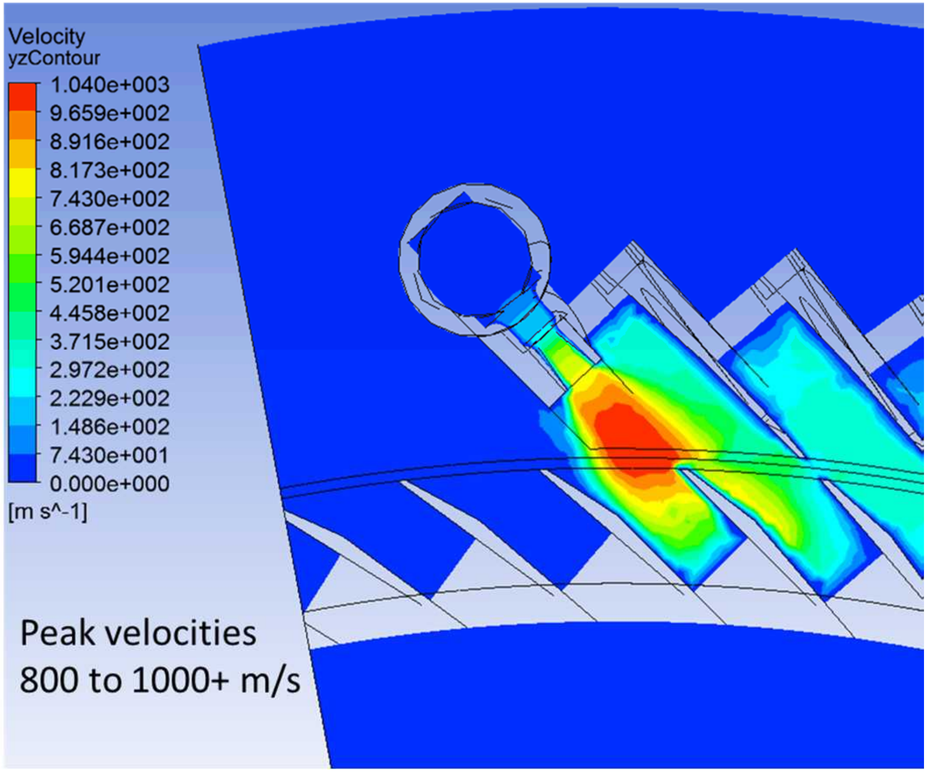
Convergence of mass flow rate and reasonable magnitude increases technical confidence of the CFD models

Velocity profile exiting nozzle

250 psia (1.7 MPa) inlet pressure

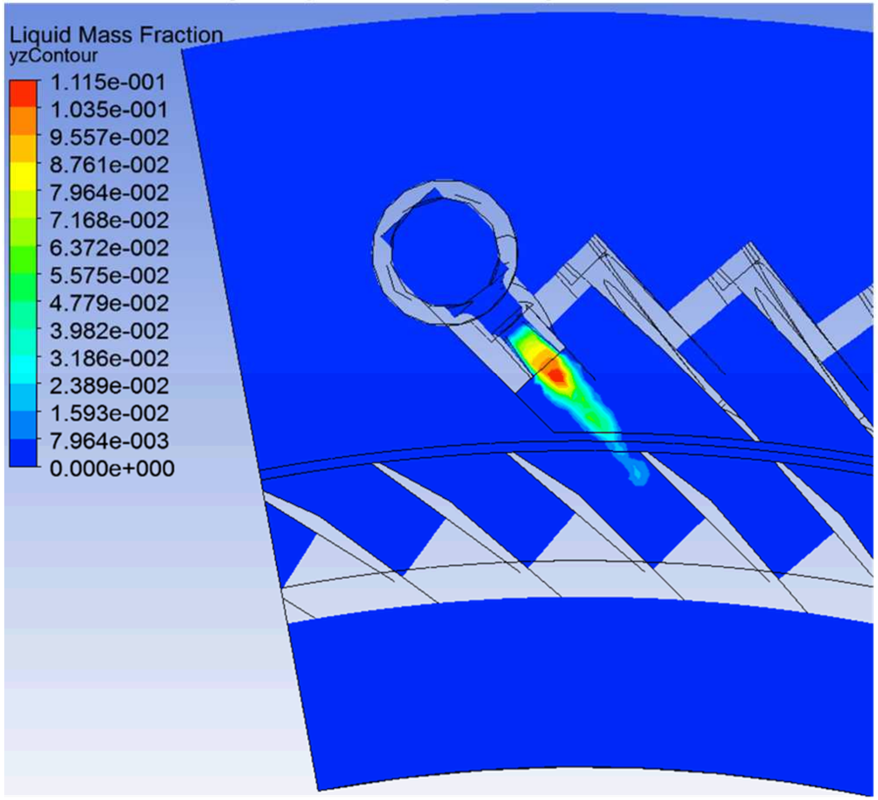


1000 psia (6.9 MPa) inlet pressure

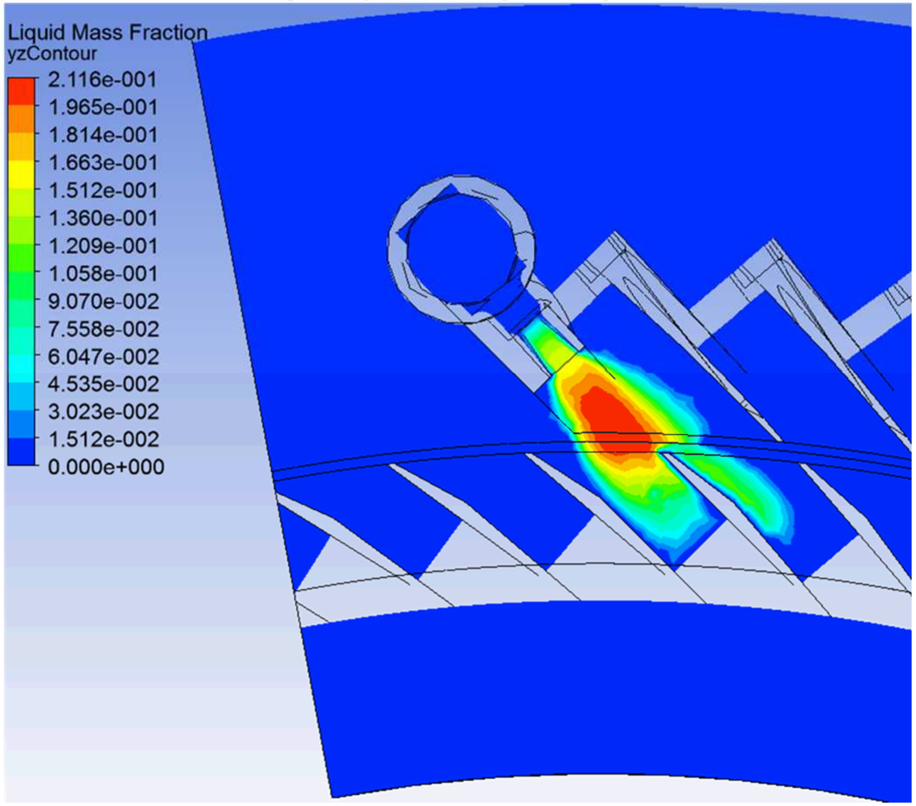


Liquid mass fraction – condensation after throat

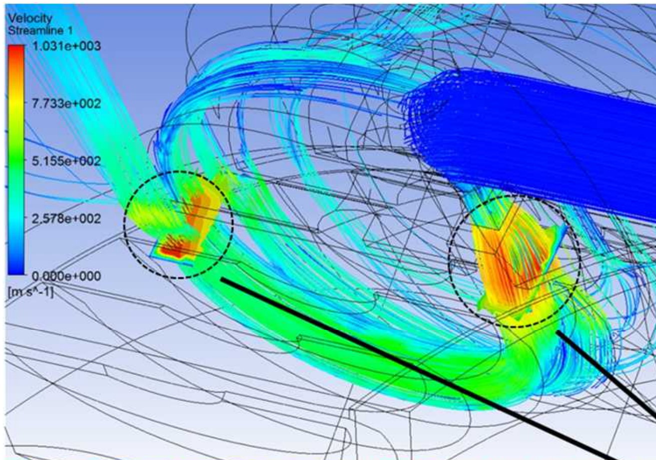
250 psia (1.7 MPa) inlet pressure

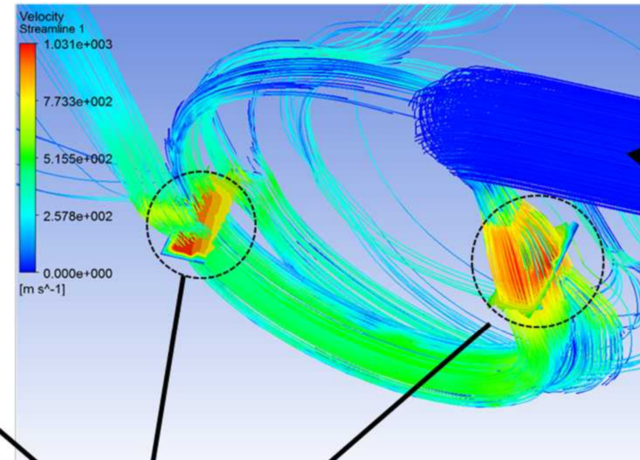


1000 psia (6.9 MPa) inlet pressure



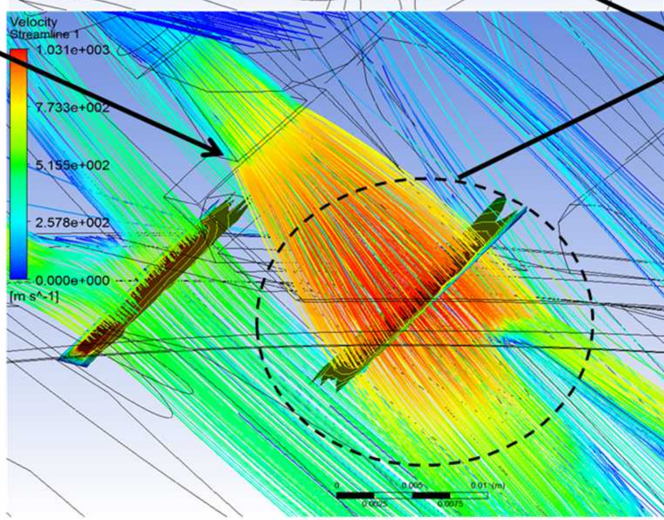
Liquid mass fraction – condensation after throat





Nozzle pressure inlet

Nozzle exit



<u>Define bucket inlet and outlet surfaces</u>

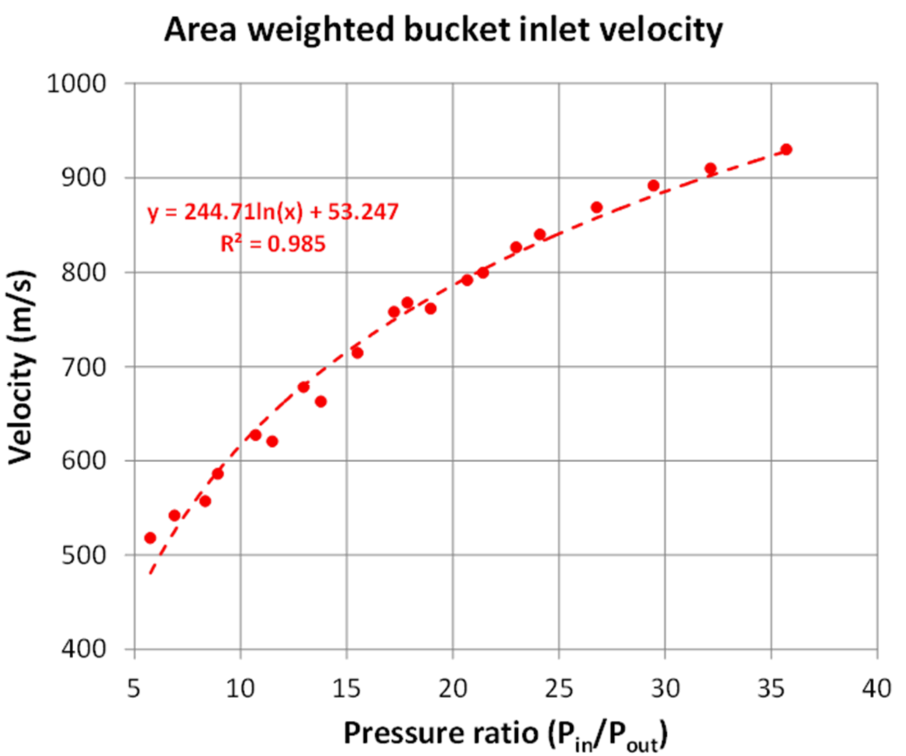
Surfaces are perpendicular to the outlet plane of the nozzle; flow is predominately perpendicular to these surfaces.

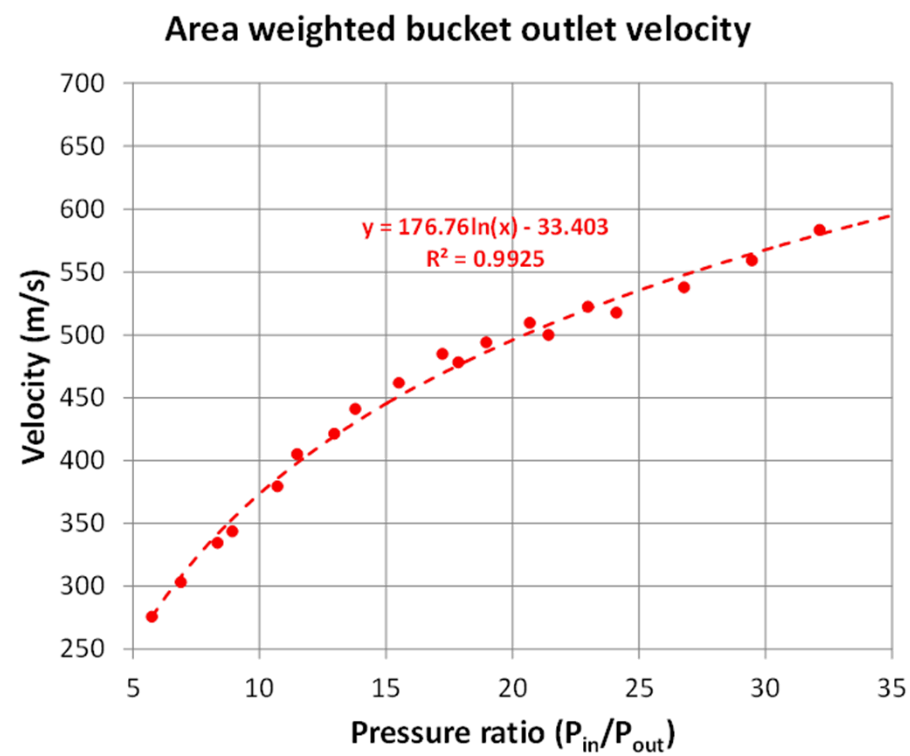
Fluent calculations are steady and static – the bucket is not moving. This represents the turbine at startup or low speed. The bucket flow is aligned such that there is a split in flow between two adjacent buckets (~75/25 split); most of the time, flow is being split between two buckets since the nozzle jet width is comparable to bucket width.

A moving bucket would probably have some influence on the outlet velocity, but would not directly affect the bucket inlet velocity

Abstract CFD insights for lumped parameter model

- Table lookup or functional fit of nozzle velocity vs. pressure (and/or other variables) – do the same for bucket exit velocity
- Eventually account for two-phase nozzle inlet or slug of water (perhaps with simple multipliers)





3. RELAP5 analyses (ongoing)

- Clear need to account for and understand system-level **flow regimes**
- There exists 50-80+ m of variable diameter piping from the RPV/MSL to the governor valve
  - Large geometry change at MSL-RCIC piping junction
  - Many bends
  - Elevation change of 30+ m
- Potential for significant losses through piping during two-phase flow
- Potential large pressure drop across governor valve
- Flow regime questions leading to nozzles
- **Validate MELCOR analyses and demonstrate code-independence of RCIC governing equations**

4. Future modeling plans

- Continue MELCOR and RELAP5 modeling efforts, using CFD analyses in a complementary fashion
  - CFD simulations of water slug through nozzles; two-phase flow into nozzle inlet; moving bucket calculations
- Expand RCIC governing equation(s)
  - Turbine-pump coupling in momentum equation
  - Turbine-pump energy equation
  - Turbine bucket mass/volume conservation equation – only so much can fit into the bucket at any given time
- Improve numerical algorithms
  - Homologous pump curves
  - Distinct RCIC model source code
  - Multi-physics coupling between RCIC code and system thermal-hydraulic code (e.g., via LIME) – demonstrate portability of RCIC model