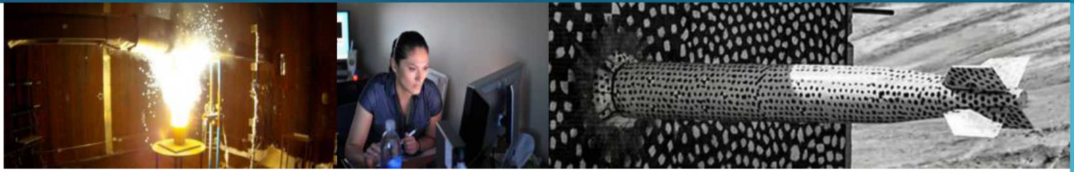
Sandia National Laboratories

SAND2019-6271PE

SNL Modeling of TAMU ZS-1 and GS-2 Terry Turbine Air Testing



PRESENTED BY

Lindsay Gilkey

U.S. DEPARTMENT OF ENERGY NNSA

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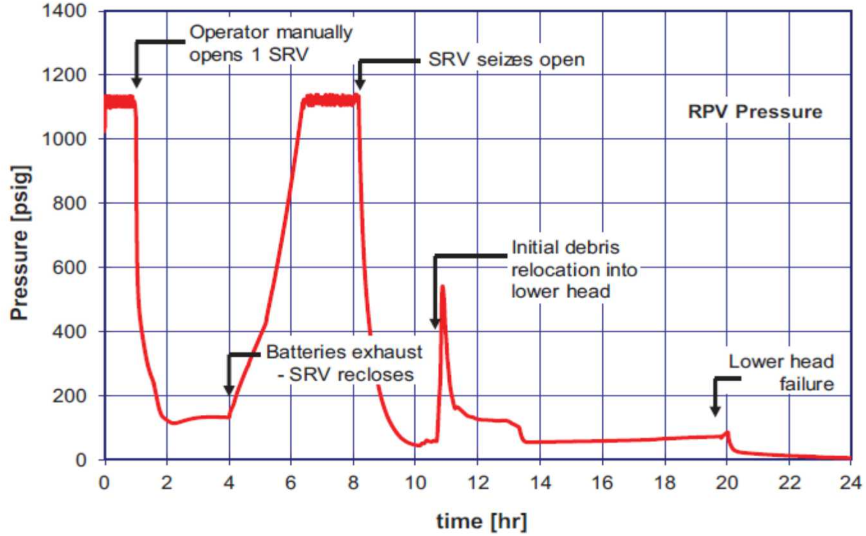
Motivation / Background

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

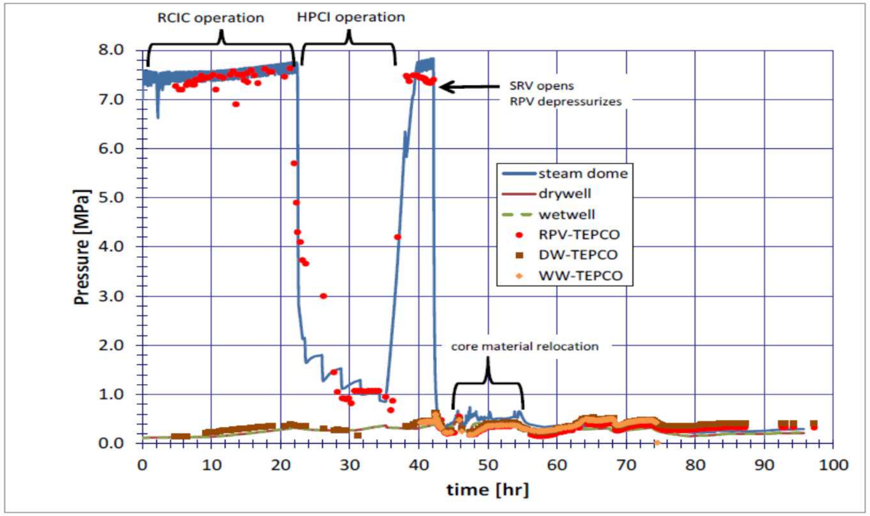
- Sequences observed at Fukushima
  - *Striking similar trends*
- Accidents are classic and 'usual suspects' for analysis

Fukushima critical equipment performance brought new insights

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



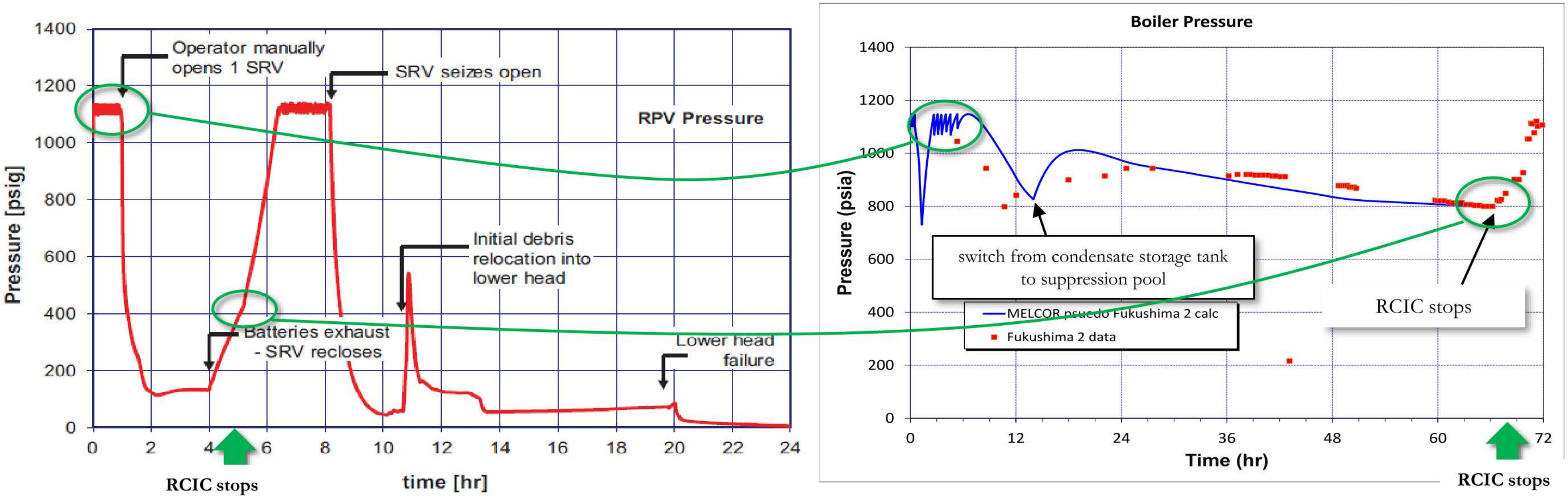
SOARCA BWR LTSBO



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*

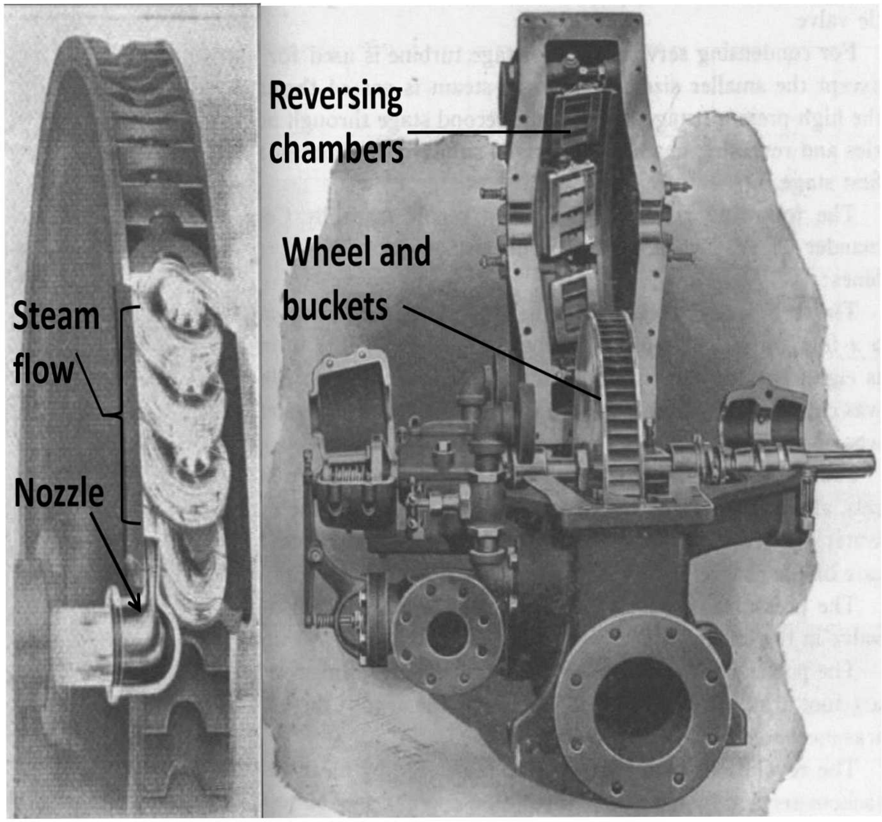
Core damage avoided for nearly 3 days

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.

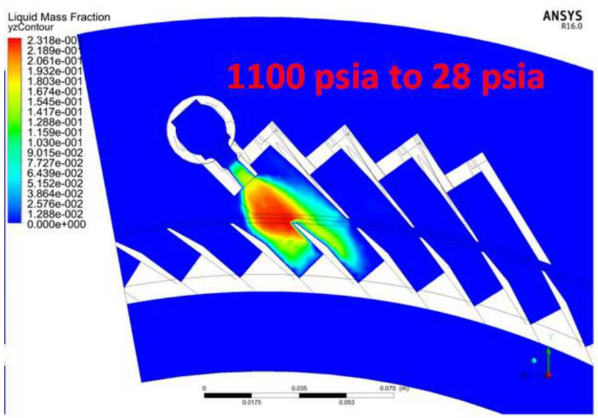


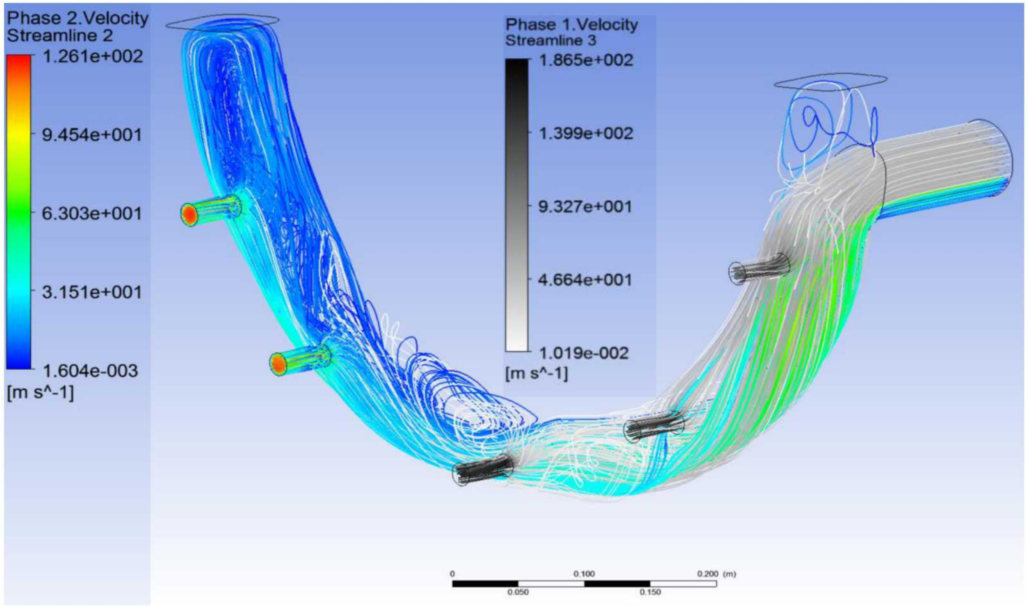
Terry Turbopump CFD

Previous CFD analysis was performed using older, less detailed CAD models. More detailed geometry information became available, and analysis was reperformed.

Analysis was performed in Fluent.

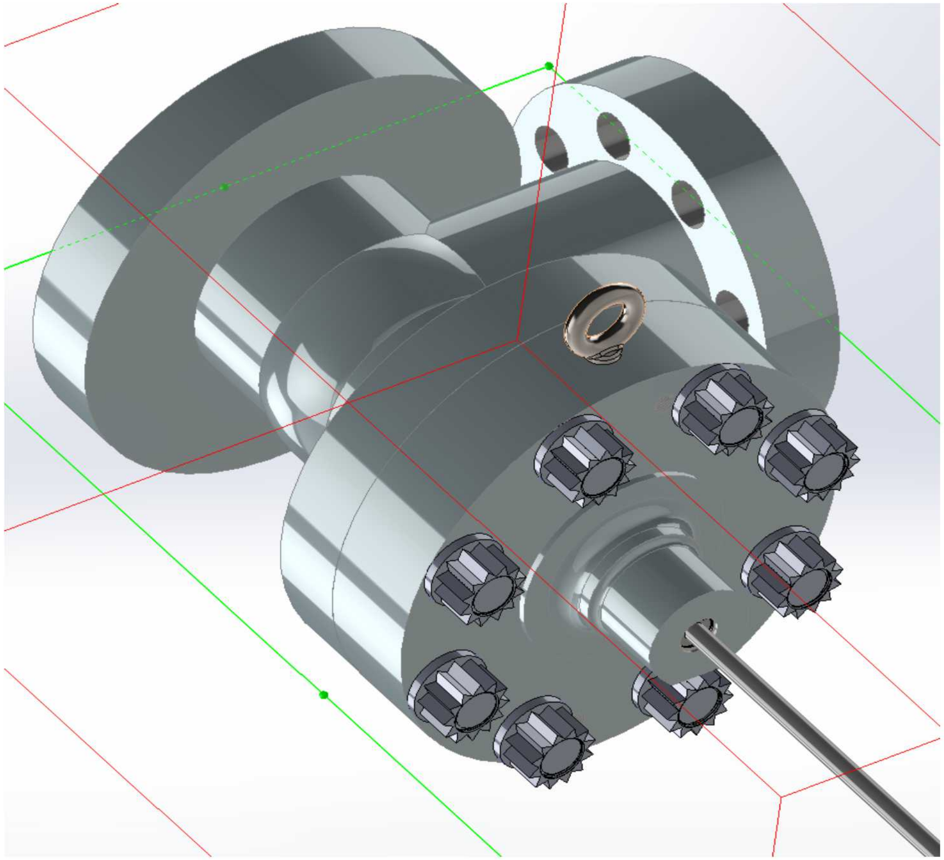
Focus of the CFD analysis was on the governor valve and nozzles (shown on next slides). Focus given to nozzle CFD, as it was used to inform the MELCOR modeling of the ZS-1 and GS-2.



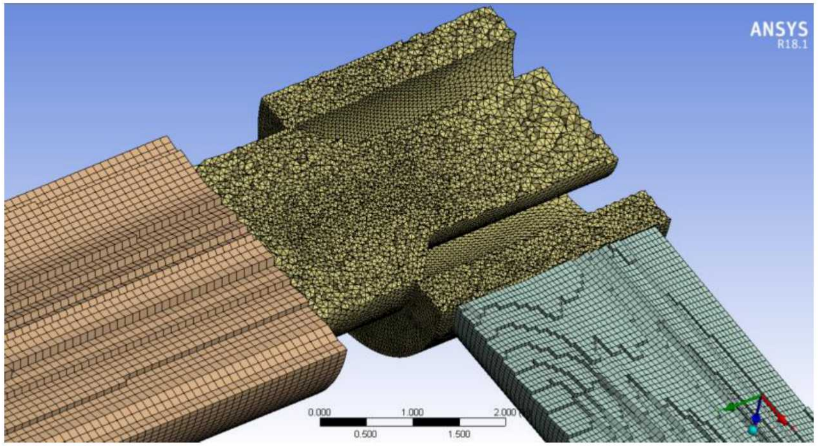


Terry Turbopump CFD, Governor Valve

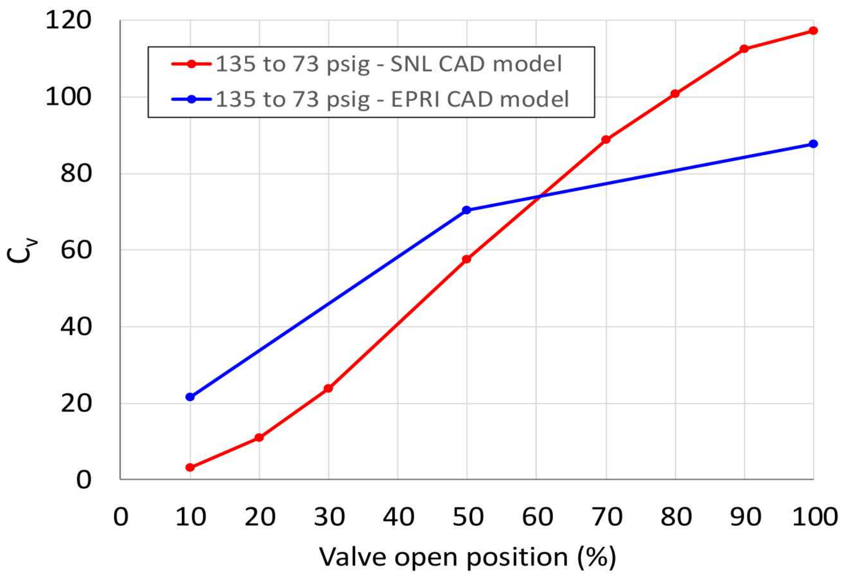
Updated CAD model for governor valve

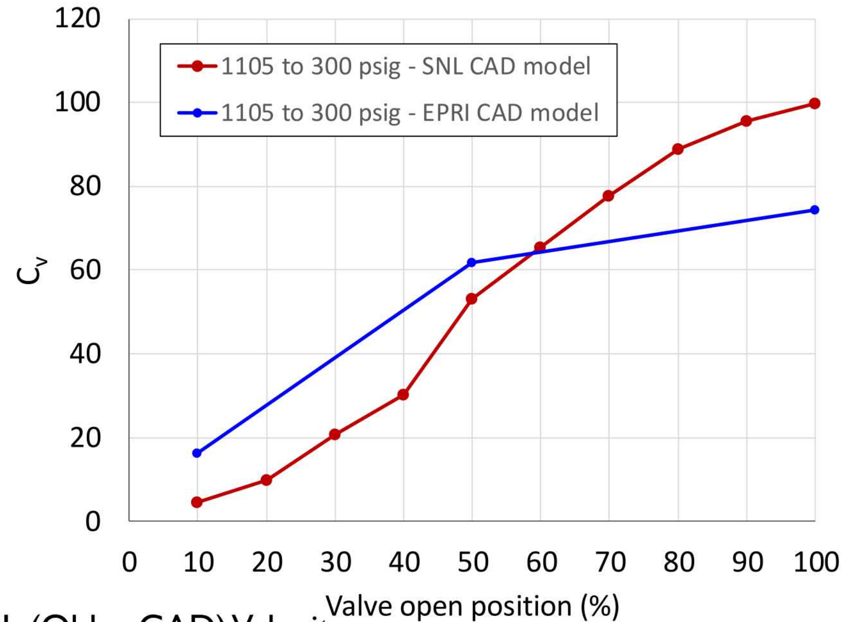


Updated CFD mesh for governor valve

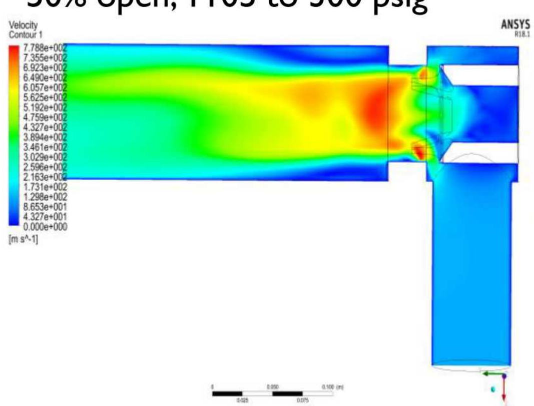


Terry Turbopump CFD, Governor Valve Results

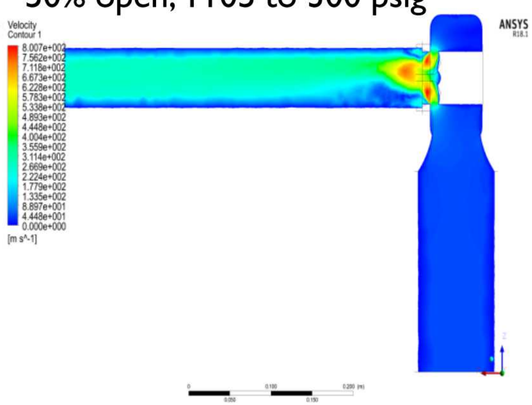




EPRI (Updated CAD) Velocity
50% open, 1105 to 300 psig

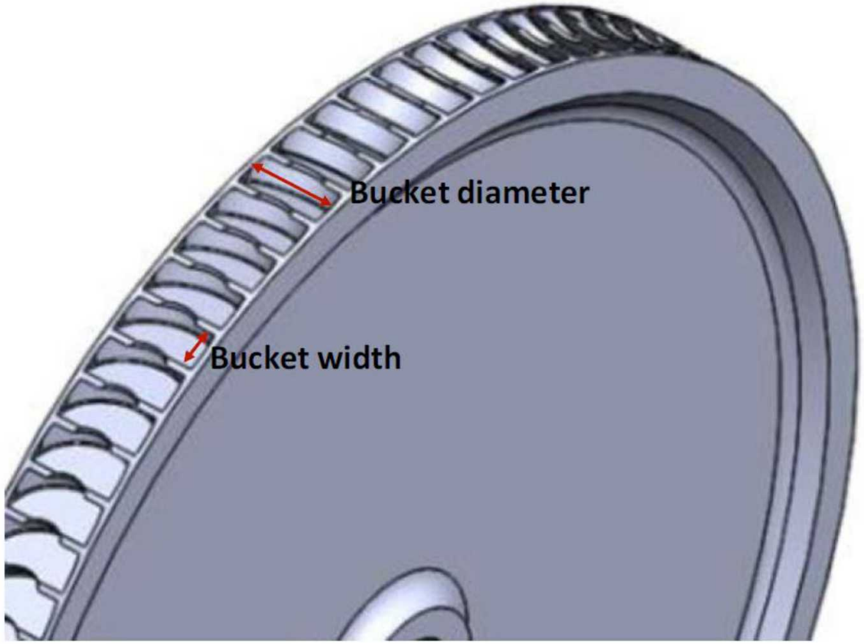


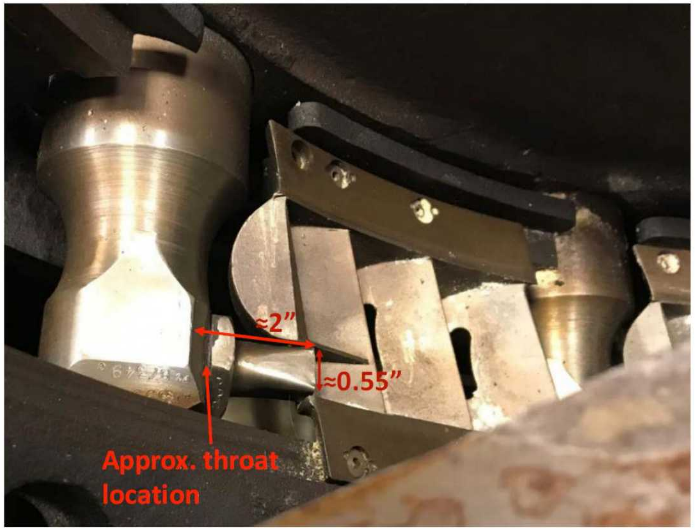
SNL (Older CAD) Velocity
50% open, 1105 to 300 psig



Terry Turbopump CFD, Nozzle Geometry

Model feature	Old model (in)	New model (in)
Throat diam. (circular)	0.22	0.38 or 0.48
Nozzle exit side length (square)	0.25	0.55
Overall length	0.67	2.07
Expanding section length	0.45	1.93
Bucket width	0.25	0.60
Bucket diameter	2.75	2.50
Nozzle exit to bucket inlet	0.7	1.0 – 1.2



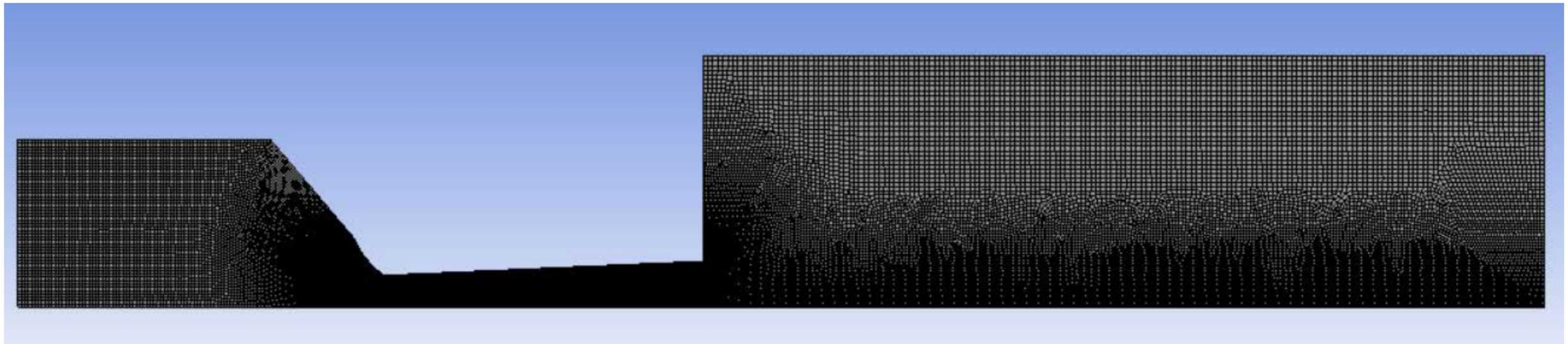


Terry Turbopump CFD, Nozzle Solution Settings

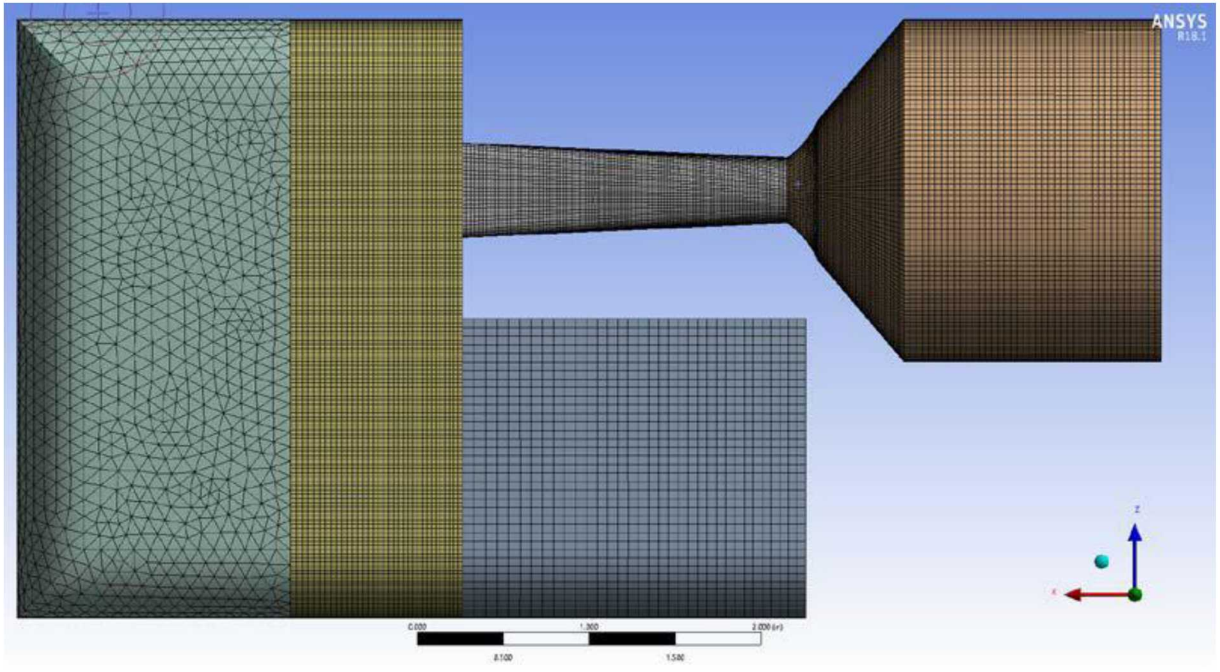
Model variable	Fluent setting
Two-phase formulation	Wet steam with phase change
Turbulence model	k-ω SST
Turbulent intensity	3%
Turbulent viscosity ratio	6
Mesh type	Hexahedral, conformal
Number of cells	1-2 million
Inlet boundary condition	Pressure specified
Outlet boundary condition	Pressure specified
Time-dependence	Steady state
Solver method	Density-based
Solve formulation	Explicit (3D), Implicit (2D)
Flux type	ROE-FDS
Spatial discretization	Least squares cell-based, all variables resolved with first-order upwind scheme (second-order upwind used in select 2D calculations)
Courant number	0.5

Terry Turbopump CFD, Nozzle Mesh

2D Mesh



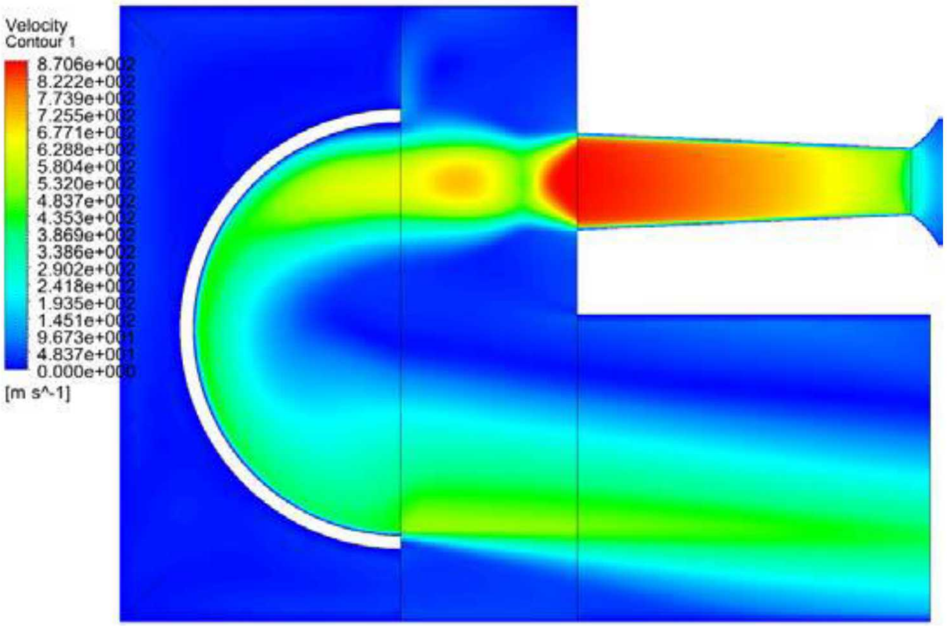
3D Mesh



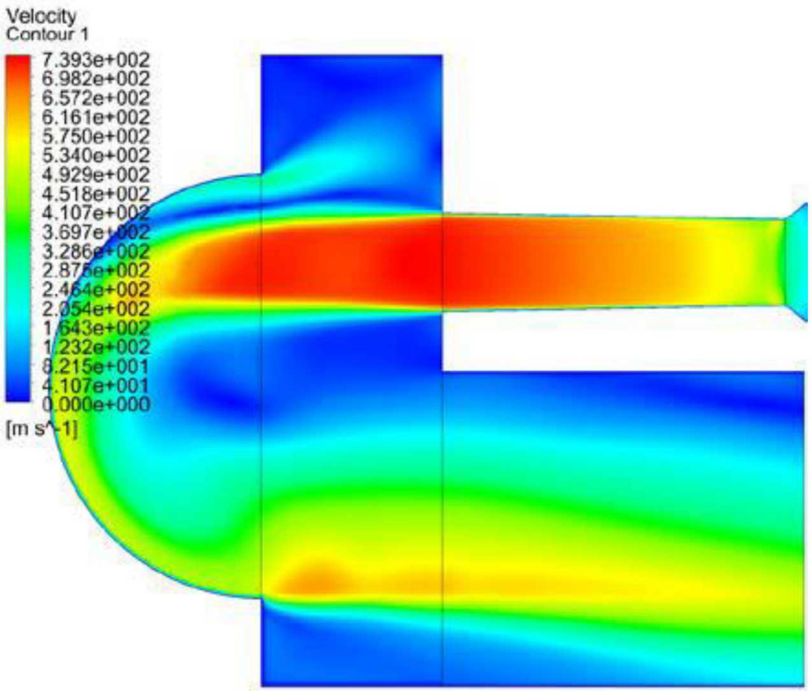
Terry Turbopump CFD, Nozzle Velocity

CFD was used to inform MELCOR table values related to modeling the supersonic plume.

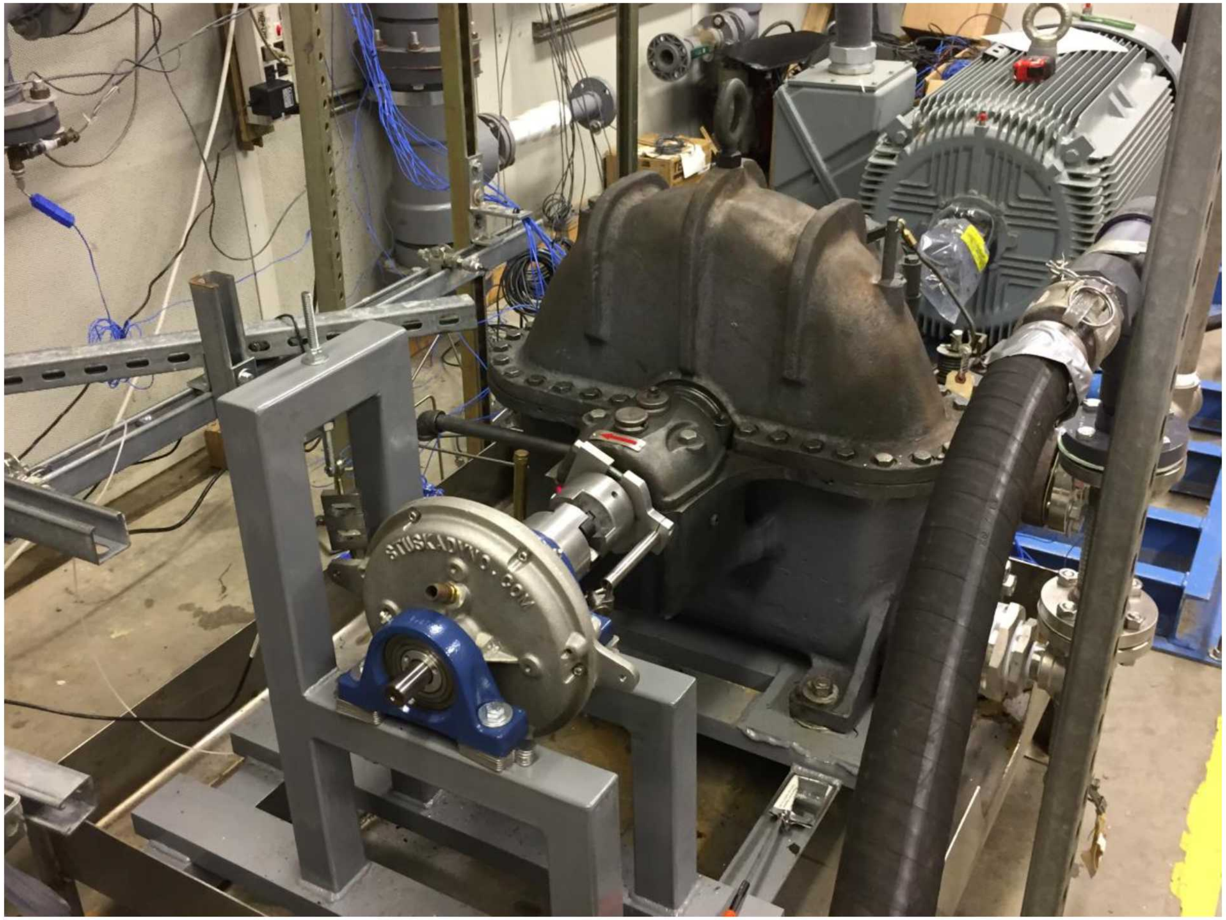
0.38” nozzle, 70 psia steam



0.48” nozzle, 70 psia steam

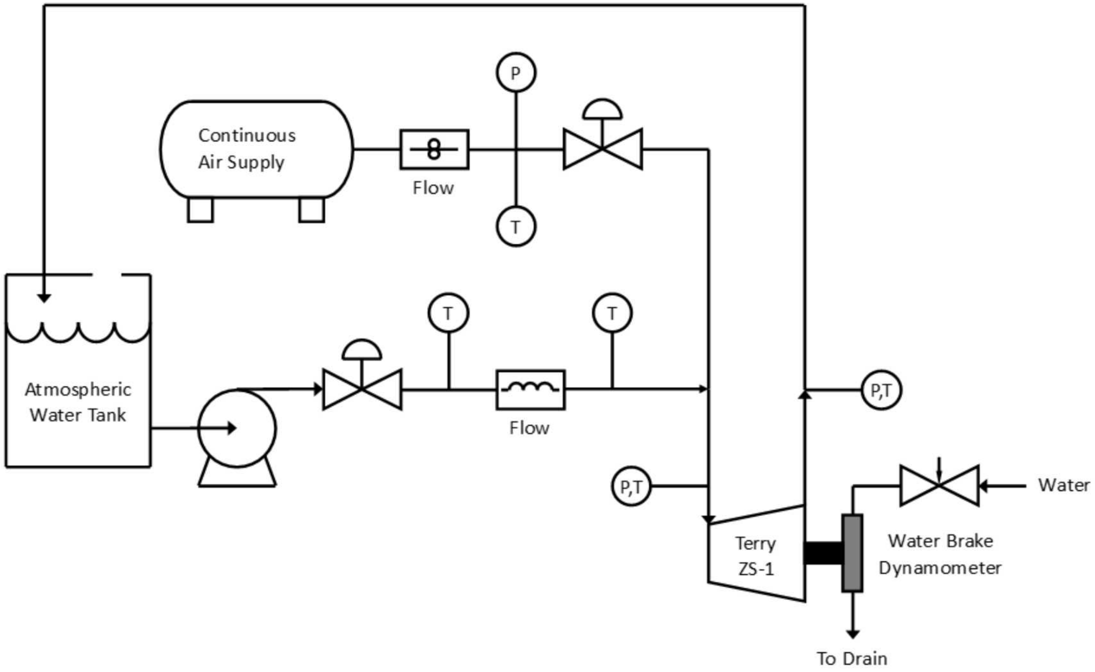


TAMU Experimental Configuration for Testing a ZS-1 Terry Turbine



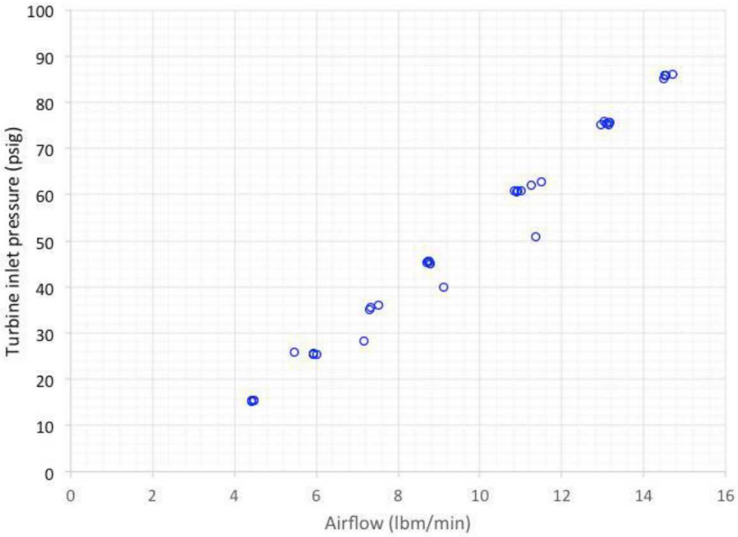
TAMU Experimental Configuration for Testing a ZS-1 Terry Turbine

Goal of the ZS-1 testing configuration: Characterize turbine performance as a function of speed and airflow.

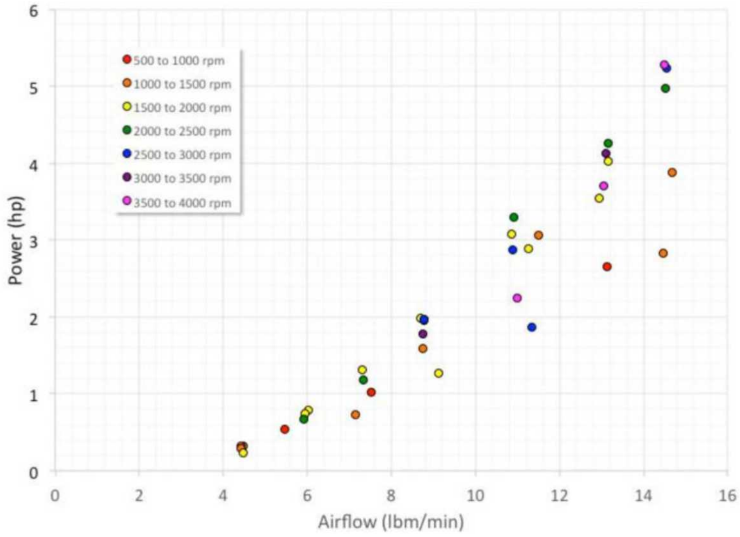


Single-phase (100% air) and two-phase (air and water) flows.

ZS-1 Measured Turbine Power and Pressure vs Airflow



Inlet Pressure vs Airflow



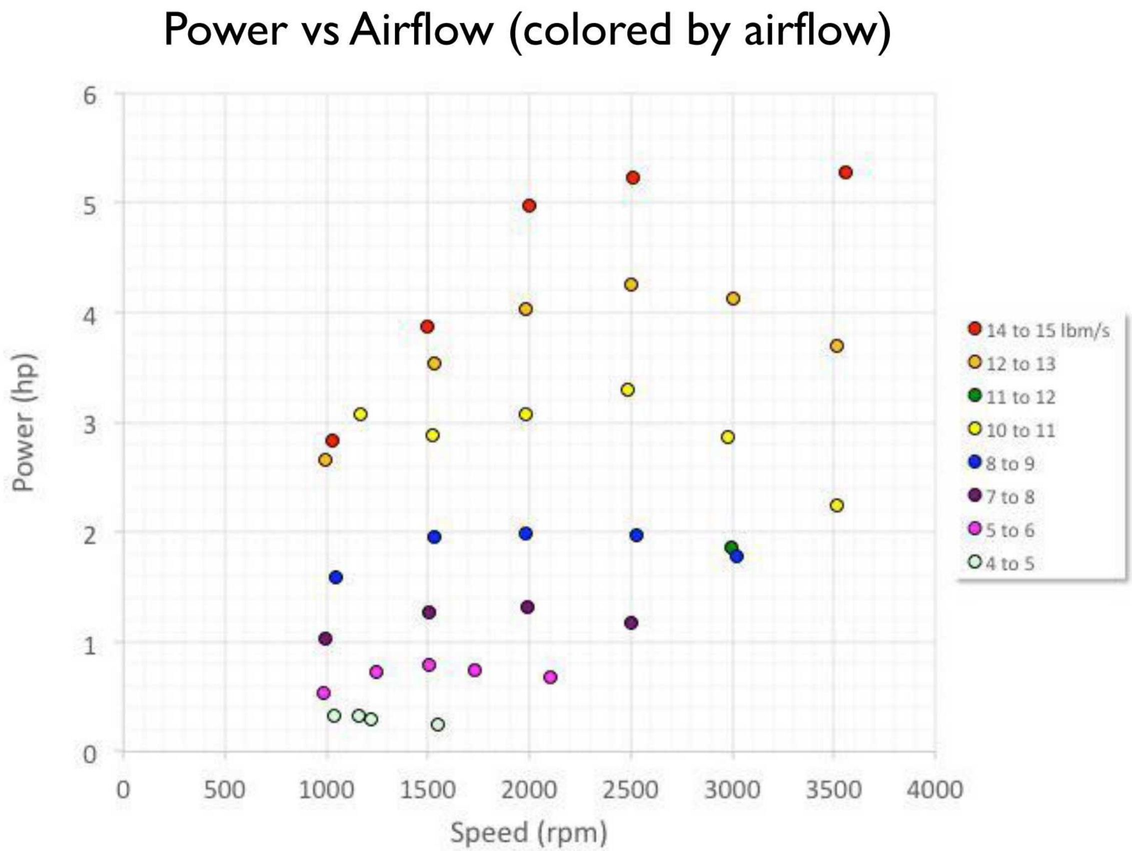
Power vs Airflow (colored by speed)

Only single-phase (100% air) flow is considered here.

Relationship between inlet pressure and airflow is linear, indicating choked flow in nozzle.

Modeling and experiments revealed same powers can be produced by different speeds / pressures at a given airflow.

ZS-1 Measured Turbine Power vs Airflow



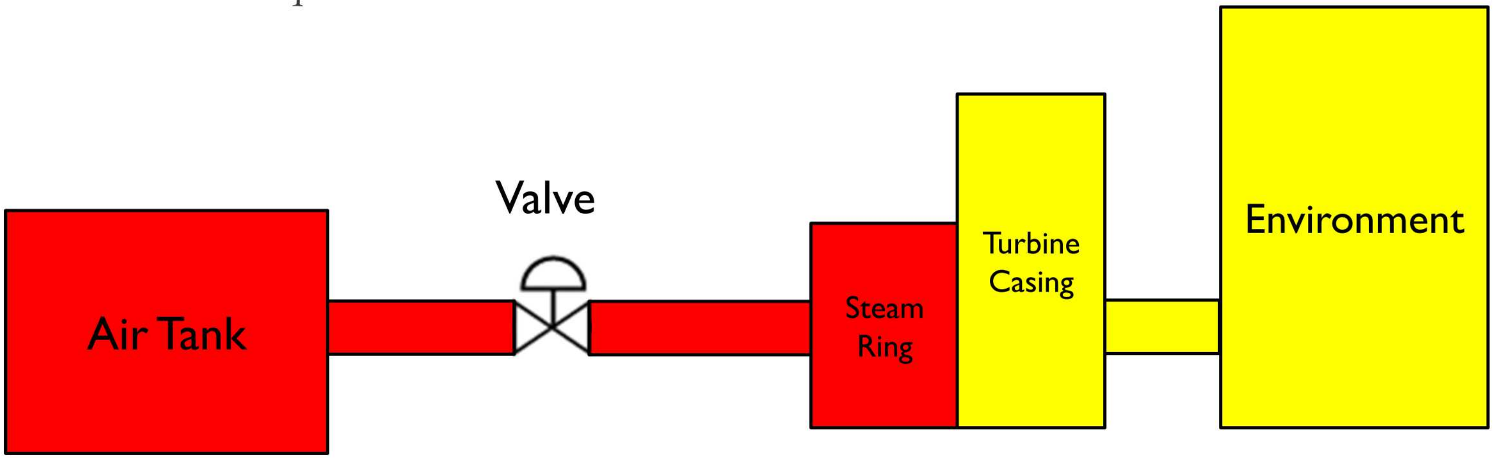
Modeling and experiments revealed same powers can be produced by different speeds / pressures at a given airflow.

Constant pressure trends identify a most efficient speed for the ZS-1 of 2,500 rpm.

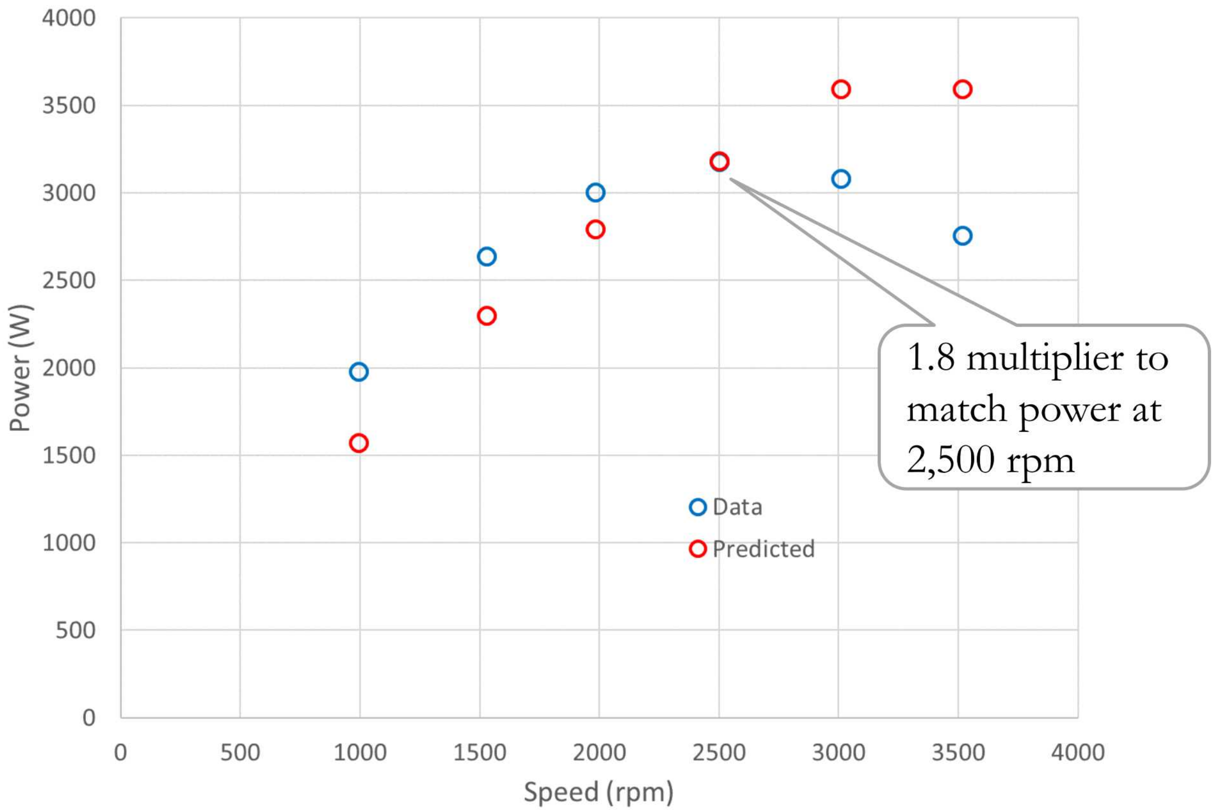
Z1 Turbine Air Testing Model in MELCOR

Methodology:

- Define the pressure and temperature in the air supply tank
- Position the flow control valve to admit air at the reported experimental flowrate
- Specify the reported peak resistive torque developed by the dynamometer
- Specify the reported speed associated with the peak torque
- Allow the model to steadily increase from zero speed to the speed associated with peak dynamometer torque (or to the highest speed below this speed that can be achieved)
- Compare the peak turbine power predicted by the model to peak reported dynamometer torque

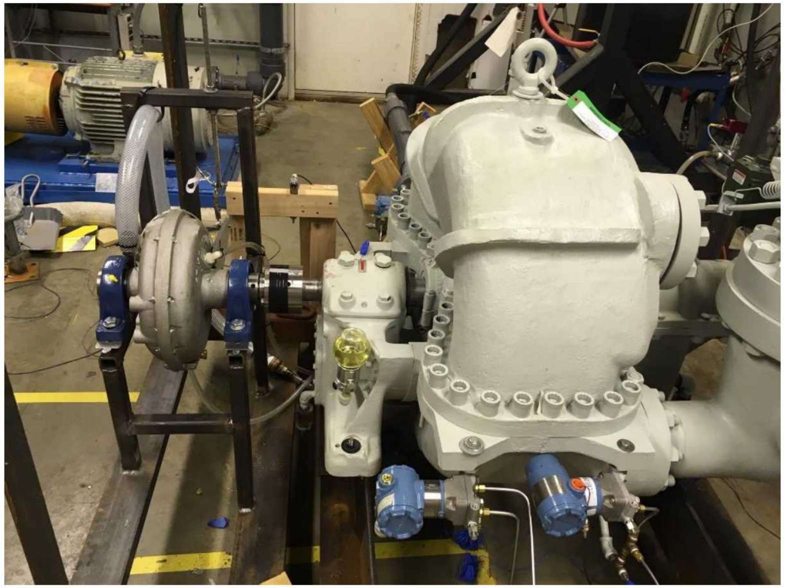


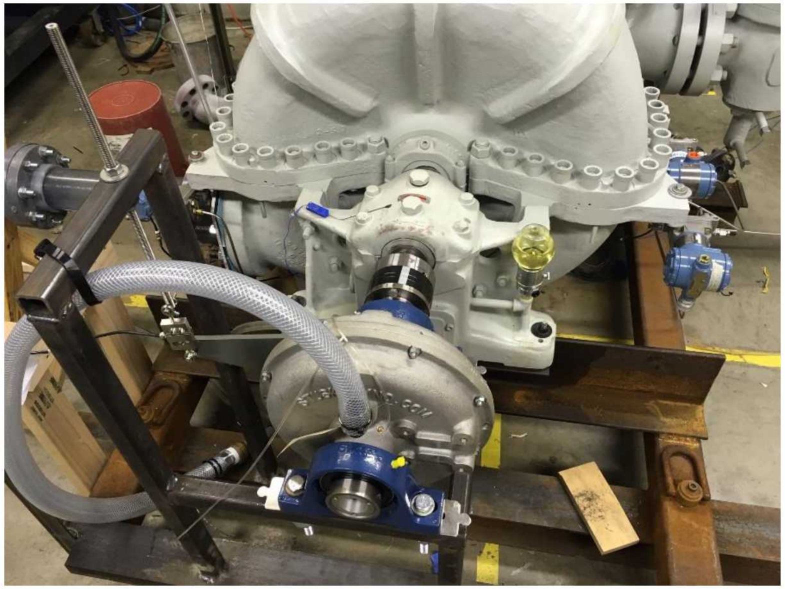
Measured and Predicted ZS-1 Power at an Inlet Pressure of 90 psia and Differing Speeds



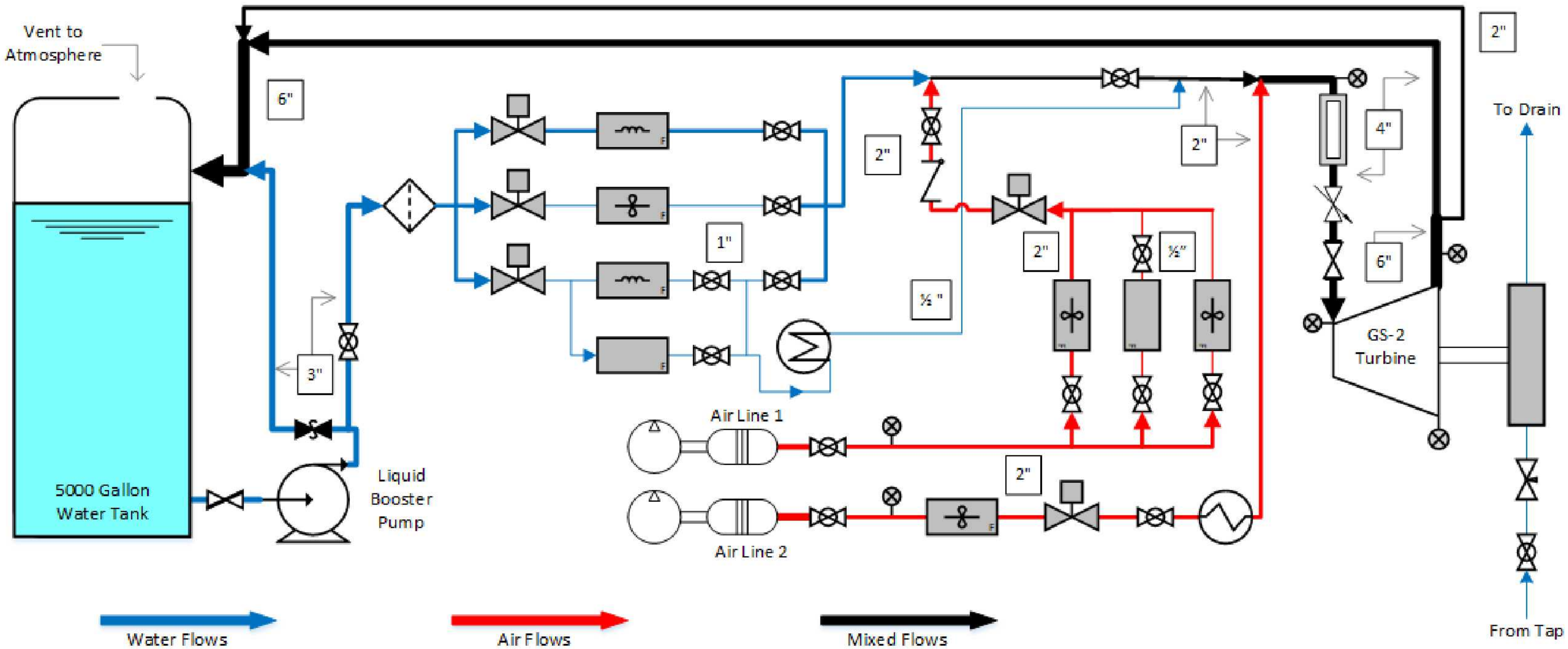
Multiplier on predicted torque of 1.80 used to match power at 2,500 rpm, 1.8 multiplier applied in all predictions.

TAMU Experimental Configuration for Testing a GS-2 Terry Turbine





TAMU Experimental Configuration for Testing a GS-2 Terry Turbine



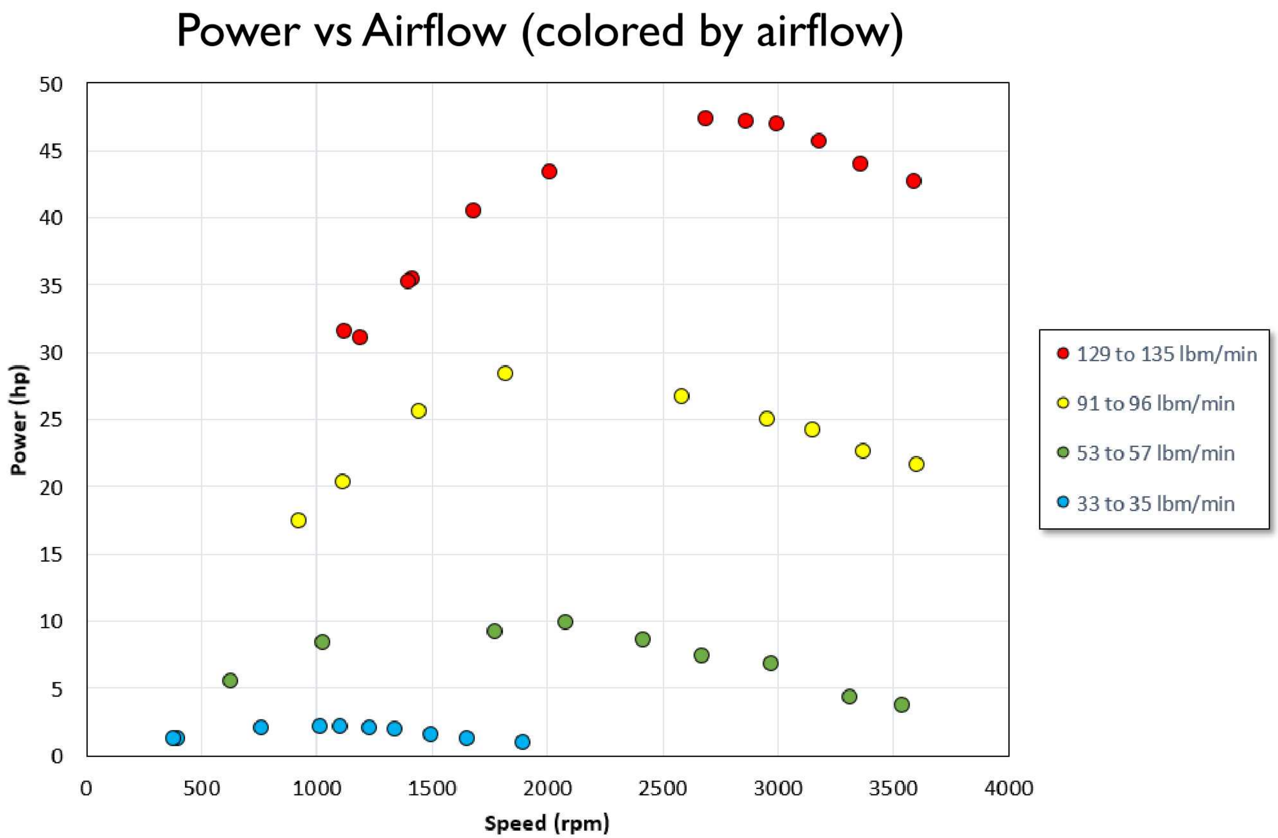
ZS-1:

- Turbine diameter: 18 inches
- 1 nozzle
- Single and Two-Phase Flows

GS-2 (shown above):

- Turbine diameter: 24 inches
- 5 to 10 nozzles
- Single and Two-Phase Flows

GS-2 Measured Turbine Power vs Airflow



Only single-phase (100% air) flow is considered here.

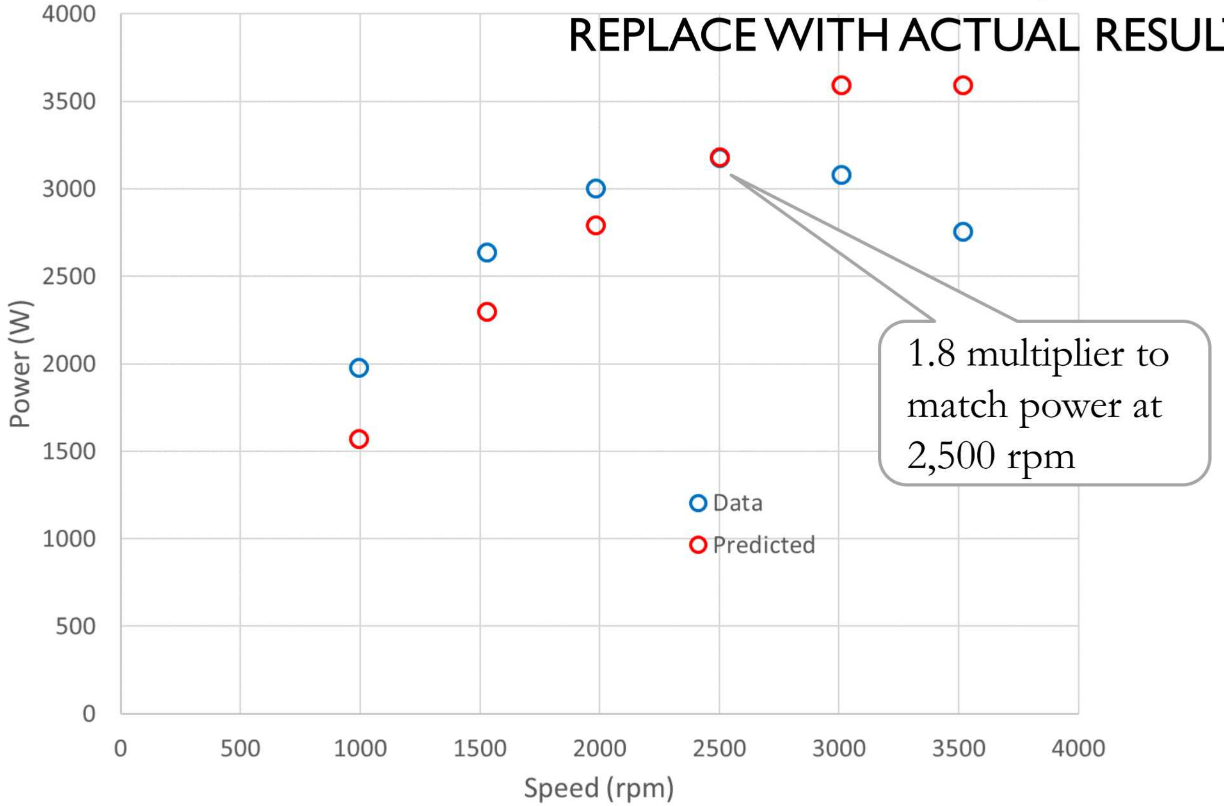
Testing is at higher airflow rates and power than for ZS-1.

Experiments reveal same powers can be produced by different speeds / pressures at a given airflow.

Constant pressure trends identify a most efficient speed for the GS-2 of 2,000 rpm. (note, will revise later).

Measured and Predicted GS-2 Power at an Inlet Pressure of 70 psia and Differing Speeds

NOTE: PLACEHOLDER, WILL REPLACE WITH ACTUAL RESULTS…

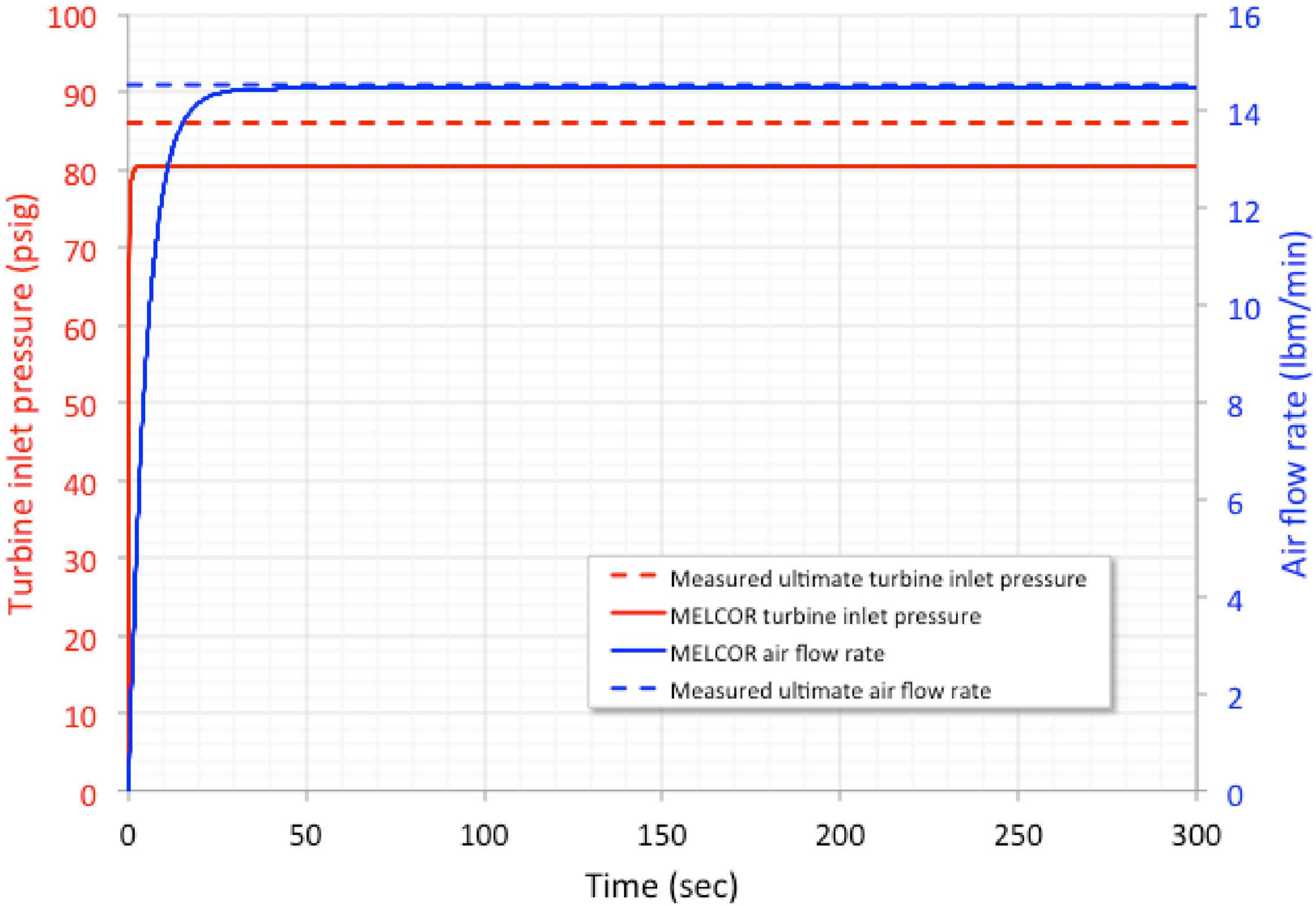


Multiplier on predicted torque of BLANK used to match power at 2,500 rpm, BLANK multiplier applied in all predictions.

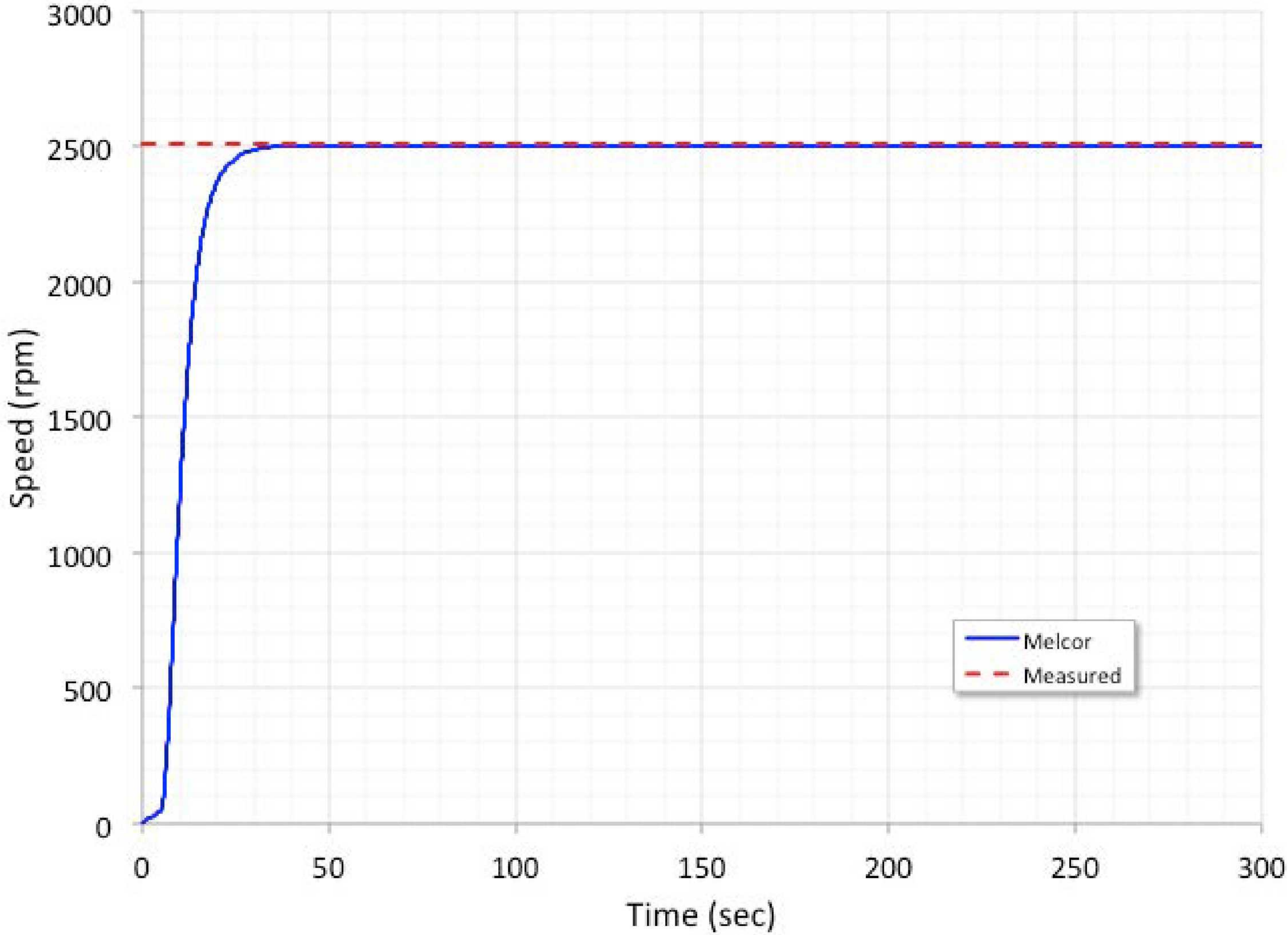
How does multiplier on GS-2 compare to multiplier on ZS-1?

- Preliminary Results, Modeling Air Tests: 1.80 (ZS-1) vs BLANK (GS-2)

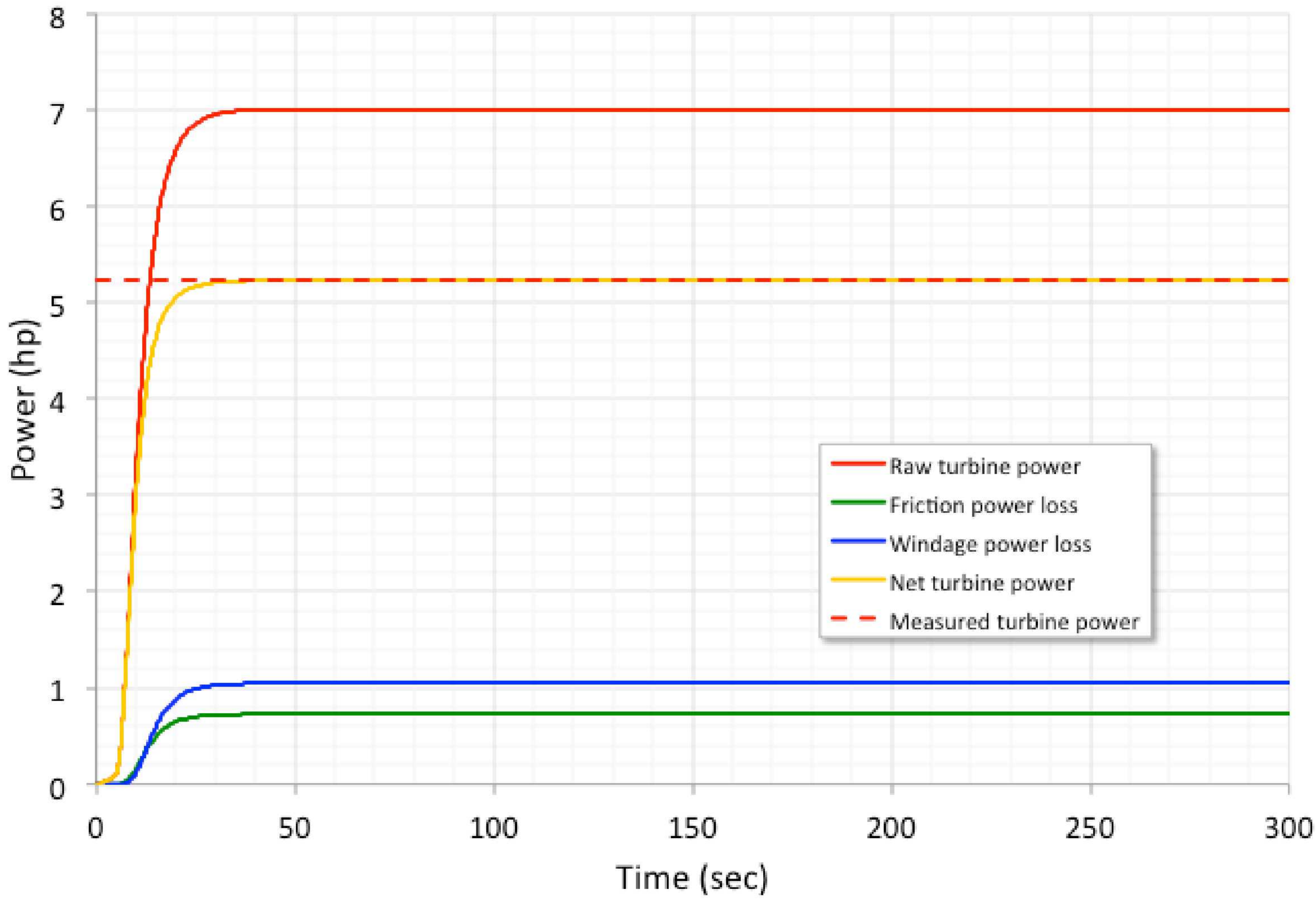
Measured and Predicted GS-2 Inlet Pressure and Airflow History



Measured and Predicted GS-2 Speed History



Measured and Predicted GS-2 Power History



GS-2 Future Modeling

Continue development of GS-2 model in MELCOR.

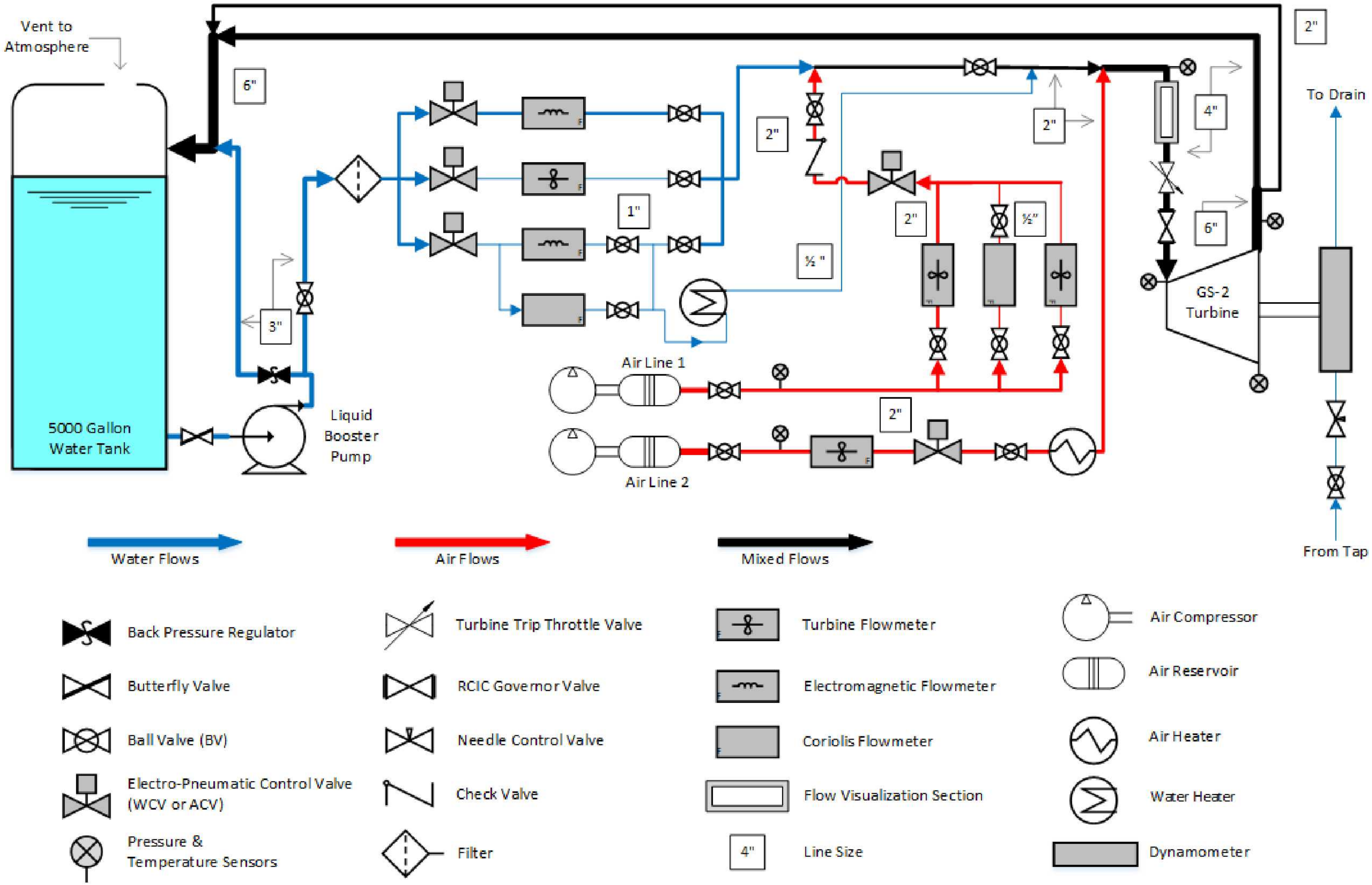
Model additional air and water tests performed by TAMU for GS-2:

Inlet Pressure (psia)	Min Test % Air	Max Test % Air
20	50	100
30	20	100
50	5	100
70	5	100

Data for the steam tests has not been received for the GS-2 yet. Modeling of steam flows will be performed later.

Extra Slides

TAMU Experimental Configuration for Testing a GS-2 Terry Turbine



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.