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Terry Turbopump Expanded Operating Band Modeling and Simulation Efforts in Fiscal Year 2020 – Progress Report

Lindsay Gilkey[2], Matthew Solom[3], Bradley Beeny[1], David Luxat[1]

[1] 08852 Severe Accident Analysis Department
[2] 08853 Structural and Thermal Analysis Department
[3] 06812 International Nuclear Security Engineering Department

Sandia National Laboratories
P. O. Box 5800
Albuquerque, New Mexico, 87185-0748

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

The Terry Turbine Expanded Operating Band Project is currently conducting testing at Texas A&M University as part of a revised experimental program meant to supplant previous full-scale testing plans under the headings of Milestone 5 and Milestone 6. In consultation with Sandia National Laboratories technical staff and with modeling and simulation support from the same, the hybrid Milestone 5&6 plan is moving forward with experiments aimed at addressing knowledge gaps regarding scale, working fluid, and turbopump self-regulation. Modeling and simulation efforts at Sandia National Laboratories in FY20 fell under the broad umbrella of Milestone 7 and consisted exclusively of MELCOR-related tasks aimed at:

1) Constructing/improving input models of Texas A&M University experiments,
2) Constructing a generic boiling water reactor input model according to best practices with systems-level Terry turbine capabilities, and
3) Adding code capability in order to leverage experimental data/findings, address bugs, and improve general code robustness

Project impacts of the Covid-19 pandemic have fortunately been minimal thus far but are mentioned as necessary when discussing the hybrid Milestone 5&6 progress as well as the corresponding Milestone 7 modeling and simulation progress.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

This annual report documents the progress made under the Terry Turbine Expanded Operating Band (TTEXOB) program's modeling and simulation (MODSIM) work performed at Sandia National Laboratories (SNL). It describes the US Federal Fiscal Year 2020 (FY20) MODSIM work to-date with due reference to the Texas A&M University (TAMU) experimental program. SNL MODSIM work in FY20, which falls under Milestone 7 of the TTEXOB program, complements the hybrid Milestone 5&6 experiments.

The TTEXOB program uses a milestone approach to define the operating limitations (margins) of the Terry turbopump systems used in the nuclear industry. Milestone 3, Full-Scale Separate-Effect Component Experiments, performed testing on full-scale components used in reactor core isolation cooling (RCIC) and turbine-driven auxiliary feed water (TDAFW) Terry turbopumps, such as nozzles, valves, etc. The tests were intended to better understand component behavior under both normal and abnormal conditions. Milestone 4, Terry Turbopump Basic Science Experiments, performed testing on a scaled Terry turbopump system to develop performance data under a wide range of normal and off-normal conditions. It also included a limited amount of full-scale Terry turbine testing to establish scaling between the full-scale and small-scale systems. Milestones 1 through 4 have been completed as of FY20 with the caveat that a few tasks formerly filed under Milestone 3 and Milestone 4 have become a part of the hybrid Milestone 5&6.

Milestone 5, Integral Full-Scale Experiments for Long-Term Low-Pressure Operations, was designed to explore the effects of off-normal conditions (low pressure, wet steam, high oil temperatures, etc.) on turbine operability and performance. Milestone 6, Scaled Experiments Replicating 1F2 Self-Regulating Feedback, was intended to provide an integral experiment that explores self-regulating feedback in Terry-turbine based nuclear systems when water provided by the turbopump enters the turbine's steam inlet. Due to reduced funding across the consortium entities beginning in FY20, the full-scale testing program required to complete Milestone 5 and Milestone 6 was abandoned in favor of a hybrid Milestone 5&6 with reduced scope.

Hybrid Milestone 5&6 is aimed at obtaining a measure of confidence in scaling effects/factors and Terry turbopump self-regulation. Gaps to address with the hybrid Milestone 5&6 experimental program include:

- Full-scale steam test data,
- Full-scale duration test with steam,
- Self-regulation (full-scale), and
- Impact of steam quality

Fortunately, the Covid-19 pandemic has not severely impacted progress at TAMU on the hybrid Milestone 5&6 experimental program. TAMU has not stopped experimental work though it has perhaps been hindered as a side-effect of recently imposed restrictions on and precautions in the lab. The exigent circumstances have altered SNL technical staff's approach in terms of supporting the TAMU experiments.

Milestone 7 is an umbrella for MODSIM efforts complementary to the experiments of all the other milestones (to now include the hybrid Milestone 5&6). Prior Milestone 7 MELCOR modeling and simulation exclusively employed user-implemented control function (CF) models to represent the Terry turbopump. For all FY20 modeling and simulation tasks complementing hybrid Milestone 5&6, the built-in systems-level MELCOR Terry turbopump models were used. This is better general practice and demonstrates a new facet of code capability. The Covid-19 pandemic has had little to no impact on the MODSIM activities at SNL.

Several new MELCOR capabilities were added as a part of code development MODSIM activities:

- Extra torque terms for rotor and/or pump objects
- Sensitivity coefficient capabilities to incorporate raw turbine torque multipliers and a windage torque term
- An independent mode for turbine operation wherein a rotor object can be computed without an explicit connection to a pump object

Existing MELCOR input models representing TAMU experimental facilities were improved and a new generic BWR input model is in development and has demonstrated its usefulness in:

- Modeling turbopump self-regulation capability
- Exploring model sensitivities and uncertainties
- Drawing useful insights about turbopump phenomenology

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
1F2	Fukushima Daiichi Unit 2
BDBE	Beyond Design Basis Event
BWR	Boiling Water Reactor
CF	Control Function
CST	Condensate Storage Tank
CVH	Control Volume Hydrodynamics
CY	Calendar Year
DAQ	Data Acquisition
DC	Direct Current
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy's Office of Nuclear Energy
EPRI	Electric Power Research Institute
FL	Flow Path
FY	Fiscal Year
IAE	Institute of Applied Energy
INL	Idaho National Laboratory
MODSIM	Modeling and Simulation
MSL	Main Steam Line
NHTS	Nuclear Heat Transfer Systems
P&ID	Piping and Instrumentation Diagram
PIV	Particle Image Velocimetry
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling

Abbreviation	Definition
RPV	Reactor Pressure Vessel
SC	Sensitivity Coefficient
SNL	Sandia National Laboratories
TAMU	Texas A&M University
TDAFW	Turbine Driven Auxiliary Feedwater
TTEXOB	Terry Turbine Expanded Operating Band Committee
TTUG	Terry Turbine User Group
Turbo-TAG	Nuclear Grade Terry Turbopump Advisory Group
VFD	Variable Frequency Drive

1. INTRODUCTION

This annual report documents the progress made under the Terry Turbine Expanded Operating Band (TTEXOB) program's modeling and simulation (MODSIM) work performed at Sandia National Laboratories (SNL). It describes the US Federal Fiscal Year 2020 (FY20) MODSIM work to-date with due reference to the Texas A&M University (TAMU) experimental program. This work, which falls under Milestone 7 of the program, provides a counterpart to the various experiments. The overall TTEXOB program and its milestone-based approach are described in the program's Summary Plan [1]. Details of the individual milestone test plans can be found in the corresponding detailed test plan, e.g. the Milestone 3 and 4 Detailed Test Plan [2]. SNL MODISM is conducted alongside experiments performed at TAMU, and SNL technical staff regularly consults with TAMU on the experimental program.

The testing at TAMU is – as of FY20 - supported by two primary groups: the U.S. Department of Energy (DOE) largely through SNL and Idaho National Laboratory (INL), and the U.S. nuclear industry. Formerly, Japan's Ministry of Economy, Trade, and Industry – by way of the Institute of Applied Energy (IAE) – was a source of support as outlined in the project's charter [3].

Details on the experimental work have previously been reported to the IAE [4] in alignment with the Japanese fiscal year and subsequently to the DOE [5] in alignment with the US fiscal year. This report for FY20 builds upon the experimental and MODSIM progress reported in prior fiscal years [6, 7, 8, 14, 18, 19,20].

Results and analyses introduced here are expected to be disseminated in relevant scientific and industrial publications and conferences such as the Terry Turbine Users Group (TTUG) [9]. Journal publications have already come out of the past fiscal years [10, 11], and future publications are expected.

In addition to the MODSIM work performed at SNL as the Milestone 7 reflections of the hybrid Milestone 5&6, this report will provide some updates on the hybrid Milestone 5&6 experiment program.

1.1. Background

Prior to the accidents at the Fukushima Daiichi Nuclear Power Plant, assumptions about and modeling of Terry turbopump performance came mostly from generic vendor operational limits based on the National Electrical Manufacturers Association standard SM23 *Steam Turbine for Mechanical Drive Service* [12] established for turbines intended to deliver continuous reliable service with little or no maintenance. The standard has since been deemed obsolete and was withdrawn.

The Reactor Core Isolation Cooling (RCIC)/Turbine-Driven Auxiliary Feedwater (TDAFW) system performance under beyond design basis event (BDBE) conditions is poorly known and is largely based on conservative assumptions used in probabilistic risk assessment (PRA) applications. For example, common PRA practice holds that battery power (DC) is required for RCIC operation to control the reactor pressure vessel (RPV) water level, and that a loss of DC power results in RCIC flooding of the steam lines with an assumed subsequent failure of the RCIC system. This assumption for accident analysis implies that RCIC operation should terminate on battery depletion, which is conservatively estimated to range from 4 to 12 hours. In contrast, real-world observations from Fukushima Daiichi Unit 2 (1F2) show that RCIC function was affected but not terminated by uncontrolled steam line flooding, and in fact provided coolant injection for nearly three days [13, 14, 15, 16].

Use of conservative assumptions regarding equipment function limits the possible mitigation options for normal and emergency operations. Even in the PRA application space, a best-estimate approach via mechanistic modeling may be a preferable alternative to conservative assumptions. Improved understanding of Terry turbopumps can be realized through an iterative process of advanced modeling and full-scale experimental testing.

The events at Fukushima Daiichi, qualitative analysis, and experience in other industries demonstrate the Terry turbopump has significantly greater operating flexibility than credited in nuclear power plant operations. In particular, operating experience indicates that the Terry turbopump system was qualified for plant operations only to a small subset of its capability. Defining (expanding) this operating band through modeling and testing provides operational flexibility to preclude the occurrence of core damage events such as those that occurred at Fukushima Daiichi with minimal cost to the fleet of plants (i.e., update the operations procedures and train staff on its capability).

The RCIC systems in Fukushima Daiichi Units 2 and 3 operated for extended time periods of up to 68 hours under various RPV pressures, poor steam quality, and with high lube oil and suction temperature values. Data indicates that the Terry turbopump also ran in a 'self-regulating' mode; steam quality impacted the turbine speed such that RPV make-up maintained a relative steady level without any electronic control feedback [13, 14].

The Terry turbopump is used in a wide variety of commercial applications which are not as well controlled as the nuclear industry design limits. The history of the Terry turbopump dates back to the early 1900's and it has a reputation for reliable and rugged performance under a broad range of operating conditions. It is commonly known within other commercial industries that the Terry turbopump can run with water ingestion into the turbine [14]. In addition, a turbine qualification test was run at extreme conditions including ingestion of a large slug of water showing no loss of function or damage to the turbine [17].

Based on the experiences at Fukushima and the nuclear industry at large, the Terry turbopump system is hypothesized to have the capability to operate for days or weeks over an extended range of steam pressures, steam conditions, and increased lube oil temperature conditions with limited to no active control features.

1.2. TTEXOB Program Approach – Review and Summary

The TTEXOB program, guided by the Nuclear Terry Turbopump Advisory Group (Turbo-TAG), uses a milestone approach to define the true operating limitations (margins) of the Terry turbopumps used in the nuclear industry. Milestones 2 through 7 are briefly described below as is the recent change in project scope that involved the creation of hybrid Milestone 5&6 as a replacement for Milestone 5 and Milestone 6.

Milestone 2 – Principles & Phenomenology

- Scoping work to develop and refine the later Milestones (i.e., development of detailed test plans)
- Initial modeling and analysis using existing knowledge and tools
- Complete (as of FY20)

Milestone 3 – Full-Scale Separate-Effect Component Experiments

- Testing on full-scale components (nozzles, valves, etc.) used in RCIC/TDAFW Terry turbopumps to better understand their behavior in normal and off-normal conditions
- Complete (as of FY20) after a few lingering experimental tasks were migrated to the hybrid Milestone 5&6 and completed

Milestone 4 – Terry Turbopump Basic Science Experiments

- Testing on smaller-scale systems (i.e., a Terry ZS-1 instead of a GS-series turbine) to develop performance metrics and profiles under a variety of normal to off-normal conditions
- Limited testing of full-scale (Terry GS-series) systems to establish scaling parameters between the small-scale and full-scale systems
- Complete (as of FY20) as a few lingering experimental tasks have been migrated to the hybrid Milestone 5&6

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

- Deprecated as of FY20
- Replaced by hybrid Milestone 5&6

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

- Deprecated as of FY20
- Replaced by hybrid Milestone 5&6

Hybrid Milestone 5&6 – Steam, Scale, and Self-Regulation

- Initial considerations at end of FY19
- In progress as of FY20

Milestone 7 – Collection and integration of the Milestone 3 to hybrid Milestone 5&6 modeling efforts

- Complete as of FY20 for Milestone 3 and 4 complementary analyses
- In progress as of FY20 for hybrid Milestone 5&6 complementary analyses

The generic technical approach for Milestone 3 and Milestone 4 was to:

1. Model the planned tests,
2. Test the equipment's performance for specified test requirements,
3. Analyze the tests across the test requirements range,
4. Compare model analyses to the test results,
5. Report any differences and possible technical reasons,
6. Extrapolate the results to full-scale BDBE conditions, and
7. Evaluate the results for Turbo-TAG expectations and adequate confidence

Milestone 5 and Milestone 6 – before their cancellation – entailed a similar technical approach, and replacement hybrid Milestone 5&6 is on the same track. The MODSIM efforts reported here pertain primarily to FY20; see [18] for FY17, [19] for FY18, and [20] for FY19.

1.2.1. Milestones 3 and 4

As of late FY20, Milestone 3 and Milestone 4 are both concluded on the experimental and MODSIM sides with the caveat that some lingering experimental tasks have been sorted under the new hybrid Milestone 5&6 discussed subsequently. The experimental portions of Milestones 3 and 4 were performed at TAMU, and the MODSIM portions were performed by several collaborating organizations under the TTEXOB program. Further details on the experimental details can be found in [5].

Under Milestone 3, Full-Scale Component Experiments, several components were experimentally investigated. The Milestone 3 efforts were divided into four categories of experiments:

1. Free jet testing (Terry nozzle flow visualization),
2. GS-series turbine governor valve and trip/throttle valve testing (ANSI/ISA S75 based profiling),
3. Lubrication oil degradation testing, and
4. Bearing performance tests under adverse conditions

Note that a few recently completed tasks under Milestone 3 are discussed in the hybrid Milestone 5&6 progress report section.

The Milestone 4 (Terry Turbopump Basic Science Experiments) tests were intended to provide information allowing for better design and operation of full-scale testing (i.e., Milestone 5), as well as to provide benchmark data for code validation. Additionally, the development of scaling parameters theoretically enables the translation of any future small-scale (i.e. cheaper, simpler) tests to full-scale systems. The Milestone 4 efforts were divided into three areas of experiments:

1. ZS-1 Terry turbopump testing,
2. Full-scale (Terry GS-series) testing technique confirmation, and

3. Initial scoping of Fukushima Daiichi Unit 2 uncontrolled feedback with a ZS-1 Terry turbopump

The ZS-1 and GS-series Terry turbopump tests provided data for modeling efforts (including a broad set of performance curves), provided initial scaling factors, and provided initial investigations into potential failure modes of a GS-series Terry turbopump under a BDBE. These efforts also provided initial confirmatory data for the Milestone 5 and 6 full-scale tests despite their cancellation. The initial scoping of uncontrolled feedback with a ZS-1 Terry turbopump also provided confirmation that 1F2 observations are potentially applicable across all Terry turbopump models.

Milestone 4 testing at TAMU has been completed for the ZS-1 and GS-2N performance curves under air and air-water mixtures. Steam and steam-water testing on the ZS-1 fell under Milestone 4. Turbine performance was largely characterized by torque-speed-pressure-moisture content data/curves. The collected test data provided benchmark results for MODSIM efforts. If required, the test data could be used to make corrections to MELCOR source code (physics models) and or input models. The single-phase air and two-phase air-water performance tests of a GS-2N operated as a GS-1 were the primary tests of interest. Note that a few tasks formerly filed under Milestone 4 were migrated to hybrid Milestone 5&6 and are discussed in its progress report section.

1.2.2. *Milestones 5 and 6*

See [20] for a more thorough description of the original Milestone 5, which was intended to pick up where Milestone 4 ended. Milestone 5 has been cancelled. Full-scale steam and steam-water tests are now beyond the scope of the TTEXOB program according to the revised goals of hybrid Milestone 5&6.

See [20] for a more thorough description of the original Milestone 6, which was intended to explore the hypothesized "self-regulating mode" of RCIC operation. Milestone 6 was conceptualized as consisting of either 1) scaled ZS-1 tests extrapolated to the GS-2N, or 2) full-scale testing with a GS-2N. The former option was supposed to draw upon a scaled proof-of-concept demonstration performed as part of TAMU tests under Milestone 4. Despite the cancellation of Milestone 6, some of the original intent is preserved by hybrid Milestone 5&6.

1.2.3. *Hybrid Milestone 5&6*

Hybrid Milestone 5&6 is a compromise aimed at replacing both Milestone 5 and Milestone 6. Hybrid Milestone 5&6 endeavors to explore – without full-scale steam and steam/water testing:

1. Scaling effects/factors, and
2. Terry turbopump self-regulation

Knowledge gaps include:

- Full-scale steam test data,
- Full-scale duration test with steam,
- Self-regulation (full-scale), and
- Impact of steam quality

To deal with the question of scaling effects/factors including full-scale steam test data and full-scale duration:

- GS Terry turbine data will be taken from power plant operation (various inlet pressures, 8 + hours of injection)
- Plant data will be compared to ZS-1 steam test data

To deal with the question of self-regulation, TAMU will run air/water tests with the GS Terry turbine. Possible effects of steam quality will be investigated by expert elicitation.

1.2.4. Milestone 7

The complete suite of MODSIM work complementing all other milestones – including hybrid Milestone 5&6 - is grouped together under Milestone 7. Details on Milestone 7 MODSIM pertaining to Milestones 3 and 4 can be found in [20]. Details on Milestone 7 MODSIM pertaining to hybrid Milestone 5&6 can be found in Section 3. MELCOR source code development and input model development is informed by the qualitative observations and quantitative data gleaned from experiments. It is possible that preliminary MELCOR predictions could feed back into the experimental design process. In FY20, Milestone 7 MODSIM for hybrid Milestone 5&6 was two-pronged:

1. MELCOR source code development, and
2. MELCOR input model development and improvement

2. HYBRID MILESTONE 5&6 PROGRESS – SCALING FACTORS AND SELF-REGULATION

As efforts for Milestones 3 (Full-Scale Separate-Effect Component Experiments) and 4 (Terry Turbopump Basic Science Experiments) concluded, the Turbo-TAG, in conjunction with SNL and INL, identified a suite of full-scale integral experiments required to 'fill in' the remaining parts of the program. Milestone 5 was intended to provide full-scale steam test data and Milestone 6 was intended to study the self-regulating capability of the Terry turbopump in context of an integral experiment. Despite the plans in place for full-scale tests, these milestones were cancelled due to diminished funding across the consortium entities as of (approximately) the beginning of FY20. At that point, there were a few options for moving forward to project conclusion, namely [21]:

- Cease without closing out (no further work or results documentation)
- Cease with closing out (more graceful termination, but with gaps pertaining to full-scale effects and self-regulation still open)
- Defer action on milestones 5 and 6 as they were planned
- Pursue an alternate strategy of addressing gaps targeted by Milestones 5 and 6

The first two options would incur minimal further costs but would jeopardize the integrity of the project as gaps (questions about the applicability of small-scale tests, for example) would remain open and any conclusions drawn about full-scale steam operation and/or self-regulation would come with a lower level of confidence. The option to defer entailed too much uncertainty in the present and a greater ultimate cost in the future if funding did come through for original Milestones 5 and 6. In all likelihood, deferring would have resulted in project cessation without future start-up (thus jeopardizing the integrity of the project due to remaining knowledge gaps). An alternate strategy known as hybrid Milestone 5&6 was the clear preference in view of the circumstances.

2.1. Milestone Overview

The essential goal of hybrid Milestone 5&6 as formulated by the consortium is to obtain a greater level of confidence with respect to the original issues of Milestones 5 and 6. Certain actions that incur comparatively small incremental costs could be taken in order to study scaling effects (original Milestone 5 goals) and self-regulation (original Milestone 6 goals). The components of hybrid Milestone 5&6 include:

- A short (3 to 4 month) experimental program exclusively conducted at/by TAMU with existing or gently modified apparatuses (ZS-1, GS-2 air facilities)
- Existing utility experience and resources to include full-scale Terry turbopump operational data (injection of various durations over various inlet pressures)
- ZS-1 steam data obtained by TAMU
- ZS-1 air and air-water self-regulation data obtained by TAMU
- Certain expert elicitation on the issue of the impact of steam quality

- A cost-mitigated spending plan detailing commitments of consortium members
- Milestone 7 type MODSIM activities targeted at:
    - Supporting the new experimental program and/or
    - Leveraging forthcoming experimental data
    - Scaling effects and self-regulation from a MODSIM perspective

SNL – as part of the TTEXOB consortium under the heading of DOE - is committed to completing hybrid Milestone 5&6. DOE (SNL and INL) was committed to account for 40% of the hybrid Milestone 5&6 funding. This included a $200,000 transfer in FY20 to TAMU in support of the experimental program. SNL helped to meet this DOE obligation by diverting some of its FY20 funds originally allotted for Milestone 7 MODSIM activity.

SNL technical staff has been in regular communication with TAMU throughout FY20 in order to consult on the experimental program. SNL involvement has been somewhat limited given exigent circumstances imposed by the COVID-19 pandemic. The original plan was to lend SNL technical support in the form of short-term staff visits during the experimental phase of hybrid Milestone 5&6. However, SNL technical staff was relegated to a remote support role (due to severely limited travel options) as of March FY20 before the hands-on experimental program began. Should circumstances change, SNL technical staff would reevaluate options for in-person visits and experimental support.

The period-of-performance for SNL as it pertains to hybrid Milestone 5&6 was recently extended well beyond the conclusion of FY20 (tentatively to March of FY21) at no extra cost. Thus, SNL will continue to lend support to TAMU/industry in some form as the experimental program winds down.

2.2. Milestone Progress

Certain tests now included in Hybrid Milestone 5&6 had previously been categorized as part of Milestone 4; this is primarily the steam testing of the Terry ZS-1 turbine at Texas A&M University. The steam testing planned under Milestone 4 included a suite of turbine profiling tests corresponding to those previously conducted with air and air/water mixtures as well as a proof-of-concept test for the demonstration of a self-regulating mode of operation. The planned tests have been expanded upon from their originally envisioned conditions to include tests identified as needed by non-dimensional analysis to fill in data gaps. The self-regulation tests will now proceed with an expanded scope and will explore more of the operating space for the ZS-1 much in the way of the extended testing proposed in FY19 [20].

In addition to the steam tests, scoping work has been performed on the feasibility of performing uncontrolled air/water feedback in the same manner as with steam and water, with the key difference being scale. Should it prove feasible with the existing budgetary and time limitations, the Turbomachinery Lab at TAMU will perform air/water uncontrolled feedback testing on a Terry GS-2N adapted to operate as a GS-1; the air/water testing would be comparable in design and operation to the steam/water test loop.

Construction on the steam test loop in the Laboratory for Nuclear Heat Transfer Systems (NHTS) at TAMU was near completion in late Q1 of CY20, and was able to complete a preliminary set of sanity-check shakedown tests. At that point, Milestone 3 testing for the ZS-1 heated oil/bearings was completed and final testing of the GS-2 heated oil/bearing assembly was underway. While the final Milestone 3 tests were able to be completed, the COVID-19-related shutdowns, social distancing, and travel restrictions eliminated any chance for on-site assistance at TAMU from SNL and caused delays in bringing the steam testing facility online. Long-term on-site support at TAMU from SNL had ended in late November 2019, with the intention of switching to more focused short-term support visits. As a result, steam-based shakedown tests were not performed until mid-Q3 of CY20.

2.2.1. Final Milestone 3 Work

The completion of the main remaining Milestone 3 tasks enabled researchers to focus their efforts on Hybrid Milestone 5&6 tasks. In late FY19, the remaining Milestone 3 testing included heated oil characterization, ZS-1 bearing tests, and GS-2 bearing tests. In addition, the free/impinging jet and related testing performed at TAMU's Thermal-Hydraulic Research Laboratory, while largely complete, has continued to have results disseminated in relevant publications. The facility has undergone maintenance intended to retain the capability to perform add-on or ad-hoc testing needed to fill in any knowledge gaps so identified by the TTEXOB.

A battery of tests was run with a Terry ZS-1 turbine driven by an electric motor to explore the shaft bearing and oil performance under adverse conditions. The turbine was driven entirely by the motor via computer-controlled Variable Frequency Drive (VFD) electronics rather than by working fluid (air or steam) flow; the mating process connections were blocked off and the turbine's mechanical governor was removed. Electric immersion heaters and associated control electronics were employed to maintain desired temperatures in the oil reservoirs.

By operating the ZS-1 bearing test assembly with multiple oil temperatures up to 121 °C and a range of rotating speeds (both forward and reverse) while measuring the motor torque needed to maintain steady-state rotation, parasitic loss profiles were developed. Even at the highest tested oil temperature, the selected oil was able to maintain a stable wedge in the journal bearing as well as a trend of increasing temperatures leading to decreasing parasitic losses. In addition, the forward vs. reverse operation was able to identify the buckets in the turbine wheel as significant contributors to windage losses. Tests were performed with fresh oil as well as oil that had undergone a limited amount of pre-test degradation; no measurable performance difference was identified between the fresh and pre-degraded oil tests.

The GS-2 bearing test assembly was essentially a larger version of the ZS-1 assembly, and took the operating experience gained from the ZS-1 assembly into account. While multiple oil temperatures were tested, the battery of tests was substantially different and focused on wear on the bearing surfaces; only one steady-state rotation rate was employed. After the complete battery of tests was performed, only slight wear was seen on the bearings and appeared to be the result of the high number of start-stop cycles rather than continuous operation at high temperatures.

In both the ZS-1 and GS-2 tests, oil samples were taken before and after each test. Characterization tests (e.g., acid number, NMR and IR spectroscopy) were performed in the Petroleum Engineering department at TAMU. The tests found that, while the oil had darkened, there was little to no permanent degradation in its composition that would affect its ability to lubricate.

2.2.2. *Hybrid Milestone 5&6 Test Facilities*

The steam test loop in the NHTS laboratory at TAMU, designed to run the originally planned Milestone 4 steam/water tests, was completed in FY20 and has performed its initial shakedown testing. This includes the pipework, instrumentation, insulation, and support system installation and maintenance. It also includes the calibration of instruments, connections to the data acquisition (DAQ) system, completion of the DAQ software, and the development and vetting of initial operating procedures. Shakedown testing identified and corrected standard issues (i.e., leaky pipe fittings), and there were no critical/showstopper issues in the facility (those that would prevent testing without major facility redesigns or rebuilds).

The test facility is designed to be easily switchable between the different tests and operational modes explored under the Hybrid Milestone 5&6 test suite. The configuration difference between uncontrolled feedback and pump-based profiling tests, for example, is the alignment of a few relevant valves. It is also intended to be a relatively quick realignment to switch between a pump mounted to the turbine and a dynamometer. An oversimplified piping and instrumentation diagram (P&ID) of the test loop, given in Figure 2.1, illustrates this concept: by alternating the position of the valves downstream of the turbine-driven pump, one can select between an uncontrolled feedback (self-regulating mode) test and a test using the pump as a turbine load (additional unshown pathways exist in the facility to regulate the steam quality to the desired value in this mode). The test facility is instrumented for pressure, temperature, and flow in a number of locations. In addition, the turbine output torque and speed are measured.

In addition to the steam testing in the NHTS Laboratory, a full-scale test facility is under development for uncontrolled feedback testing. This will be operated in the Turbomachinery Laboratory at TAMU under Dr. Adolfo Delgado using air and water. It will leverage the GS-2N turbine tested in Milestone 4 as well as the techniques and existing facilities constructed for the Milestone 4 tests, and the final test loop design is anticipated to resemble the concepts presented in [20]. Both the ZS-1 and GS-2N tests under Hybrid Milestone 5&6 will have their test matrices informed by the data gaps identified by the TTEXOB consortium.

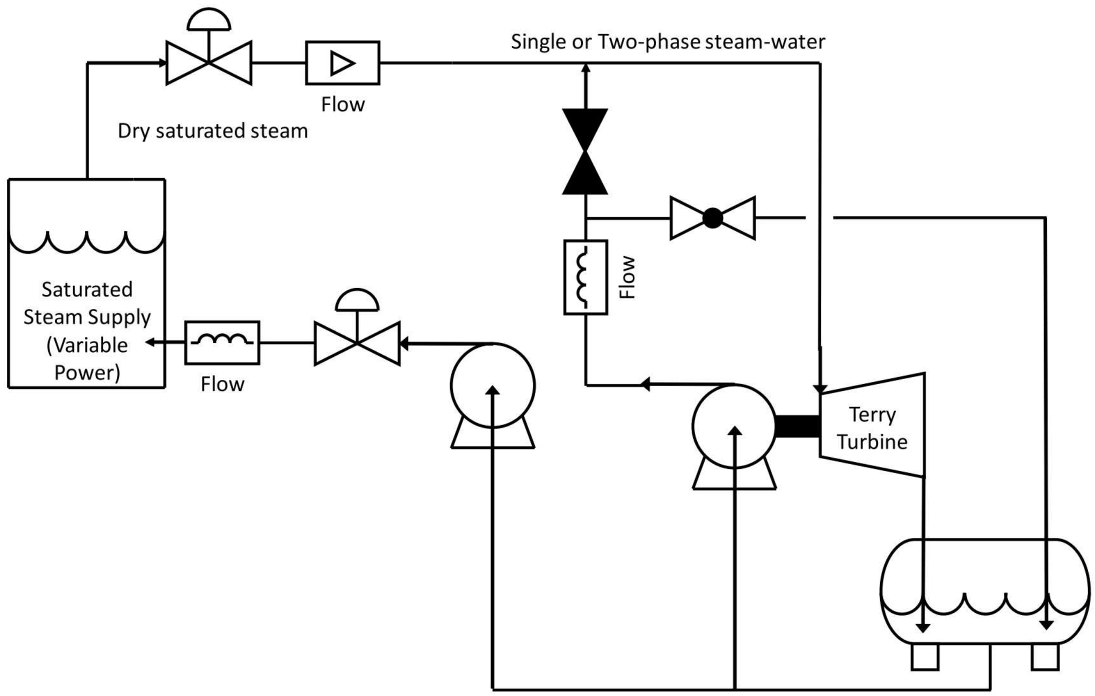

Figure 2.1: P&ID of TAMU ZS-1 Test Loop

2.2.3. Hybrid Milestone 5&6 Analytical and Expert Elicitation Efforts

With the abandonment of full-scale steam testing, it was determined that heavy reliance on the smaller-scale ZS-1 testing could result in a data gap if there was not a physical basis for scaling the data from the ZS-1 to a GS-size system. While the turbine affinity laws provide a basis for comparison, the geometric differences and any fluid property differences between test cases and plant conditions may necessitate incorporation of additional scaling factors. Any such factors would be applied to the affinity law calculations in order to fully scale the collected ZS-1 data and make it applicable to operating conditions in a plant.

Fortunately, several nuclear power plants have kept excellent operational records of normal and transient operations of their RCIC/TDAFW systems and have made that data available to the TTEXOB project.

MPR Associates, under contract with EPRI, has analyzed the plant data and cast the set into turbine affinity law curves based on their respective operating conditions. These curves were then compared to dry air-based ZS-1 curves from the Milestone 4 data collected at TAMU. It was found that the ZS-1 air and plant steam curves did not align and that a scaling/correction formulation was required. Further analysis revealed that the typical plant turbine and the ZS-1 employ nozzles with different expansion ratios, and that the inclusion of a new geometrical scaling term in the affinity law formulation based on the nozzle expansion ratio brought the non-dimensional affinity law curves into approximate alignment.

Additional inspection of the aligned curves indicates that, while an approximate alignment in the curves was shown, the ZS-1 test data was somewhat sparse in the region of greatest interest and may constitute a data gap. As a result, TAMU will perform additional tests concentrating in the area of greatest interest to remedy the sparseness of the currently available data. The testing will also work toward providing sufficient support in recorded data for the improvement of the geometric scaling terms applied to the affinity law analysis.

2.2.4. Remaining Experimental Tasks

To complete the Hybrid Milestone 5&6 tasks and close out the experimental data collection work under the TTEXOB program, several tests remain. These include both the remaining Milestone 4 tasks that now fall under Hybrid Milestone 5&6 as well as the new tasks from the Hybrid Milestone and enhancements of the previously planned Milestone 4 work. These tasks are currently identified to include:

- ZS-1 steam/water dynamometer profiling (torque vs speed, pressure, and steam quality curves akin to those generated for air/water mixtures)
- ZS-1 steam/water performance with the turbine loaded by a pump
  - o Uncontrolled (self-regulating) feedback performance
  - o Limited performance profiling tests similar to the dynamometer profiling
  - o Limited dynamic/transient tests, i.e., response to step-changes in interfacing conditions
- GS-2 air/water self-regulating tests as requested by the TTEXOB consortium
- Any additional testing needed to fill in the remaining data gaps/sparseness and support the scaling factors, as identified by the TTEXOB consortium

These tests - including data analysis and reporting - are scheduled for completion in FY21.

3. MILESTONE 7 PROGRESS – MELCOR SYSTEMS-LEVEL MODELING AND SIMULATION

MODSIM activities falling under Milestone 7 for FY20 fall into one of two categories: MELCOR source code development and MELCOR input model development. Source code development refers to an addition of:

- Mathematical/physics model(s) to capture physical phenomena, or
- Code capabilities to expand modeling options and/or increase user convenience

Input model development refers to construction of a MELCOR input model meant to represent a given physical system, e.g. an experimental facility or a boiling water reactor (BWR). Input development also encompasses any control logic required to impose a particular experimental condition or plant transient.

A considerable amount of MELCOR source code development aimed at Terry turbopump physics has occurred in recent years (since FY14). However, Milestone 7 MELCOR modeling activities through FY19 did not incorporate those features, and the TTEXOB program has had only limited exposure to them over the last several years. An overview of previous (FY14-FY19) and recent (FY20) source code development activity is given here because FY20 input models use the new systems-level Terry turbopump models/capabilities in order to model both experiments and representative nuclear power plants.

Through FY19, Milestone 7 MODSIM work (complementing Milestone 3 and Milestone 4) entailed MELCOR input development exclusively. No new systems-level turbopump models were used to perform those analyses. Rather, MELCOR capabilities in the form of user-programmed control function (CF) sequences were leveraged to model the Terry turbopump. SNL built input decks and generated code predictions for TAMU experiments (GS-2 air tests, ZS-1 tests) and for a representative 1F2 plant model. The outcomes of previous MELCOR analyses are reviewed here as they had implications for FY20 Milestone 7 MODSIM activities.

FY20 Milestone 7 MODSIM activities are also detailed here. They focused on:

- Developing a generic BWR input model (for risk-informed decision-making)
    - Using latest MELCOR models/capabilities
    - Considering lessons learned to date from TAMU experiments
    - Preserving lessons learned from past plant models (e.g. 1F2 input model)
- Updating/Improving existing TAMU ZS-1 and/or GS-2 (air) input models
    - Anticipating certain experimental data
    - Leveraging new systems-level Terry turbopump models/capabilities
    - Preserving lessons learned from past ZS-1/GS-2 input models

3.1. MELCOR Source Code Development

Beginning in FY14, an independently-funded effort was undertaken – as a complement in parallel with the TTEXOB program - to develop new MELCOR physics models meant to represent the various components of the RCIC Terry turbopump. The models – though designed with the RCIC/TDAFW systems in mind – improved the general usefulness and capability of the MELCOR code. While model development was in progress, the TTUG, the BWR Owners' Group (BWROG), and the TTEXOB consortium were generally made aware of the new MELCOR capabilities including their performance and predictive capability.

3.1.1. Overview of Terry Turbopump Model Development (through FY19)

To briefly review the order of model development and implementation: First, a homologous pump model was added. This was useful for modeling centrifugal pumps, e.g. the RCIC/TDAFW pump. Then, pressure-stage and velocity-stage models for a Pelton/Terry-type turbine were added. These were useful for representing steam/water-driven turbines, e.g. the RCIC/TDAFW turbine. These sets of models were coupled by a rigid shaft model that enabled a torque-inertia solution for rotor/shaft/impeller synchronous angular speed considering all possible terms/inputs from the pump and turbine. This was useful for uniting the RCIC/TDAFW pump and turbine models so as to represent a steam-driven turbopump, i.e. the primary feature of the RCIC system. This section recounts the noteworthy aspects of systems-level RCIC physics model development from approximately FY14 through FY19.

3.1.1.1. Homologous Pump Model

A homologous pump model was integrated into the MELCOR flow path (FL) package to predict the attending fluid momentum source (pressure head) of a centrifugal pump as a function of the pump impeller speed and the pump capacity (volumetric flow). The model also computes hydraulic torque (indicative of the brake power), pump friction torque, pump inertia, and pump energy dissipation (and thus efficiency). The homologous pump performance model therefore predicts the "brake power" (proportional to hydraulic torque) and the "hydraulic power" (proportional to the product of head and flow), with the difference between the two being the pump dissipation energy. Pump inefficiencies are "baked-in" to the pump performance model, but user input of rated conditions can account for extra inefficiencies if necessary.

The new MELCOR homologous pump model includes a polar homologous pump curve representation and a "universal correlation" that basically allows a centrifugal pump – operating in its normal mode – to be modeled even when a full set of homologous data is unavailable. Additionally, pump data from both the Semiscale and Loft experiments are available as "built-in" performance curves.

Several new input records have been added that allow the user to specify:

- Rated pump conditions,
- Single/two-phase pump performance via homologous curve input,
- Pump friction torque,
- Pump inertia,
- Pump speed and motor torque controls (to include connections to shaft/turbine)
- Pump trips,

- Pump numerical treatment options

Extensive mathematical details and a more comprehensive modeling description can be found in [23],[24].

3.1.1.2. Terry Turbine Pressure Stage Model

The pressure stage model treats the flow of steam (dry saturated or superheated) or of a noncondensable gas mixture (e.g. air) through converging/diverging nozzles as are present in the Terry turbine. Without specialized models for these phenomena, the user is relegated to the existing MELCOR critical flow model or some other user-supplied prescription (e.g. experimental data, CF side models, etc.).

Steam nozzle flow is modeled as either an isentropic expansion or – in an attempt to account for certain potentially important two-phase and irreversibility effects - as a sequence of expansion processes:

- An isentropic expansion from the nozzle inlet through the throat and to a point where condensation heat release begins to introduce entropy
- A Rayleigh flow process between the end of the last isentropic expansion and the Wilson point (point of maximum nucleation, maximum steam super-saturation)
- A Rayleigh flow process between the Wilson point and the point of full reversion from thermodynamic non-equilibrium (re-establishment of saturation)
- An isentropic expansion between the end of the last Rayleigh flow process and the nozzle outlet with provision for standing normal shocks
- A standing normal shock (over-expanded flow with respect to back-pressure) or a jet expansion (if under-expanded flow with respect to back-pressure)

Noncondensable gas mix nozzle flow can assume one of several flow configurations:

- Isentropic, subsonic flow with choking
- Isentropic, subsonic flow without choking
- Fully-expanded isentropic flow
- Over-expanded isentropic flow
- Under-expanded isentropic flow
- Non-isentropic flow

Whatever the nozzle flow conditions, the effluent jet velocities can be fed into the Terry turbine velocity stage model so as to compute an impulse exerted on the turbine rotor. Extensive mathematical details and a more comprehensive modeling description can be found in [24].

3.1.1.3. Terry Turbine Velocity Stage Model

The Terry turbine compound velocity stage model is based on a control-volume angular momentum balance approach originally proposed for Pelton turbine analysis. This is the same formulation upon which the previous MELCOR MODSIM CF input models are based. When the formulation is built into the code, however, the use of such a model is more straightforward for any given user. The model is also more generalized relative to the CF side model but preserves all the capabilities one requires to build in a similar level of detail. Extensive mathematical details and a more comprehensive modeling description can be found in [24].

3.1.1.4. Rigid Turboshaft Model

The shaft torque-inertia equation represents the rigid coupling between the driving turbine rotor on one end and the following/resisting centrifugal pump impeller on the other. Shaft speed is computed as a function of torques exerted on the shaft by the turbine (typically in a "positive" direction as flow impinges on rotor buckets) and on the shaft by the pump (typically in a "negative" direction as pumped fluid resists the impeller). The resistance of the pumped fluid is "felt" immediately on the turbine side via the rigid shaft. In addition to the driving turbine rotor torque and resisting pump torque, some peripheral quantities like moments of inertia, friction torques, and extra CF-specified pump/turbine torques require user definition. Extensive mathematical details and a more comprehensive modeling description can be found in [24].

3.1.2. Recent Code Development Activities (FY20)

New developments for the RCIC systems-level models include strategic expansions of user capabilities and miscellaneous add-ons deemed advantageous for some purpose. This section recounts the noteworthy aspects of systems-level RCIC physics model development for FY20. Note that all capabilities developed during FY20 are scheduled for public release (to the licensed MELCOR user base) in late FY20 or early FY21.

3.1.2.1. Extra User Torque Term (Pump and Rotor)

To ensure that lessons and data gathered from experiments can be directly and conveniently incorporated into the systems-level RCIC models, extra CF-specified torque terms (one for the pump, one for the turbine) were added. These terms intervene at the point where the rigid shaft torque-inertia equation is solved. General parasitic loss terms for which there is no specific allowance can now be incorporated into the RCIC turbopump calculations. The CV_REX (turbine/rotor) and CV_PEX (pump/impeller) records [23] were added to help define the extra user torque terms.

3.1.2.2. Sensitivity Coefficients for Turbine Torque Multiplier and Windage Torque Term

Milestones 3 and 4 furnished an experimental data set that was previously incorporated into MELCOR input models via use of a turbine torque multiplier (applied directly to the computed rotor torque) and use of a windage torque term. These aspects of the input model were again incorporated as part of the CF model and previously had no special allowance in the system-level RCIC models as originally developed.

To allow for a turbine torque multiplier, a single constant sensitivity coefficient (SC) value (SC #4502) was added to the control volume hydrodynamics (CVH) package database [23]. This SC can be changed according to user input and is applied to the turbine torque as computed from the systems-level velocity stage Terry turbine model. A default SC4502 value of 1.0 is assumed.

To allow for a turbine windage torque term, a set of SC values (elements of SC #4503) were added to the CVH package database [23]. The elements of this SC together comprise a polynomial function of rotor speed whereby a windage torque term may be computed. Default

SC4503 values are assumed according to findings from the FY19 experimental data and MELCOR input models.

3.1.2.3. Independent Turbine Operation Mode

To more easily model TAMU experiments under the hybrid Milestone 5&6 program, SNL developers and modelers determined it would be useful to allow a MELCOR systems-level model wherein a turbine may be defined without connection to a homologous pump object. Instead, the code would allow a user-supplied CF stand-in such that, for example, torque data from the dynamometer in the TAMU ZS-1 experiment could be more readily incorporated into the input model. This development task is complete and is being tested in-house by SNL MELCOR modelers.

3.2. MELCOR Input Model Development

MELCOR input models represent a variety of nuclear and non-nuclear systems. Properly configured, they generate predictions of thermal-hydraulic response under steady or transient conditions. MELCOR is generally concerned with radionuclide transport and source term generation but is deployed in this instance for its thermal-hydraulic modeling capabilities which align with an integral, systems-level modeling approach and philosophy.

Through FY19, several MELCOR input models were developed to support Milestone 3 and 4 TAMU experiments, to investigate experimental findings, to identify knowledge gaps, to explore uncertainties, and to ascertain their relative importance in context of an integral analysis. Additionally, MELCOR input models representing nuclear power systems were built to reproduce real-world accident conditions and to learn lessons about code performance and/or accident progression. All MELCOR input models through FY19, however, did not avail themselves of the latest systems-level RCIC models. They resorted instead to user-programmed CF models that suffered from two distinct disadvantages:

- They were not standardized by a formal collection of input structures, and
- They were impenetrable to scrutiny from all users besides the original modeler as they consisted of complicated, interconnected sequences of dozens of CFs

Key takeaways from MODSIM activity through FY19 are reviewed here.

The FY20 MODSIM agenda for Milestone 7 in terms of MELCOR input model development focused on complementing the experimental program of hybrid Milestone 5&6. Previous MELCOR input models (through FY19) that could still reasonably find application given the hybrid Milestone 5&6 agenda were revised and updated to utilize best practices plus the new systems-level RCIC models. As such, the TAMU GS-2 (air) and ZS-1 (air, air/water, steam, steam/water) input models were revised/updated. The 1F2 input model was developed no further. However, a generic BWR input model was developed to demonstrate the new systems-level RCIC models in context of a best-estimate PRA study for risk-informed decision-making. This particular product is more generally useful (e.g. than 1F2) for several reasons:

- Model shake-down in context of a full reactor model (improves code robustness)
- Lays a foundation for future studies (best-estimate, risk-informed approach)

  - Industry investigating operating procedures or accident management
  - Regulators investigating the level of credit to grant RCIC/TDAFW (perhaps moving away from severe, conservative assumptions)
- More general demonstration of capabilities that users can adapt to fit needs

Key points of the FY20 MODSIM activities are summarized here.

3.2.1. Overview of Modeling and Simulation Activities (through FY19)

By way of review for SNL MODSIM activities:

- 2015
  - Initial MELCOR input development
  - SNL Solidworks and computational fluid dynamics (CFD) work (Fluent)
- 2016-2018
  - Solidworks and Fluent computations ongoing
  - MELCOR input developments for 1F2, TAMU experiments
  - Analyses to support full-scale testing plan
  - TAMU ZS-1 input model (CF Terry turbine model)
- 2019
  - TAMU ZS-1 and GS-2 (air) input models (CF Terry turbine model)
  - 1F2 input model (CF Terry turbine model)

In FY18, the TAMU ZS-1 input model (CF Terry turbine model) was developed. A main takeaway from MELCOR modeling of ZS-1 experiments was that rotor losses (friction and wheel windage) may be larger and more consequential than initially anticipated. This has obvious implications for the 1F2 model or any other RCIC/TDAFW applications.

In FY19, the TAMU experimental program called for development of a MELCOR GS-2 input model that used air in its turbine. The input model was in several ways similar to that of the ZS-1, but some of the turbine characteristics were different (bigger turbine wheel, different nozzles).

3.2.2. Input Development for TAMU GS-2 and ZS-1 Experiments (FY20)

FY20 input development for the TAMU GS-2 and ZS-1 experiments builds on the work completed in FY18 and FY19. The work during previous years represented Terry turbine physics/torque with a user-specified CF sequence representing a system of equations expressing conservation of angular momentum, as described briefly in Section 3.2.2.1. The FY20 modeling updated the input to utilize the MELCOR systems-level RCIC capabilities, and these changes are discussed in Section 3.2.2.2. Near-future MELCOR ZS-1 input model development will take advantage of new code capabilities to better approximate the TAMU experiments (dynamometer loading). The independent turbine operation capability will be utilized as developed in MELCOR source during FY20. These plans are presented in Section 3.2.2.3.

3.2.2.1. Overview of Previous (FY18 and FY19) Modeling

Section 3.2.1 briefly discussed modeling and simulation activities through FY19 for the TTEXOB. These activities included system-level MELCOR modeling in FY18 and FY19 of the ZS-1 and GS-2 Terry turbine airflow experiments that were performed at TAMU. This modeling is discussed in detail during previous FY18 [19] and FY19 [20] TTEXOB progress reports. During FY20, the MELCOR input decks originally developed for the FY18 and FY19 modeling of the TAMU ZS-1 and GS-2 Terry turbines were updated to include new model and input developments.

A visual representation of the FY18 and FY19 MELCOR modeling of the ZS-1 and GS-2 TAMU experiments is shown in Figure 3.1. The air/water tests were not modeled; however, the input was developed so these experiments could be modeled in the future. The following methodology was used for modeling the TAMU airflow experiments. For a given flow condition, air tank pressure and temperature were set according to the experimental values. The water source was isolated by specifying a valve open fraction of zero. The air tank valve open fraction was adjusted until the model mass flow rate matched the experimentally observed value. Once these matched the experimental values, the model's Terry turbine representation was brought up to speed. The modeling used the experiment's dynamometer peak resistive torque to load against the Terry turbine inertia.

The FY18 and FY19 Terry turbine modeling used a set of control functions to represent the Terry turbine and to express conservation of angular momentum. Equations 3.1, 3.2, and 3.3 show the control functions for the raw torque, windage losses, and net torque developed by the turbine.

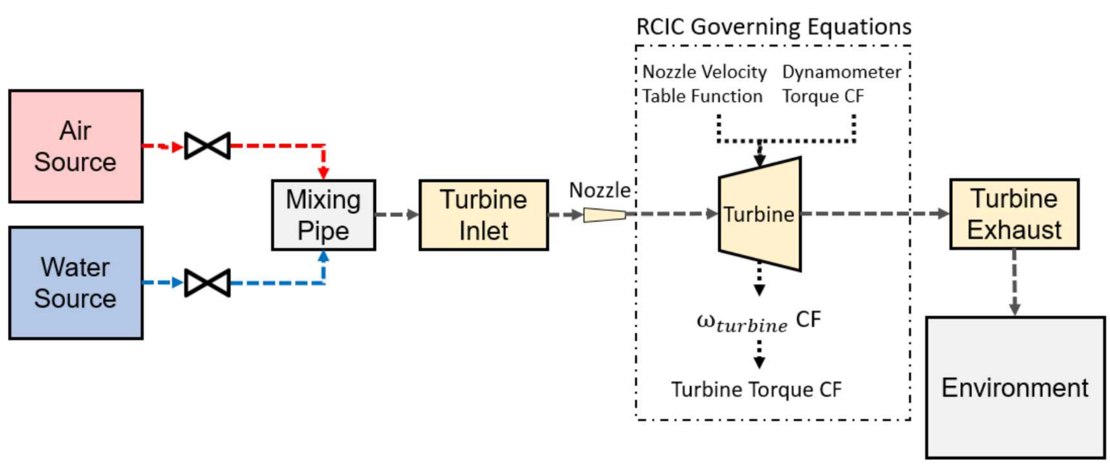

Figure 3.1: MELCOR Model of TAMU Experiment With CF-Based Terry Turbine

$$torque_{raw} = r \times \dot{m} \times c_{torque} \times \left[(V_{in} - V_{out})\cos(\alpha) - 2r\omega\right] \tag{3.1}$$

$$windage = c_{windage} \times \omega^2 \tag{3.2}$$

$$torque_{net} = torque_{raw} - windage \tag{3.3}$$

In Equations 3.1, 3.2, and 3.3, r is the turbine radius, $\dot{m}$ is the mass flow rate of the air jet through the steam nozzles, c_{torque} is a multiplier used to scale the raw torque to match the net torque data, V_{in} and V_{out} are the velocities of the air jet entering and leaving the turbine buckets (respectively) determined by a table function look-up, α is the incident angle of the air jet relative to the incident angle of the turbine wheel, ω is the angular velocity of the turbine wheel, and $c_{windage}$ is a loss coefficient scaling the turbine wheel windage. The net torque developed by the turbine is the combination of the raw torque and the windage terms.

The FY18 and FY19 modeling identified the following coefficients for the raw turbine torque and the windage losses:

Table 3.1: ZS-1/GS-2 Coefficients for Raw Torque and Windage Losses

Turbine	Torque Coefficient c_{torque}	Windage Loss Coefficient $c_{windage}$
ZS-1	2.32	4.50×10^{-7}
GS-2	2.53	3.07×10^{-7}

3.2.2.2. Recent Input Development (FY20)

The FY20 modeling replaced the mechanistic/control function representation of the ZS-1 or GS-2 Terry turbine with a Terry turbine model object. The updated MELCOR geometry nodalization is shown in Figure 3.2.

The Terry turbine rotor model object is similar to the control function representation as the rotor object torque is determined by the conservation of angular momentum; however, the Terry turbine model is different from the control function representation, with one of the key differences being that the Terry turbine model object can determine the jet/bucket velocities by modeling the flow through a converging/diverging nozzle as a sequence of expansion processes. The original control function representation relied on table look-ups to determine the velocity of the jet entering/exiting the turbine buckets. The Terry turbine rotor object is specified by the CVH block in the input deck for the RCIC control volume. Reference [23] contains documentation of the Terry turbine model input specification, with key aspects described below as they relate to the input development for the ZS-1 TAMU Terry turbine airflow test modeling.

- The CV_ROT card specifies a single rotor with a single steam nozzle (ZS-1 only has 1 nozzle), 2 reversing chambers, and the turbine radius as 0.2286 m (9").
- The CV_RIN card specifies a polynomial expression of the turbine moment of inertia. This polynomial will need to be readdressed in the future. Inertia was given an estimated initial value of approximately 10 kg-m^2.
- The CV_RFR card specifies a polynomial expression of the turbine friction torque as a function of the turbine speed. During previous modeling, turbine friction torque was specified using a control function with turbine speed as an input.
- The CV_RBE card sets the Terry turbine bucket angle as 30º.
- The CV_NFP card specifies the flow path of the steam nozzle(s) that injects into the Terry turbine control volume.
- The CVH_SC card can be used to add a polynomial expression for the raw torque and the windage losses. The expressions, which are described in Section 3.1.2.1, can be used to create multipliers on the raw turbine torque and the turbine windage, which are analogous to c_{torque} and $c_{windage}$ in Equations 3.1 and 3.2.

Additionally, the Terry turbine rotor object in MELCOR is coupled to a pump object. It should be noted that the experiments did not include a pump in the system, but the pump object is currently needed in the analysis for the Terry turbine rotor object to function correctly. A "stand-in" homologous pump object was added to the input. The homologous pump object was given generic input values and was coupled to the Terry turbine by specifying the Terry turbine rotor in the FL_TSH card of the FL block in the MELCOR input deck. Figure 3.2 shows the homologous pump object control volume as well as the upstream and downstream control volumes for the pump object. The upstream control volume is a large reservoir of water, which is transported by the homologous pump to the environment.

The addition of the sensitivity coefficients to the CVH_SC card enables a more direct comparison of the FY18 and FY19 modeling to the planned modeling using the current input developments. Most notably, it allows the coefficients presented in Table 3.1 to be incorporated into the current modeling, which uses the Terry turbine rotor object. Once this modeling is completed, the results can be compared the FY18 and FY19 modeling, which used the control function approach to model the Terry turbine rotor physics.

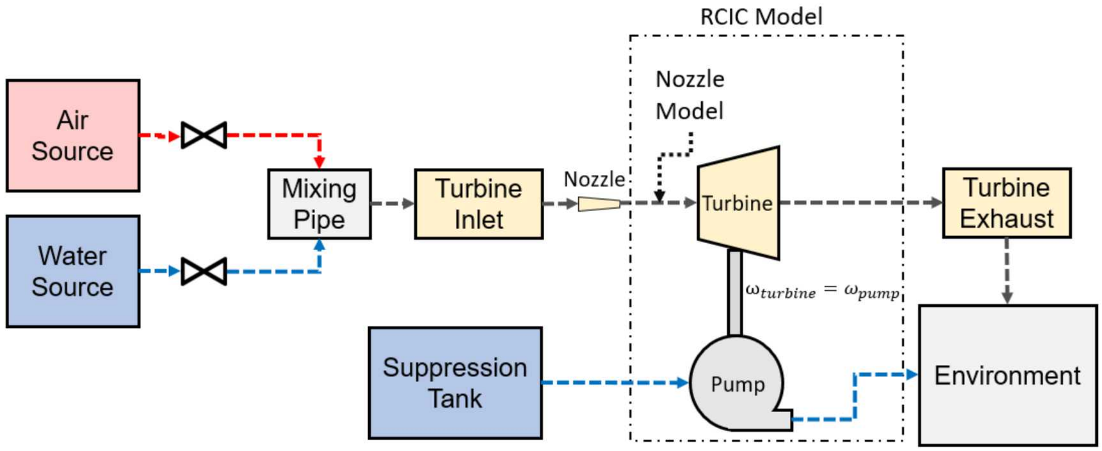

Figure 3.2: Revised/Updated MELCOR Model of TAMU Experiment

3.2.2.3. Future Input Development

Input development plans include removal of the homologous pump object entirely from the TAMU ZS-1 and GS-2 models. Via the independent turbine capability, a user supplied CF will be connected to the Terry turbine object in lieu of a pump object. This independent turbine operation mode is simpler to implement and as well as more analogous to the experimental configuration. By removing the homologous pump in this instance, it removes several unknown parameters that need to be determined to specify a pump with the same "loading" on the pump-turbine turboshaft as the dynameter that existed in the experiment. As there is coupled feedback between the pump and the turbine objects transferred by the turboshaft, removing the pump object in this instance removes the coupled feedback mechanism and allows direct specification of the resistive torque maintained by the dynamometer during the course of the experiment. Figure 3.3 shows the MELCOR nodalization after the planned input and model development updates, which removes the need for a homologous pump object to be coupled to the RCIC turbine.

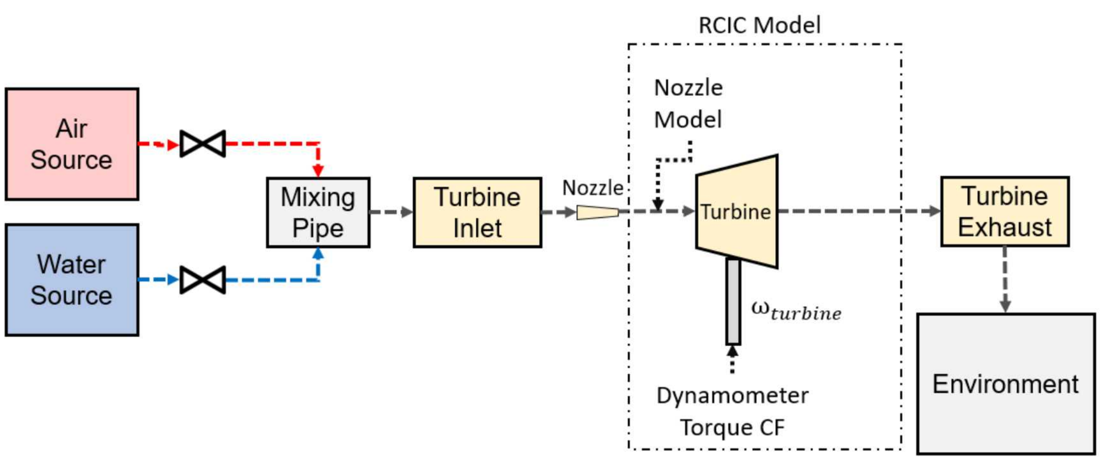

Figure 3.3: MELCOR Model of TAMU Experiment in Independent Turbine Mode

Planned modeling with these updates will include modeling of the TAMU airflow experiments and comparison to the previous modeling that used the CF approach to specify the RCIC turbine. Additionally, newly determined coefficients for the raw turbine torque and the windage losses can be compared to those determined with the CF approach. During FY19, these coefficients were determined as a major modeling unknown [20]. The coefficients are difficult to correctly determine as the primary known quantities from the experiment are the turbine upstream and downstream conditions (pressure, temperature, and mass flow rate), the peak dynamometer torque, the turbine speed, and the net turbine torque. As only the net torque quantity is known, this may make the coefficient pair for c_{torque} and $c_{windage}$ unidentifiable, i.e., there may not be an unique coefficient pair that will result in the experimentally observed net torque. However, by looking at different experiments performed by TAMU, we will have a better understanding of the coefficient behavior and how the coefficients influence the Terry turbine behavior in the system-level modeling.

3.2.3. Input Development for Generic BWR (FY20)

The generic BWR input deck is being developed for modeling various accident sequences, with an emphasis on capturing the behavior of the RCIC turbopump system. This includes input developments that allow the RCIC system to run without electrical controls in a self-regulating mode of operation. The generic BWR input has been developed extensively from the "base" input that it was originally based upon. These changes and other notable model sensitivity are discussed in this section. Once this input is further developed, it can be used to model accident scenarios/sequences of interest.

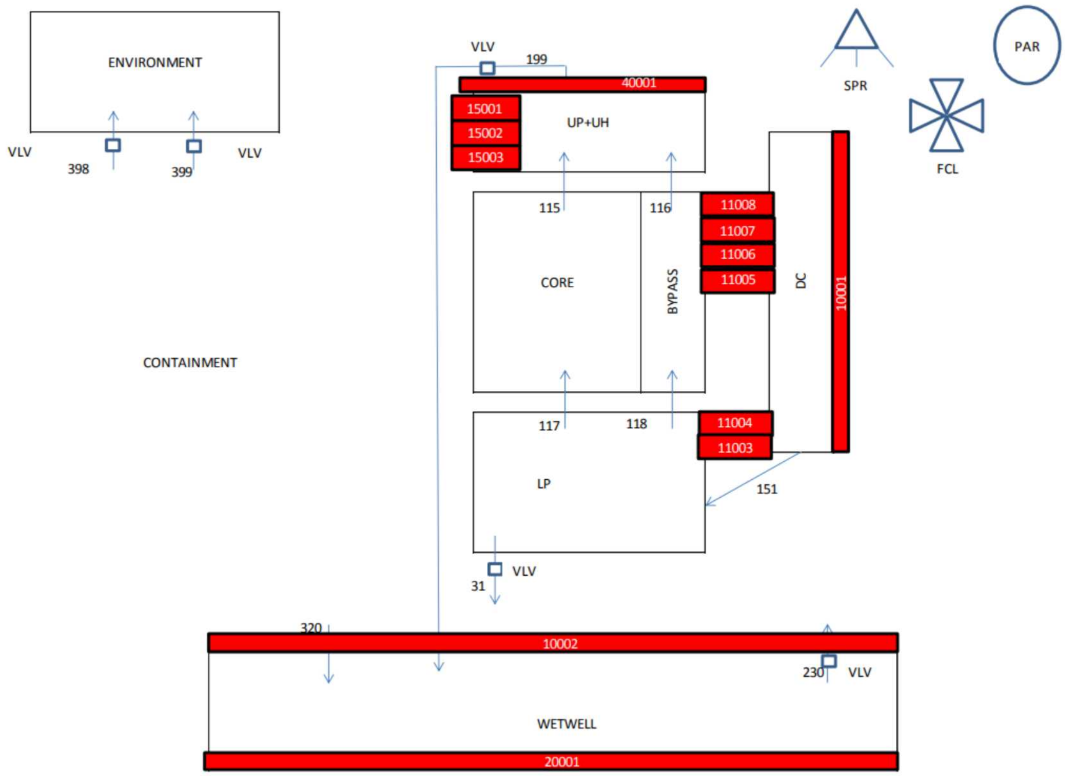

Figure 3.4: Generic BWR Nodalization With Emphasis on RCIC

The RCIC model for the generic BWR uses the recent MELCOR code developments described in Section 3.1.1 and 3.1.2. This is a notable change from the FY19 modeling, which used the mechanistic (i.e., CF driven) model for the RCIC system by coupling the pump motor torque to the mechanic RCIC turbine model's net torque control function.

The RCIC pump and turbine specifications are shown in Table 3.2. These specifications were taken from several sources to construct the generic BWR model, with the main source for the specifications being SAND2015-10662 [14]. These design parameters characterize the RCIC pump and turbine. The RCIC pump was specified to model two-phase pump performance via homologous curve input. The RCIC pump was coupled to the RCIC turbine model to control the pump speed and motor torque using the FL_TSH card in the input deck.

Table 3.2: RCIC Pump and Turbine Base Specifications

Parameter	Value
RCIC Turbine Specifications	
Turbine Radius	0.3048 m
Turbine CV Volume	0.106 m^3
Turbine Moment of Inertia	30.0 kg-m^2

Parameter	Value
Turbine Friction Torque	10.0 N-m
Turbine Bucket Exit Angle	30º
Turbine Nozzle Diameter	6.35 mm
Number of Nozzles	5
RCIC Pump Specifications	
Rated Pump Speed	4287.0 RPM
Rated Pump Head	7.59 MPa
Rated Pump Torque	448.8 MPa
Rated Pump Power	2.0147×10^5 W
Rated Pump Injection Rate	0.03886 m^3/s
Pump Moment of Inertia	30.0 kg-m^2
Other RCIC Related Specifications	
RCIC CF Target Injection Rate	38.733 kg/s
RCIC CF Target Relative Downcomer Level	2.54 m

During RCIC operation, RCIC flow to the Terry turbine is controlled by the trip and governor valves, which can open or close to admit or restrict RCIC flow. The trip and governor valve open fractions are determined by control functions. After an initiating event and reactor scram at time = 0.0 s, the RCIC turbine is actuated at time = 60.0 s by the trip valve opening. This represents operation actions being taken to manually actuate the RCIC system. The trip valve CF attempts to maintain the relative downcomer water level at 2.54 m below the steam line base to prevent flooding of the RCIC system. The governor valve open fraction is controlled by a CF and maintained at a nominal value until the RCIC pump begins to inject coolant. RCIC suction is originally aligned to the CST but will switch to the wetwell if the CST is depleted. After this, the governor valve open fraction is controlled by a CF to maintain the RCIC injection rate at approximately 38.733 kg/s by increasing or decreasing the valve open fraction.

During active control (prior to battery depletion), these two CFs dynamically control the flow into the RCIC turbine and attempt to maintain a relatively stable pump/turbine system. When the downcomer water level exceeds the target level, the trip valve open fraction decreased and the RCIC pump injection is ceased as the turbine torque transmitted through the turboshaft coupling is sharply decreased. The governor valve CF will only be dynamically updated when the pump is injecting water to the RPV, which prevents the governor valve opening to the full allowed open fraction when the trip valve is closed in an attempt to compensate for the decreasing pump injection. Once the downcomer water level decreases past the target level, the trip valve is opened again and RCIC will begin injection once again. The governor valve additionally has a maximum open fraction allowed at varying RPV pressures. This functionally was built into the CF to prevent the RCIC turbine from exceeding the turbine overspeed limit due to sudden changes in the RPV pressure.

Losses on the RCIC Terry turbine were introduced by including the extra torque term described in Section 3.1.2.1. This allows the turbine loss formulation to be directly controlled by the user.

During controlled operation of the RCIC system, RCIC will fail (and close the trip valve) if the system meets any of the following criteria:

- The main steam line pressure falls below 0.5171 MPa,
- The wetwell pressure exceeds 0.3447 MPa,
- The wetwell temperature exceeds 373 K if the RCIC suction is aligned to the wetwell, or
- The RCIC turbine speed exceed 5625 RPM

Control of the trip and governor valves ceases after battery depletion. In the generic BWR input deck, this is currently set in the input to occur at time = 2 hours.

Prior to modifications discussed in Section 3.2.3.1, the upon battery depletion, the trip valve CF would close to isolate the RCIC turbine and stop further RCIC injection. During FY20, the input was developed to introduce an uncontrolled (i.e., no battery powered controls) and self-regulating mode of operation for the RCIC turbopump system, which was assumed to have happened during the 2011 accident at 1F2 [13]. Modifications made to introduce this mode of operation are discussed below in Section 3.2.3.1.

3.2.3.1. Introducing RCIC Turbopump Self-Regulation

The RCIC system in 1F2 operated for an extended time period of up to 68 hours under various RPV pressures, poor steam quality, and with high lube oil and suction temperature values[13][14]. Data from 1F2 and modeling performed during FY19 [20] indicates that the Terry turbopump operated in a self-regulating mode, where the RCIC performance was driven by feedback from the RPV level without any electronic control feedback, which was unavailable due to the loss of station power.

The self-regulating mode of operation for the RCIC Terry turbine is believed to be controlled by the RPV level by the following mechanism. An increase in RPV water level resulted in degraded steam quality and flooding of the main and RCIC steam lines. This resulted in water entering the RCIC Terry turbine. The degraded steam and water being injected through the nozzles in the RCIC turbine resulted in diminished turbine performance and less torque being transmitted through the turboshaft to the pump, resulting in decreased pump injection of coolant. This caused the RPV water level to drop and decreased water entering the RCIC steam line, which led to the turbine performance increasing again, leading to increased injection and RPV water level, and so on.

To capture this dynamic feedback between the turbine/pump performance and the flow conditions, modifications were made to the input, which are described in this section.

Failure behavior of the RCIC system needed to be updated in order to develop the self-regulating mode of operation for the generic BWR model. Previously, four failure initiators for the RCIC system were identified for controlled RCIC operations. After battery depletion, only two of these failure initiators are "mechanical" in nature; these two failure initiators do not need electrical controls to cause the RCIC system to fail. These two failure initiators are:

- The wetwell temperature exceeds 373 K if the RCIC suction is aligned to the wetwell and
- The RCIC turbine speed exceed 5625 RPM

The wetwell temperature failure is caused by a net loss of positive suction head that will destroy the RCIC pump if the RCIC pump is aligned to the wetwell. The turbine overspeed failure is a mechanical failure built in to prevent destruction of the turbine due to operation at high turbine speeds. However, for the purposes of the generic BWR input development, the turbine was set not to fail if the RCIC turbine speed exceeded the overspeed limit. This was done for model development purposes as it is difficult to prevent an initial turbine overspeed when the governor valve open fraction CF increases to the maximum value. This modeling assumption will be readdressed at a later time while developing this input.

The trip and governor valves open fraction CFs fail to the "full-open" position after a loss of battery power. For the trip valve, this was set to 1.0, for the governor value, this was set to 0.7869, which was the value used during the FY19 modeling to restrict the governor valve flow area to the area calculated from CAD drawings. The governor valve CF was set to increase to the full-open position over a time ranging a few seconds. This was implemented to attempt to prevent an initial overspeed of the Terry turbine due to a sudden increase of admittance to the turbine nozzles. However, an overspeed was still observed in the modeling.

Figure 3.5 shows an example of the RCIC turbine speed before and after modifications were made to the input to implement a self-regulating mode. Prior to the modifications, it can be observed that at time = 2 hours (when the batteries deplete), the RCIC turbine is totally isolated. If the turbine had a non-zero speed at this point, its behavior would be to coast down to a stand-still after the turbine was isolated, with no initial overspeed. After modifications were made, the turbine is observed to overspeed after the loss of battery power due to a large increase in steam admittance to the turbine. This is due to both the trip and governor valves failing to the full-open position.

Figure 3.6 shows the governor valve open fraction CF value. Prior to battery depletion at time = 2 hours, the governor valve CF is controlled to maintain the pump injection rate near the target rate of 38.733 kg/s. The governor valve open fraction CF has a maximum value during the controlled operation to prevent overspeeds due to sudden changes in RPV pressure. After battery depletion, the governor valve fails to the full open position.

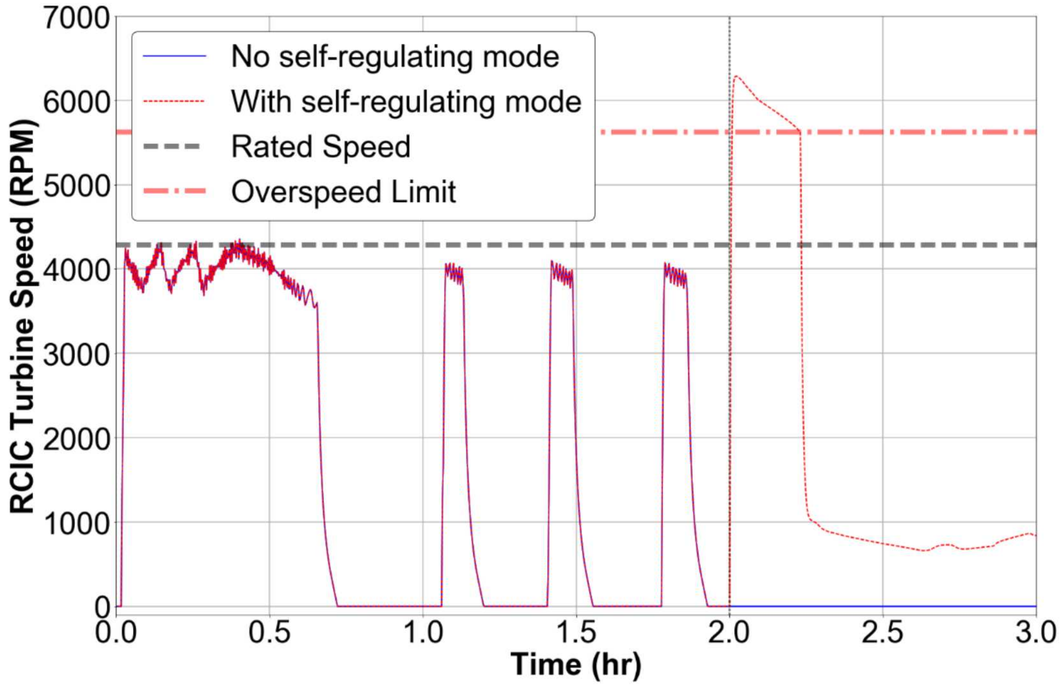

Figure 3.5: RCIC Speed With and Without Self-Regulating Modifications

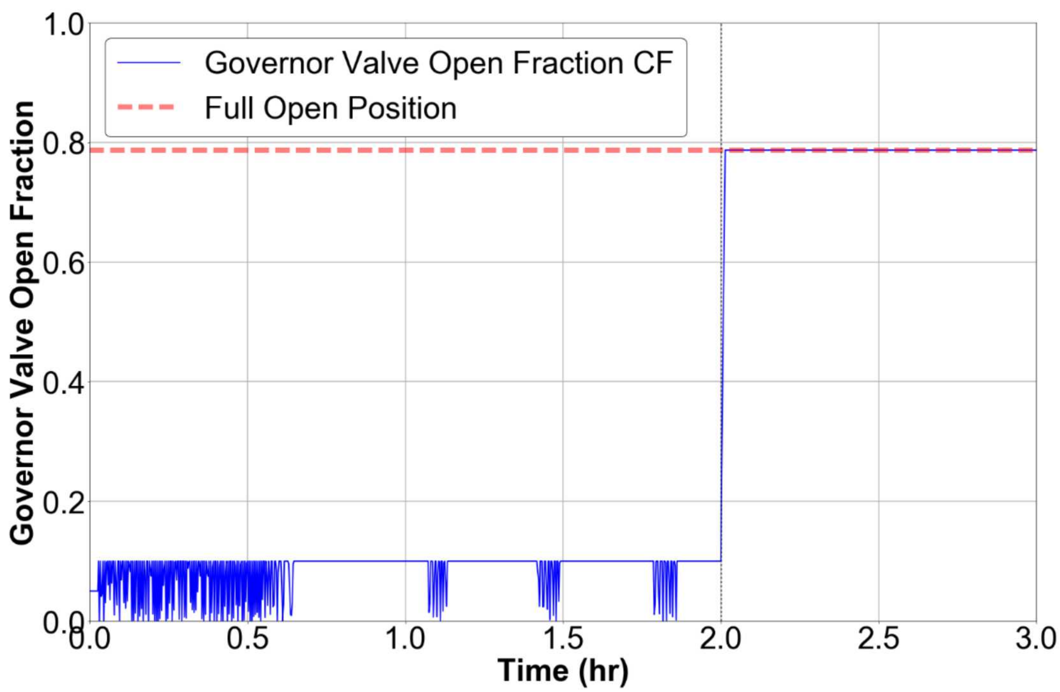

Figure 3.6: Generic BWR Governor Valve CF

3.2.3.2. Sensitivity to Model Parameters, Results, and Discussion

The generic BWR input development is still in progress. The results of the simulations are sensitive to model inputs (some of which are unknown) and are discussed in this section. Modeling and observations of the TAMU ZS-1 and GS-2 experiments will likely help in the resolution of some of these modeling unknowns. Additionally, there are issues to overcome while developing the generic BWR model input such as the simulation time step, and correctly characterizing the dynamic feedback between the RCIC system flow conditions and the RCIC response. As the feedback is coupled and dynamic, changes to turbine, pump, or general inputs cause changes in behavior that are difficult to isolate.

To aid in discussion of these topics, results of several simulations will be shown. These presented results are current results of the current work-in-progress generic BWR MELCOR model. Continued iteration on the current input deck and incorporating modeling and observations of the TAMU ZS-1 and GS-2 experiments will improve the generic BWR input deck by resolving unknown model quantities and increase the confidence in the model results.

The first model attribute to be discussed is the turbine overspeed. As mentioned in Section 3.2.3.1, the turbine is anticipated to initially overspeed when the governor and trip valves fail to the full-open position at battery depletion due to a sudden increase in the RCIC flow to the turbine. For the current modeling, the turbine is allowed over overspeed, without failing the RCIC turbine. This assumption may be readdressed later after further input and model development. The turbine overspeed can introduce problems with the simulation and results as the large overspeed can trigger the simulation to take very small timesteps (dt $<1\times10^{-3}$ s) that makes running the model impractical. Additionally, the turbine can reach speeds that are considered to be physically unreasonable depending on other input parameters. Figure 3.5 shows the initial turbine overspeed at time = 2.0 hours for an example simulation. The turbine overspeed is dominated by behavior upstream of the turbine, such as flow conditions in the RCIC steam chest. However, the initial overspeed is also influenced by the turbine losses, which are discussed next.

The previous implementation of the generic BWR modeling only had friction losses as a considered loss for the turbine. Friction losses were implemented in the model input by specifying a polynomial based on the pump speed. The addition of the extra torque terms described in Section 3.1.2.1 allow the user to implement different forms of turbine losses. The FY19 modeling of Fukushima Daiichi Unit 2 included the following losses in the modeling [20]:

- Windage losses,
- Bucket “slap” losses due to water jets moving slower than the relative turbine speed
- Friction losses

These losses have different forms, and the combination of these terms cannot be easily expressed by a polynomial function. The addition of an extra torque term makes it simple to specify the turbine losses. The turbine overspeed can be targeted directly by implementing a loss form that is significantly larger at increased speeds. The FY19 modeling of Fukushima Daiichi Unit 2 used the same windage loss form as described in Section 3.2.2.1, where windage losses scale by the speed squared. Figure 3.7 shows the results of different model inputs to characterize the turbine losses. It shows an unmodified loss term (only friction acting on the turbine), an asymptotic form that prevents the turbine from exceeding 6000 RPM, and finally, the same form used for the windage losses in the FY19 modeling, which scales losses by the speed squared. It should be noted that changing these loss terms will also influence turbine/pump coupled behavior prior to battery depletion, which can be observed in Figure 3.7.

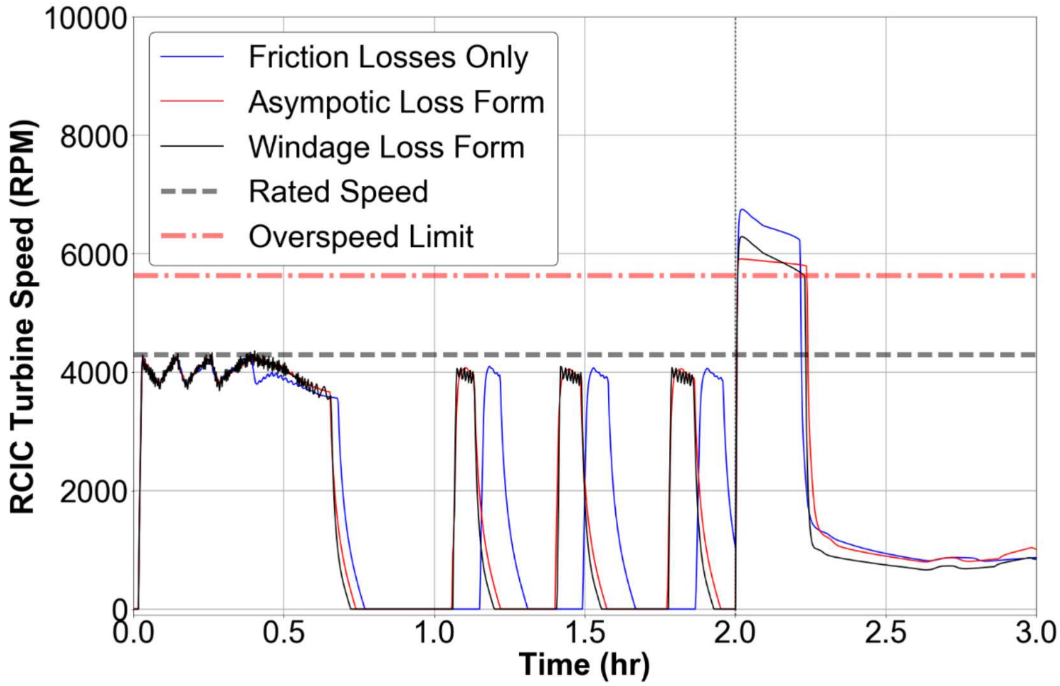

Figure 3.7: Generic BWR Initial Overspeed Using Different Loss Forms

The model results are also very sensitive to the RCIC steam chest and the turbine size. The RCIC steam chest is the control volume immediately upstream of the RCIC turbine control volume. These two control volumes are connected by the nozzle flow paths in MELCOR. At early stages during the input development, the model time step was a major obstacle for model progression. Investigation showed that this was primarily due to numerical constraints occurring in the CVH package and more specifically, the Courant limit of the RCIC turbine control volume. Updated estimates for the turbine volume were then implemented, using an estimate that the turbine control volume was approximately five times the estimated volume of the Terry turbine. Along with an updated estimate of the steam chest size, taken from the FY19 modeling, this increased the minimum model time step significantly, as shown in Figure 3.8.

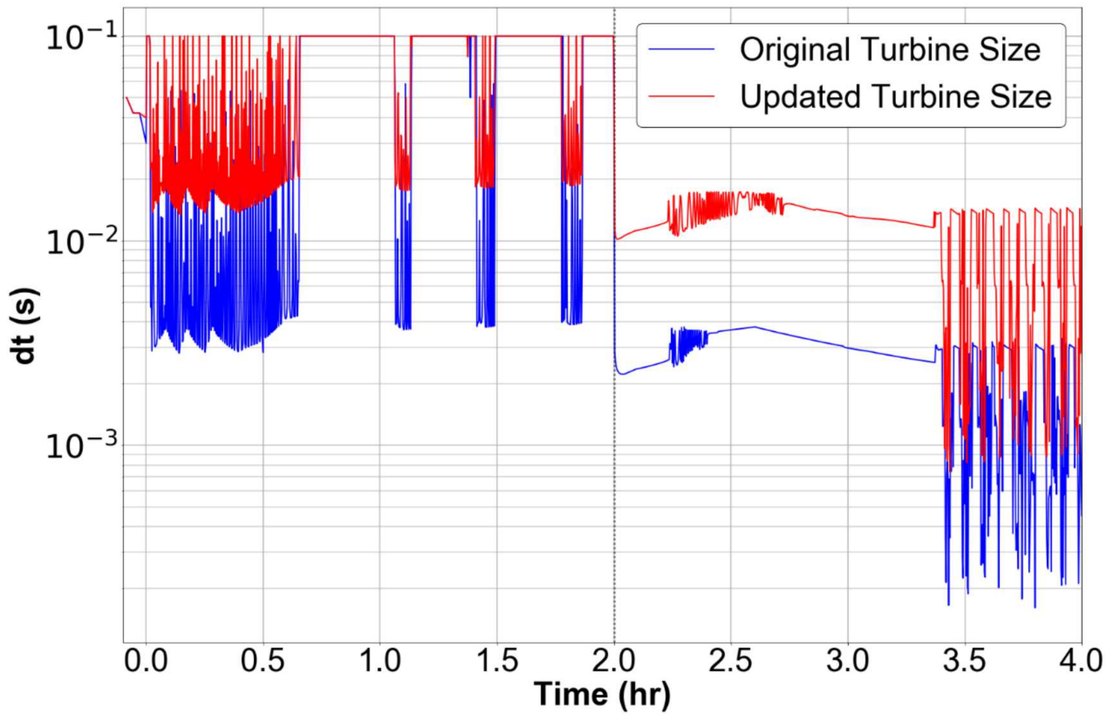

Figure 3.8: Generic BWR Time Step Using Different Turbine Sizes

The model results are also very sensitive to the RCIC turbine nozzle definition such as the nozzle height relative to the steam chest and the preferential phase of the nozzle flow path (i.e., pool or atmosphere flow first). Initially, the nozzles were grouped as "high" or "low" nozzles that were located at the top and bottom of the steam chest. The nozzles would preferentially flow steam (high nozzles) or water (low nozzles). This resulted in interesting behavior seen in the next figures. After the loss of battery power and water began to flow into the RCIC steam lines and the turbine, the lower nozzles were continually flowing water as they were flooded, but the higher nozzles would alternate between flowing water and steam, which resulted in slugs of steam or water entering the RCIC turbine. This is seen in Figure 3.9.

Changes were made so the nozzles would not preferentially flow either phase. After eliminating the specification for preferential flow of either phase, the higher nozzles flow a mix of steam and water (Figure 3.10). This resulted in significant changes in behavior.

The "preferential flow" mode of operation resulted in less frequent RCIC pump injection, however the injection periods were longer, which caused water to overflow the steam lines significantly. This behavior is shown in Figure 3.11 and Figure 3.12. Specifying a non-preferential flow path resulted in more frequent coolant injections, but over a shorter time interval. The injection rate is also lower during the self-regulating mode, which results in less overflow of the RPV after each injection (also seen in Figure 3.11 and Figure 3.12). Additional modeling will be made to investigate these model changes and determine which model input is the most appropriate.

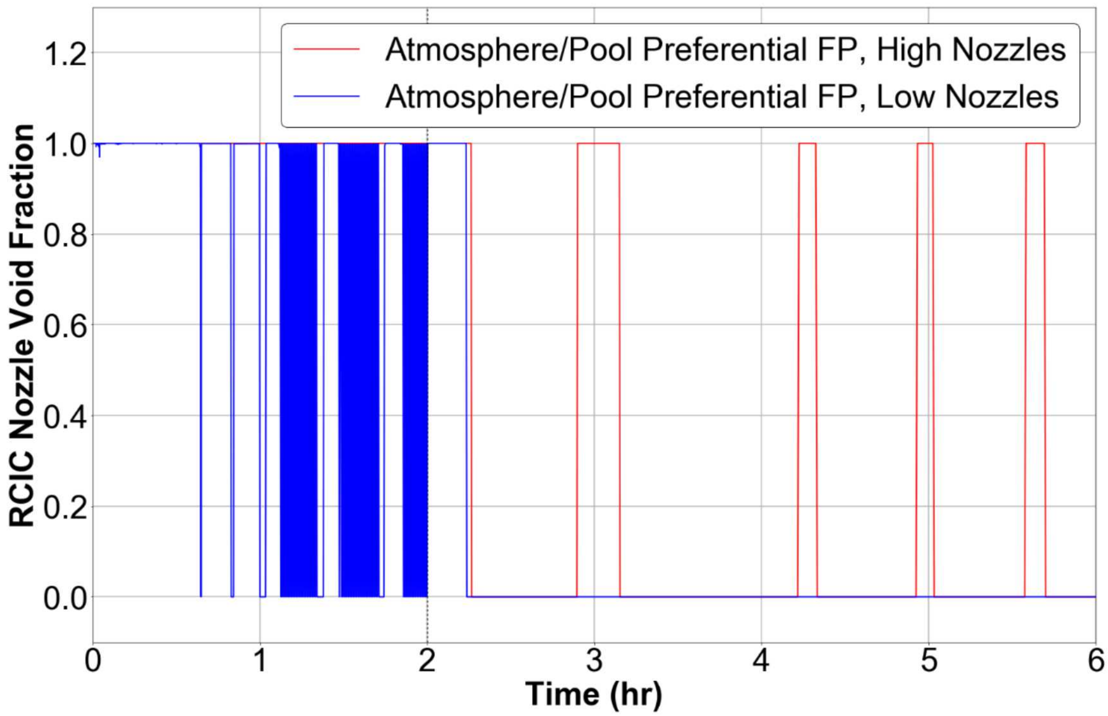

Figure 3.9: Generic BWR Nozzle Void Fraction, W/ Phasic Preference

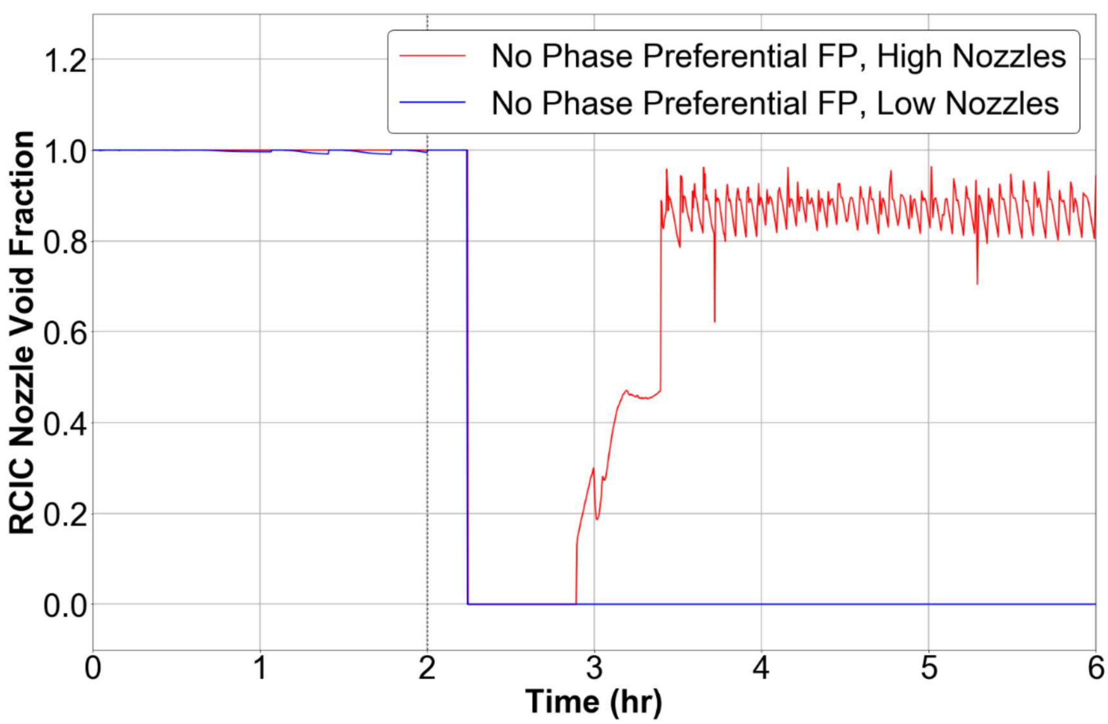

Figure 3.10: Generic BWR Nozzle Void Fraction, No Phase Preference

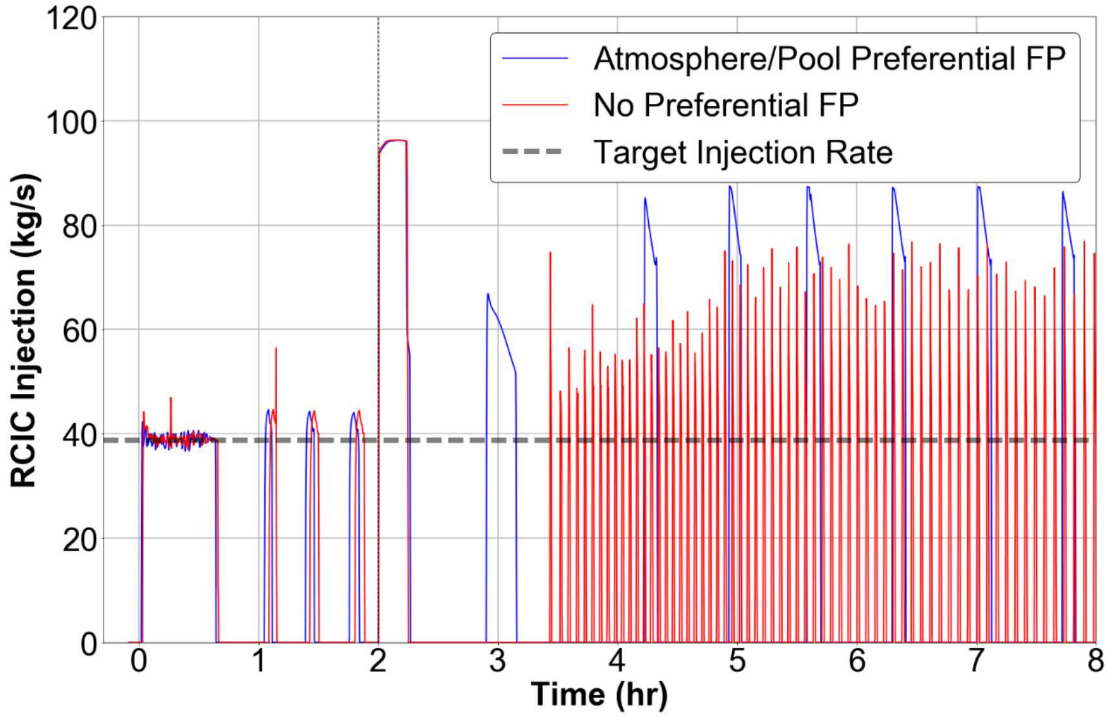

Figure 3.11: Injection Rate, With and Without Phasic Flow Preference

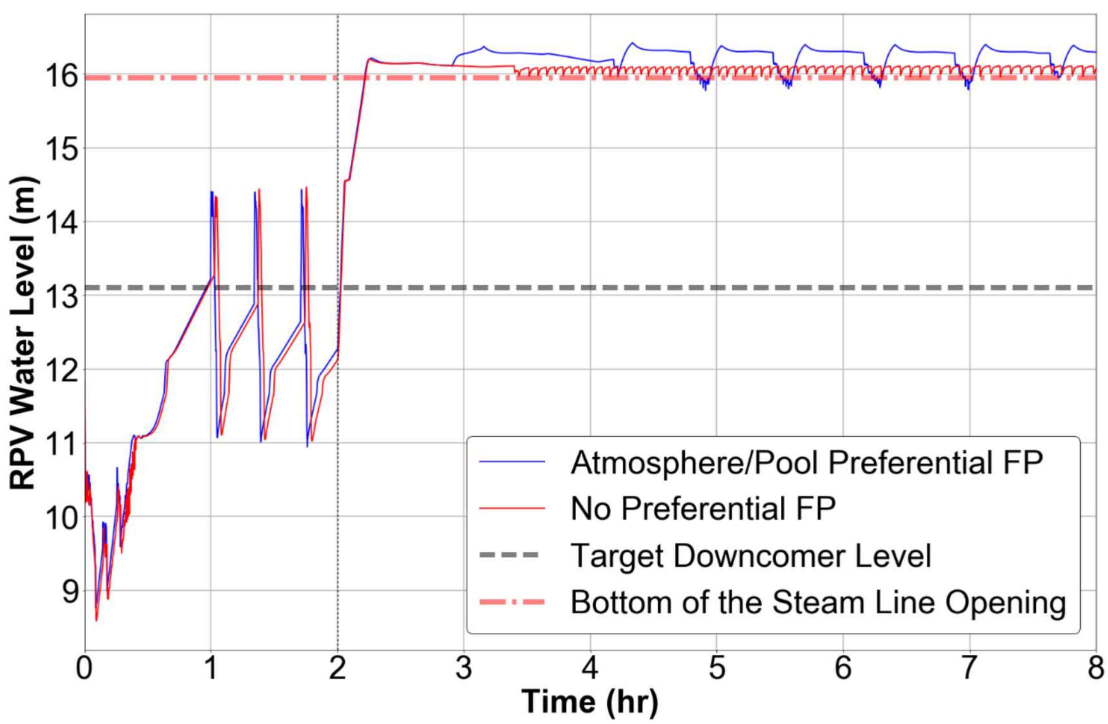

Figure 3.12: Downcomer Water Level, W/ & W/O Phasic Flow Preference

Another nozzle sensitivity investigated is the nozzle height relative to the steam chest. As mentioned previously, the nozzles were grouped into high and low nozzles, and their flow paths were placed at the top or bottom of the steam chest volume. By instead spreading the nozzles evenly across that same vertical span, the results were greatly affected. The RCIC turbopump system maintained a more stable speed and downcomer water level. Figure 3.13, Figure 3.14, and Figure 3.15. show the nozzle sensitivity to the effects of changing the nozzle elevations relative to the steam chest. In these plots the "nozzle elevation adjusted" labeling is for the case where the nozzles were spread evenly across the vertical span of the steam chest.

As mentioned previously, this input is still a work in progress, and further development and study will yield a best estimate model of a generic BWR.

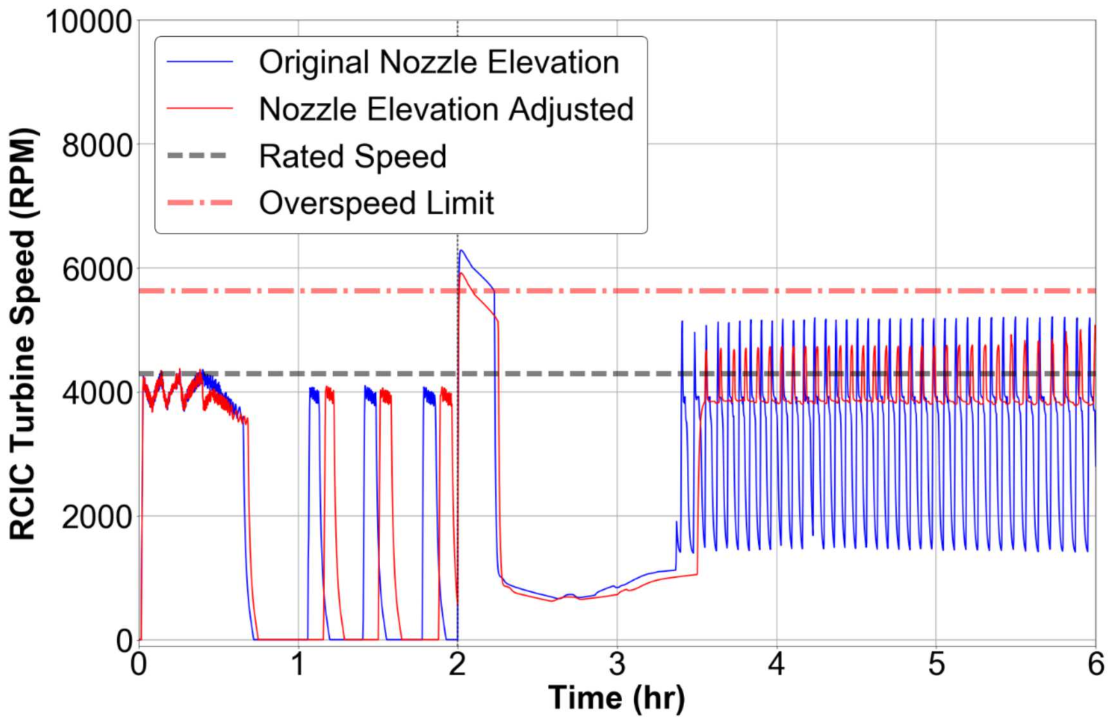

Figure 3.13: Generic BWR Turbine Speed Using Different Nozzle Elevations

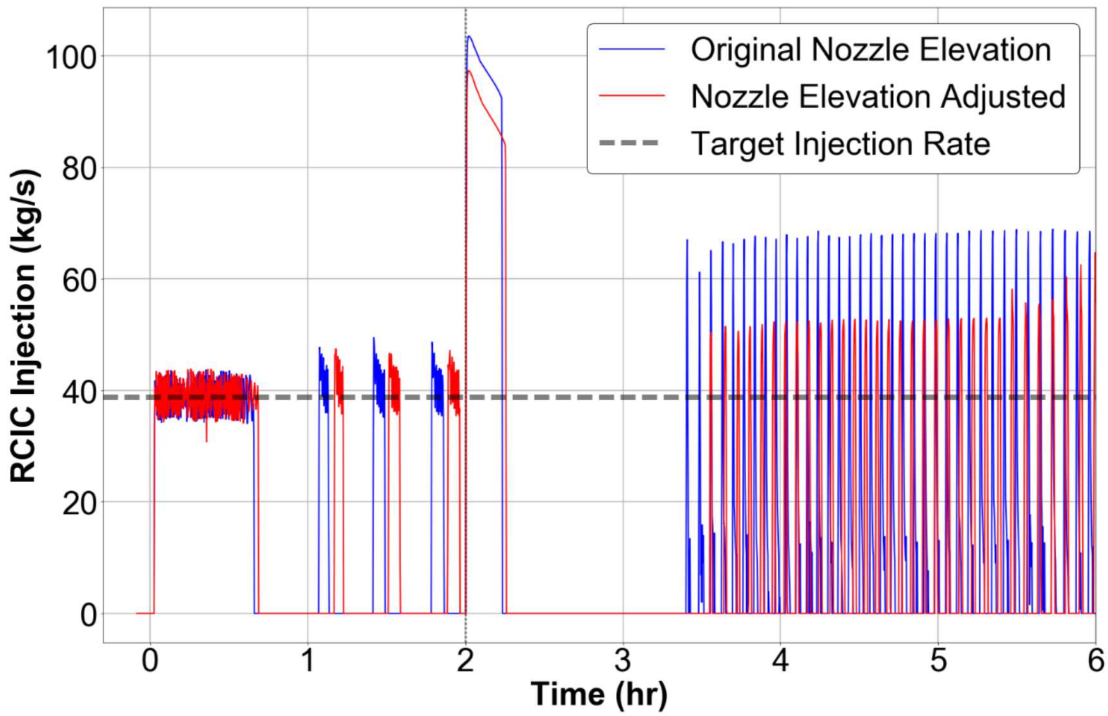

Figure 3.14: Generic BWR Pump Injection Rate With Different Nozzle Elevations

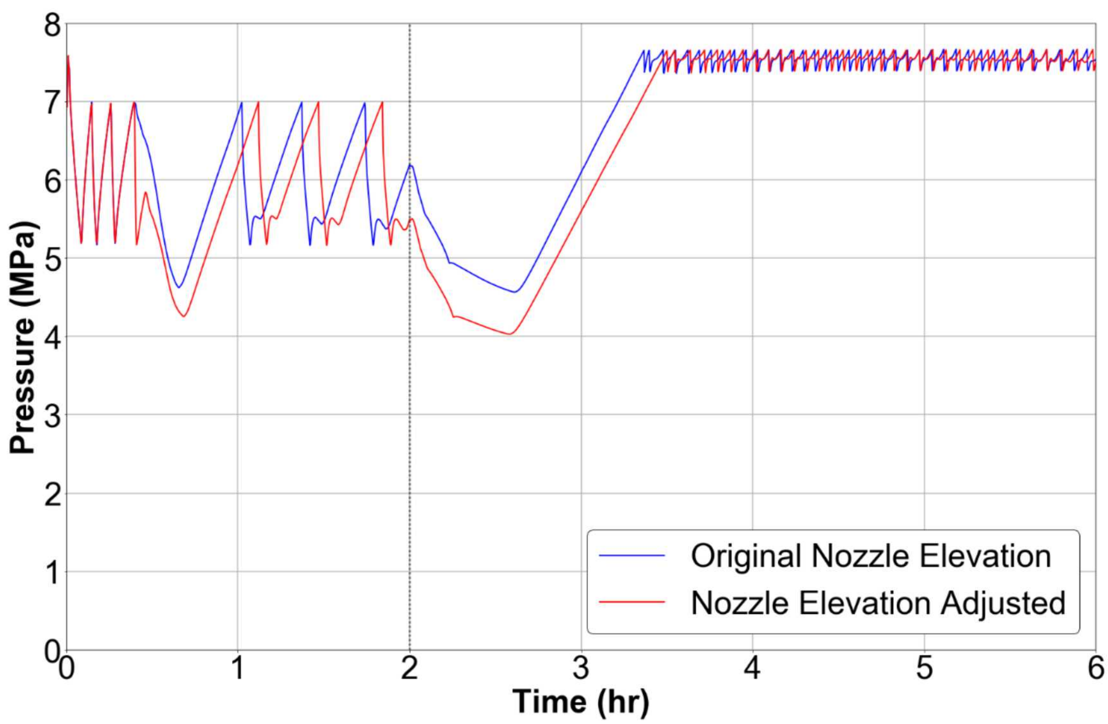

Figure 3.15: Generic BWR RPV Pressure Using Different Nozzle Elevations

3.2.3.3. Systems-Level Unknown Quantitities and Future Model Development

During FY19 MELCOR modeling of the TAMU GS-2 and Fukushima Daiichi Unit 2, several modeling unknowns were highlighted that will also affect the modeling and input development of the generic BWR MELCOR modeling. The FY19 status report [20] discusses these unknowns in detail, so their discussion will be omitted here. These include:

- Turbine size scaling,
- The coefficients associated with torque and losses,
- The quantity of water in the steam lines, and
- The losses associated with the RCIC turbine

Additionally, Section 3.2.3.2 discussed model sensitivity to input parameters that are currently unknown. The ongoing system-level modeling will continue to investigate these unknowns to better characterize the generic BWR system.

So far during input development, emphasis has been given to the RCIC turbopump system. As the generic BWR input is developed, focus can be given to other aspects of the modeling and results, resulting in a better generic BWR representation that can model the self-regulating RCIC system.

Planned future work with the generic BWR input is to further develop and better characterize the RCIC turbopump system representation, using insights gained from the TAMU ZS-1 and GS-2 modeling and experiments. On the MELCOR model development side, additional plot parameters are planned to be exposed in future code versions that will make it easier to calculate turbine and pump torques and losses. It is also planned to incorporate the sensitivity coefficients for the turbine torque and losses into the future modeling.

Overall, the FY20 MELCOR modeling of the generic BWR is an improvement over the previous state of the generic BWR model. It is now capable of modeling the self-regulating operation mode of the RCIC turbo-pump system; however, model unknowns need to be addressed and the input needs to be further developed to update the current generic BWR model. This will improve the MELCOR results and also make this input more useful for predicting the over RCIC performance.

4. SUMMARY

This annual report documents the progress made under the TTEXOB program's MODSIM work performed at SNL. SNL MODSIM work in FY20, which falls under Milestone 7 of the TTEXOB program, complements the hybrid Milestone 5&6 experiments.

Hybrid Milestone 5&6 is aimed at obtaining a measure of confidence in scaling effects/factors and Terry turbopump self-regulation. Gaps to address with the hybrid Milestone 5&6 experimental program include:

- Full-scale steam test data,
- Full-scale duration test with steam,
- Self-regulation (full-scale), and
- Impact of steam quality

Milestone 7 is an umbrella for MODSIM efforts complementary to the experiments of all the other milestones. Several new MELCOR capabilities were added:

- Extra torque terms for rotor and/or pump objects
- Sensitivity coefficient capabilities to incorporate raw turbine torque multipliers and a windage torque term
- An independent mode for turbine operation wherein a rotor object can be computed without an explicit connection to a pump object

Existing MELCOR input models representing TAMU experimental facilities were improved and a new generic BWR input model is in development and has demonstrated its usefulness in:

- Modeling turbopump self-regulation capability
- Exploring model sensitivities and uncertainties
- Drawing useful insights about turbopump phenomenology

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Name	Org.	Sandia Email Address
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