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Terry Turbopump Expanded Operating Band Modeling and Full-Scale Test Development Efforts in Fiscal Year 2019 – Progress Report

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Sandia National Laboratories

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Abstract

The Terry Turbine Expanded Operating Band Project is currently conducting testing at Texas A&M University, and the resulting data has been incorporated into MELCOR models of the Terry turbines used in nuclear power plants. These improved models have produced improvements in the Fukushima Daiichi Unit 2 simulations while providing new insights into the behavior of the plant.

The development of future experimental test efforts is ongoing. Development of and refinements to the plans for full-scale steam and steam-water turbine ingestion testing has been performed. These full-scale steam-based tests will complement the testing occurring at Texas A&M University, and will resolve the remaining questions regarding scale or working fluid. Planning work has also begun for future testing intended to explore the uncontrolled RCIC self-regulation theorized to have occurred in Fukushima Daiichi Unit 2.

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EXECUTIVE SUMMARY

This report documents the progress made under the Terry Turbine Expanded Operating Band (TTEXOB) program's modeling and simulation work performed at Sandia National Laboratories (SNL). It describes the US Federal Fiscal Year 2019 (FY19) work to-date along with preliminary/interim data and findings developed in the testing program. This work, which falls under Milestone 7 of the program, provides a counterpart to the Milestone 3 and 4 experiments. In addition to the modeling and simulation work performed at SNL, Milestone 5 and 6 testing details have been further developed and updated.

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, performs testing on full-scale components used in RCIC/TDAFW Terry turbopumps, such as nozzles, valves, etc. The tests are intended to better understand component behavior under both normal and abnormal conditions. Milestone 4, Terry Turbopump Basic Science Experiments, performs testing on a scaled Terry turbopump system to develop performance data under a wide range of normal and off-normal conditions; it also includes a limited amount of full-scale Terry turbine testing to establish scaling between the full and small-scale systems. Milestone 5, Integral Full-Scale Experiments for Long-Term Low-Pressure Operations, explores 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, is 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. Milestone 7 is an umbrella for the modeling and simulation efforts that are complementary to the experiments of all the other milestones.

Milestones 5 and 6 are both currently under development; the development of Milestone 5 testing details is more advanced than that of Milestone 6. The full-scale steam-based Milestone 5 tests will complement the testing occurring at Texas A&M University, and will resolve the remaining questions regarding scale or working fluid. These tests will occur largely at the low end of the RCIC operational pressure range to below the pressure range, and will explore certain adverse conditions which may be possible under some beyond design basis events. In contrast to the Milestone 4 turbine profiling, which involves quick tests at steady state for seconds to minutes, these tests are intended to be run for hours to days.

Discussions within the TTEXOB have led to the development of several potential design concepts that could be used to accomplish the current Milestone 6 testing goals. These designs range from scaled test loops to full-scale analogs of the RCIC system; the scaled loops could easily be operated as add-on testing after Milestone 4 using the existing Milestone 4 test facilities. Crucial to further development efforts are the results of the proof-of-concept testing that will be performed under Milestone 4.

Under Milestone 4, some full-scale low-pressure air testing has been performed, and performance curves for a Terry GS-2N were developed. This test has been used to make improvements in the Terry turbine models in MELCOR under Milestone 7. Notably, the effects of scaling on the computed windage loss terms between the Terry ZS-1 and GS-2N were limited for the selected test cases; additional modeling across a wider range of cases is needed to validate this result.

An improved turbine model was incorporated into Fukushima Daiichi Unit 2 simulations. Equations were incorporated for parasitic torque values deriving from the presence of significant amounts of liquid water in the steamflow. The water is expected to preferentially flow through the turbine's lower nozzles and produce jets that can be slower than the tangential wheel velocity; as a result, they would impede the wheel and produce a degrading parasitic torque. In addition, some of the assumptions regarding heat transfer within the reactor pressure vessel have been revisited, and it was found that these assumptions could have an effect on the behavior of the simulations. While further development of the models is recommended, it was found that the current work on the Fukushima modeling has improved the simulations and better predicts the reactor pressure evolution.

NOMENCLATURE

Abbreviation	Definition
1F2	Fukushima Daiichi Unit 2
BDBE	Beyond Design Basis Event
BWR	Boiling Water Reactor
CST	Condensate Storage Tank
C_v	Valve Flow Coefficient
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy's Office of Nuclear Energy
EPRI	Electric Power Research Institute
F_L	Valve Liquid Pressure Recovery Coefficient
FLEX	Diverse and Flexible Mitigation Capability
IAE	Institute of Applied Energy
INL	Idaho National Laboratory
L/D	[Pipe] Length-to-Diameter Ratio
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
RPM	Revolutions Per Minute
RPV	Reactor Pressure Vessel
SG	Steam Generator
SNL	Sandia National Laboratories
SRV	Safety Relief Valve
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
x_T	Valve Pressure Differential Ratio Factor

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1.   INTRODUCTION

This annual report documents the progress made under the Terry Turbine Expanded Operating Band (TTEXOB) program's modeling and simulation work performed at Sandia National Laboratories (SNL). It describes the US Federal Fiscal Year 2019 (FY19) work to-date along with preliminary/interim data and findings developed in the testing program. This work, which falls under Milestone 7 of the program, provides a counterpart to the Milestone 3 and 4 experiments. The overall program and its milestone-based approach are described in the program's Summary Plan [1]. Details of the test plans for the Milestone 3 and 4 efforts reported here can be found in the Milestone 3 and 4 Detailed Test Plan [2]; this SNL modeling work is conducted alongside experimental testing performed at Texas A&M University (TAMU).

The testing at TAMU is supported by three primary groups: Japan's Ministry of Economy, Trade, and Industry through the Institute of Applied Energy, the U.S. Department of Energy (DOE) largely through SNL and Idaho National Laboratory (INL), and the U.S. nuclear industry. The organizational relationships are described in the project's charter [3].

Details on the progress of the experimental work have previously reported to the Institute of Applied Energy (IAE) [4] in alignment with the Japanese fiscal year and subsequently to the DOE [5] in alignment with the US fiscal year. In addition, this report builds upon the experimental and modeling progress reported in prior fiscal years [6, 7, 8, 14, 18, 19].

The testing results and analyses introduced here are also expected to be disseminated in relevant scientific and industrial publications and conferences such as the Terry Turbine Users Group (TTUG) [9]. Preparation and publication of journal articles is underway [10, 11].

In addition to the modeling and simulation work performed at SNL as the Milestone 7 reflections of the Milestone 3 and 4 testing, this report will provide an update on the development of Milestone 5 and 6 testing details.

1.1.   Background

Prior to the accidents at the Fukushima Daiichi Nuclear Power Plant, assumptions and modeling of the performance of Terry turbopumps were based mostly on generic vendor operational limits. The operational limits were based the National Electrical Manufacturers Association standard SM23 *Steam Turbine for Mechanical Drive Service* [12], which was 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 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 functioning as found in PRA applications limits the anticipated mitigation options considered for normal and emergency operations. Improved understanding for expanded operations 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 plant operations. In particular, operating experience indicates that the Terry turbopump system was qualified for plant operations to a small subset of its capability; defining 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 (RCIC/TDAFW) system is hypothesized to have the capability to operate for days or weeks over an extended range of steam pressures, wet steam, and increased lube oil temperature conditions with limited to no active control features.

1.2.   TTEXOB Program Approach

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.

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

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

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

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

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

Milestone 7 – Collection and integration of the Milestone 3-6 modeling efforts.

The generic technical approach for Milestone 3 (and Milestones 4, 5, and 6) will be 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.

The modeling efforts reported here are composed primarily of those performed in FY19; see [18] for FY17 modeling efforts and [19] for FY18.

1.2.1. *Milestones 3 and 4 Experimental Summary*

The experimental portions of Milestones 3 and 4 are currently being performed at TAMU, and the modeling and simulation portions are being performed by several collaborating organizations under the TTEXOB program. Further details on the current experimental details can be found in [5].

Under Milestone 3, Full-Scale Component Experiments, several components are actively being investigated . The Milestone 3 efforts are 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.

The Milestone 4 (Terry Turbopump Basic Science Experiments) tests are intended to provide information which will allow for the overall effort to better design and operate the full-scale testing (i.e., Milestone 5), as well as to provide benchmark data for code validation. In addition, the development of scaling parameters will enable the translation of any future testing from small-scale (which is cheaper and simpler to perform) to full-scale systems. The Milestone 4 efforts are 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 will provide data for modeling efforts (including a broad set of performance curves), provide initial scaling factors, and provide initial investigations into potential failure modes of a GS-series Terry turbopump under a BDBE. These efforts will also provide initial confirmatory data for the Milestone 5 and 6 full-scale tests. The initial scoping of uncontrolled feedback with a ZS-1 Terry turbopump can also provide 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 will be performed on the ZS-1 under Milestone 4; steam and steam-water testing of a GS-2N will be performed under Milestone 5. The turbine performance is largely collected as torque-speed-pressure-moisture content curves. The collected test data provide benchmark results for the simulations. If needed, the test data can also be used to make corrections to the model. The single-phase air and two-phase air-water performance tests of a GS-2N operated as a GS-1 are the primary tests of interest.

1.2.2. Milestone 5

See Section 2 for a thorough discussion of Milestone 5, which is intended to pick up where Milestone 4 ends. While Milestone 4 includes some full-scale turbine profiling (originally a Milestone 5 task that was moved into Milestone 4), only air and air-water mixtures at low pressures are employed as working fluids for Milestone 4 full-scale tests. In Milestone 5, the data set will be extended to include full-scale steam and steam-water turbine ingestion data at low to moderate pressures [20]. In addition, certain 'long-term' and adverse conditions testing is planned.

1.2.3. Milestone 6

Section 3 outlines Milestone 6, which is intended to demonstrate and explore the proposed 'self-regulating mode' of operation for a RCIC system as is thought to have occurred in Fukushima Daiichi Unit 2. Under the proposed conditions, upon losing power, a Terry turbopump governor valve would begin to open but avoid an overspeed trip of the turbine. The pump would drive sufficient water into the reactor that it overfills and liquid spills over into the main steam line, providing liquid to the turbine inlet. The liquid would then degrade the performance of the turbine and its attached pump, reducing the amount of excess water pumped to the reactor. The turbopump would either oscillate between high speeds with low moisture and low speeds with high moisture or would approach a sort of steady state.

Milestone 6 testing is separate from that of Milestone 5. This task, which is currently in a conceptual stage, is expected to be run in a scaled manner with a ZS-1 rather than a GS-2N turbine, but there may be an option for full-scale testing with a GS-2N. Several potential designs for both small and full-scale testing are proposed in Section 3.2; only one design is expected to be used. A scaled proof-of-concept demonstration will be performed as part of the Milestone 4 testing at TAMU.

1.2.4. Milestone 7

The complete suite of modeling and simulation work performed in this program is grouped together under Milestone 7. More detail can be found in Section 4. The models are informed by the data gleaned from experiments and can be used to direct some of the testing. In FY19, modeling and simulations based on the GS-2N testing performed at TAMU in FY19 have been performed, and these improved turbine models have been incorporated into the Fukushima Daiichi Unit 2 simulations.

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2.   MILESTONE 5 PROGRESS – FULL-SCALE TESTING

As efforts for Milestones 3 (Full-Scale Separate-Effect Component Experiments) and 4 (Terry Turbopump Basic Science Experiments) neared completion, the Turbo-TAG, in conjunction with SNL and INL, identified a suite of full-scale integral experiments that would be needed in order to 'fill in' the remaining parts of the program. Milestone 5 is intended to provide full-scale steam test data.

Under Milestone 4, testing was designated for scaled steam and steam-water conditions, scaled air and air-water conditions, and full-scale air and air-water conditions on a Terry turbine inlet. While the development of scaling factors are part of Milestone 4, the use of relatively low pressure air leaves open questions about their validity for higher-pressure steam inlet conditions. A limited set of full-scale steam and steam-water tests for low and moderate pressure should address the remaining concerns and provide validation for the scaling terms. These tests would be full-scale steam equivalents of those performed under Milestone 4.

In addition, information is needed on the long-term and dynamic performance of Terry GS turbopumps operating under adverse conditions. This is similar to some of the initial bearing degradation tests that belong to Milestone 3, with an eye on the effects of integral operation under longer durations. These tests integrate the findings of earlier scaled and separate effects testing and demonstrate the ruggedness of the turbopump in fully integral operations.

2.1.   Milestone 5 Overview

Milestone 5 is expected to be performed at a commercial test facility. Initial versions of the Detailed Test Plan for Milestone 5 have been developed [20]. Revisions are expected to be developed as the testing needs and available resources (including facility limitations) are developed and further understood.

Testing under Milestone 5 is currently grouped into six areas:

1. Long-term low-pressure tests,

2. Long-term low-speed tests,

3. Select Milestone 3 and 4 tests,

4. Low-pressure two-phase tests,

5. Long-term low-pressure tests with oil heat up, and

6. Japan-specific testing.

The test loop will be largely the same across all tests, with limited modifications. A simplified Piping and Instrumentation Diagram (P&ID) of the proposed loop is shown in Figure 2.1. Some tests will load the turbine with a dynamometer, while others would replace the dynamometer with the turbine's intended pump.
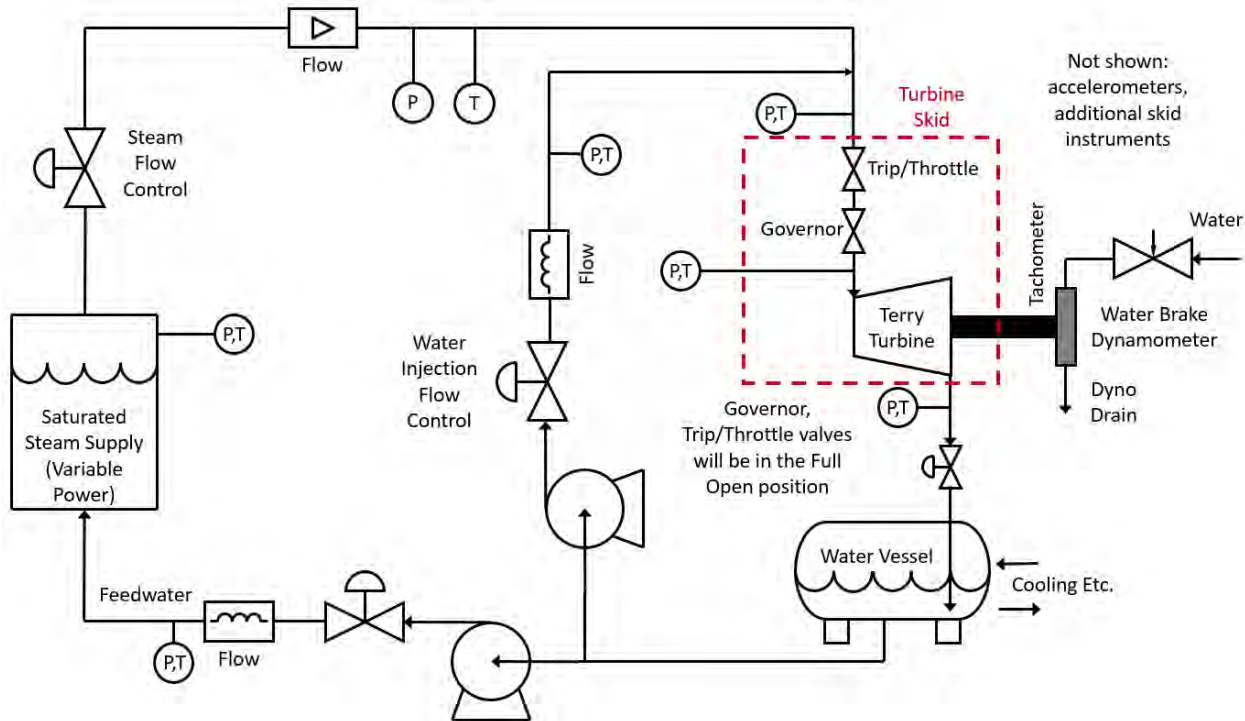
Figure 2.1: Generic Milestone 5 Test Diagram [20]

The long-term low-pressure testing consists largely of serial steady-state runs of several hours up to one week. The turbine would be fed dry saturated steam at 100-150 psi with a backpressure usually between 40 and 60 psi. The speed would be 2000 or 3000 rpm, which is on the lower side of the operating range, and it would be maintained actively through dynamometer loading. The oil cooler would be enabled; this test series would demonstrate the turbine's time-evolved capabilities toward the tail end of certain postulated events. In these events, the reactor system would be depressurized to the lower pressure ratings of the RCIC system and the suppression pool would have absorbed such quantities of heat without containment venting as to provide significant backpressure to the RCIC system.

The long-term low-speed tests are similar to the low-pressure tests but more limited in scope. They are intended to assess the 24-hour performance of the Terry GS-2 at 2200 and 1500 rpm, which will be maintained by dynamometer loading. There would be only atmospheric backpressure and a dry, saturated steam inlet condition at 75 psi. At such low speeds and pressures, the bearings may experience accelerated wear, since a thinner oil wedge in the Babbitt journal bearings is likely. In addition, there may be vibrations or issues with the nozzles being unable to produce supersonic flow past their outlets. Assessment of such potential operating occurrences and any impact on the reliability of the RCIC system will provide benefits to the nuclear industry.

The select Milestone 3 and 4 tests would produce a number of steady-state turbine torque vs. speed vs. pressure vs. steam quality curves. These would reproduce the turbine profiling in Milestone 4, except at full-scale with steam and steam-water

mixtures as the working fluids. The turbine speed will be controlled by the dynamometer, and the inlet steam pressure and quality would be controlled along with the backpressure. Torque readings would be taken at various speeds to produce many curves; with a multiplicity of inlet and outlet conditions, a significant number of data points could be needed.

One notable aspect of these tests is the resolution of anomalies that have appeared in the Milestone 3 and 4 efforts. Of significant interest is the full-scale turbine performance under slightly wet conditions. The low-pressure full-scale air-water testing at TAMU has identified certain anomalous behavior thought to involve freezing through the nozzles [5].

In addition to steady-state single and two-phase ingestion turbine profiling, consideration is given under this group of tests to perform some of the Milestone 3 and 4 testing that was found to be unachievable previously, such as producing valve flow coefficient (C_v) profiles for the valves that were unobtainable for Milestone 3 and 4 testing in a facility not credentialed under NQA-1.

The low-pressure two-phase tests are moderate-duration (1-3 hour) operating runs of the turbine or turbopump at steady state with low inlet pressures (70-150 psi) and wet vs. dry steam. These tests will explore the stability of such operations and determine if there are any issues that may arise under such short-term operations.

The long-term low-pressure tests with oil heating explore turbopump operations under adverse conditions. The lubrication oil would be above its intended operating temperature, ramping from 190 °F up to 270 °F across multiple days and low inlet pressures. The system would be carefully monitored for breakdown of the oil and bearings, and the operability of the system assessed. This group of tests has the potential to directly identify the near-term failure points or operational limits under such severely degraded conditions.

The Japan-specific testing is currently a placeholder; no specific operations have yet been planned for this group. It is intended to allow for any additional miscellaneous testing on the turbopump skid at the behest of Japanese groups—industry/utilities, government, etc.—involved in the test program that would fall outside the scope of the TTEXOB program. They would be given an opportunity to leverage the test skid while the testing facility is still set up and it is convenient to run additional tests.

2.2. Milestone 5 Development Progress

Testing has yet to begin under Milestone 5. After initial development and revision of the Milestone 5 Detailed Test Plan, discussions were held with commercial test facilities (including site visits) as part of a test site selection effort. Based on the discussions, refinements will be made to the test plan to accommodate typical test site limitations, improve the schedulability of various test operations (i.e., 8-hour vs. 24-hour tests), and improve the cost efficiency of test operations. These refinements are underway.

Upon completion of the finalized test plan and site selection, the TTEXOB and its participants will determine if adjustments are necessary and finalize the path forward.

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3. MILESTONE 6 PROGRESS – TERRY TURBOPUMP SELF-REGULATING FEEDBACK

The RCIC System employed by Fukushima Daiichi Unit 2 operated in an unregulated mode for approximately 68 hours [13]. Upon loss of power to the governor electronics, it is expected that the hydraulic components will open the governor valve to its full-open position. This is expected to result in a turbine overspeed mechanical trip; therefore, continued operation suggests there was an alternate mode of regulating the RCIC turbopump's operation. It is believed that the system overfilled the reactor pressure vessel, which then spilled water into the main steam line. The excess water was transported along with steam to the RCIC turbine, which degraded its performance and caused less water to be pumped to the reactor. A stable balance may have been achieved in the flows.

The primary goal of Milestone 6 is to replicate the RCIC system performance seen in Fukushima Daiichi Unit 2 that exhibited system regulation via means other than its normal electro-hydraulic governor system, and to do so by operating a complete system analog rather than component-by-component. Initial proposals included full-scale integral steam-water testing at full reactor pressure levels. For a full-scale test, the turbopump skid would have its pump supply feedwater to a boiler/heat recovery steam generator, which would supply the turbine with steam that is potentially wet. As this would, by intention, be able to overfill the steam supply with feedwater, it introduces challenges into the test facility design, operation, and cost. Subsequent proposed concepts introduced smaller-scale systems and/or means of mimicking the overfill condition without conducting an actual overfill.

The conceived self-regulating mode believed to have occurred in Fukushima Daiichi Unit 2 involves a reactor overfill situation. Upon loss of all AC and DC power, the electronic portion of the electro-hydraulic governor system would have caused the governor valve to move toward its full-open position. It is possible that the valve stuck in an advantageous position. Normal start and stop signals would not have worked, and the RCIC system would have pumped water to the reactor vessel in excess of boiloff, eventually raising the level to the main Steam Line. The efficacy of the steam separators and dryers in an overfill situation is unclear, and a significant amount of entrained water may have negotiated them even when the water level is below the steam line port. With water entering the main steam line from the reactor, the Terry turbine would have eventually ingested significant wetness in the steam flow. The flow regime is unknown; it could have ranged from well-mixed steam-water flow to periodic oscillations between mostly steam and mostly water.

Terry turbines are rugged pieces of equipment that are not readily damaged in the near-term by two-phase steam-water ingestion [17]. While long-term two-phase ingestion will increase wear on the turbine wheel, the short mission times seen in nuclear power plants are unlikely to see significant wear. Until recently, the turbines were known to handle two-phase ingestion but actual characterization of any performance degradation was largely unknown. Efforts at Texas A&M University [5, 6, 7, 10, 11] have demonstrated that the performance degradation of a Terry turbine under two-phase ingestion is very regular and smooth.

Therefore, when reactor overfill introduces significant moisture into the main steam line, a RCIC turbine that does not have a governor reacting to changes in conditions will see a performance degradation based on the reduction in steam quality. The decreased turbine output will in turn provide less motive power to the attached pump, and as a result less water will be returned to the reactor. This could raise the steam quality and restore some of the turbine's performance; it is unclear if the system approached a quasi-steady state of degraded turbine performance or if it oscillated between high-quality steam with high performance and very low-quality steam with significantly degraded performance.

The full set of testing for Milestone 6 is in the conceptual development stage. A set of scaled proof-of-concept tests will be performed at TAMU under Milestone 4; these scoping tests will provide valuable input for the further development of the Milestone 6 test efforts. In addition, a preliminary set of test loop designs has been conceived, ranging from minor modifications to the scaled TAMU scoping efforts to full-scale RCIC system analogs.

3.1.   Scoping of Terry Turbopump Uncontrolled Feedback

As part of the Milestone 4 experimental efforts at TAMU, proof-of-concept testing for Milestone 6 will be conducted. Here, a Terry ZS-1 turbine with a pump attached will be installed in the Laboratory for Nuclear Heat Transfer Systems (NHTS) at TAMU in a manner to closely mimic the operation of the Fukushima Daiichi Unit 2 RCIC System in the uncontrolled feedback mode of operation. This scaled testing will serve as a proof of concept as well as a source of critical operational information for the testing in Milestone 6.

The planned testing would connect the ZS-1 to a small pump. The turbine would exhaust into the lab's suppression chamber, and the pump would draw its suction from there as well. The entirety of the pump's output would be directed through a check valve into the main steam line upstream of the turbine; feedwater for the steam generator would be provided separately in a controlled manner. This arrangement is illustrated in Figure 3.1.
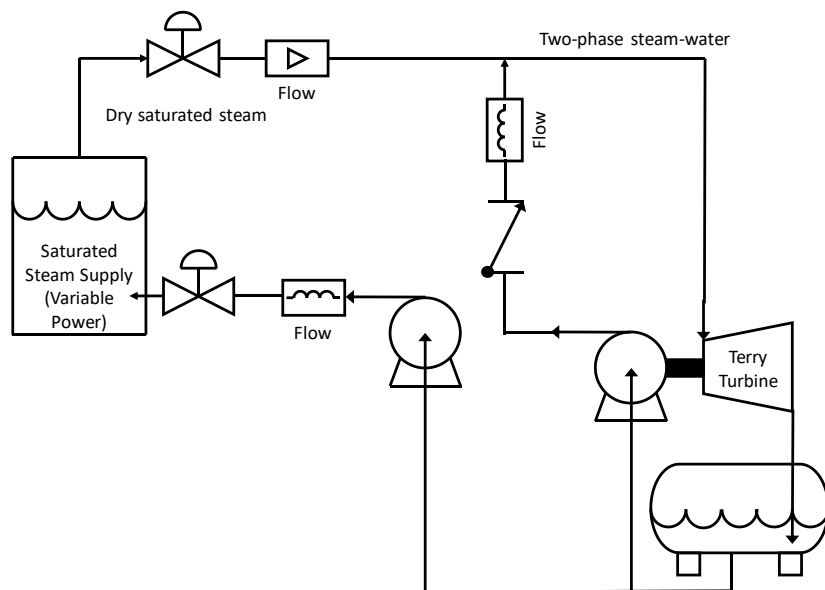
Figure 3.1: Conceptual P&ID for Milestone 4 Uncontrolled Feedback [5]

One observation from the Fukushima accidents was the difficulty in the transition to seawater injection, which took multiple tries to achieve and maintain injection. A transition from RCIC/TDAFW unregulated operations to Diverse and Flexible Mitigation Capability (FLEX) could, in reality, take multiple attempts to achieve the desired outcome. Thus, scoping tests are expected to be conducted to show how the transition from a self-regulating mode to a FLEX mode can be enabled. This series of scoping tests is intended to also consider 'failed' attempts at FLEX and whether it is feasible to allow the Terry turbopump to achieve a self-regulating mode prior to subsequent attempts at implementing FLEX.

3.2. Proposed Simple Milestone 6 Test Loops

Several concepts for investigation of a self-regulating feedback mode of RCIC systems have been proposed, ranging from small to full-scale systems. Testing may involve steam-water or air-water facilities, and some aspects of system operation may be replicated via algorithm and programmable logic controllers rather than direct physical interconnections.

The options presented here are intended to provide a broad overview of the ideas under consideration and are not intended to bar consideration of any improved design should one be suggested. Furthermore, they are simplified and conceptual in nature; details such as relative valve and instrument placements or order in the flow path may not be representative of how they would be installed in the field. The expectation is that only one of the following proposed designs would actually be used for testing, and that a scaled design is more feasible than a full-scale system.

3.2.1. Full-Scale Designs

Full-scale testing with steam would require the testing to be performed by a commercial testing facility. A Terry GS-2-based skid would be employed; the turbine may run with a full complement of 10 nozzles, or may be operated in a 'GS-1' mode in which the upper bank of nozzles is blocked. Testing with air may be performed at a commercial facility or a university research lab with sufficient air supply. The Turbomachinery Laboratory at Texas A&M University has sufficient air capacity for low-pressure testing in GS-1 mode.

3.2.1.1. Full Analog Design

The full-scale full-analog design would attempt to most directly replicate the RCIC system as installed in boiling water reactors (BWRs). Depending on resource availability at the testing site, the pump would draw water from a pressurizable suppression pool and/or atmospheric water tank. Preferably, exhaust from the turbine would be directed to a pressurizable suppression pool. Alternatively, attempts would be made to regulate turbine backpressure by means of a control valve and a (relatively) small pressure vessel system. The water flowing through the pump would be directed to a boiler or heat recovery steam generator as its feedwater. The boiler power would be controlled to reflect the decay heat generated by a reactor core. An emergency minimum feedwater guarantee line would be provided along with any other necessary support systems to prevent underfilling the boiler, but would not be used unless the primary feedwater flow falls below a critical threshold. This concept is diagrammed in Figure 3.2.
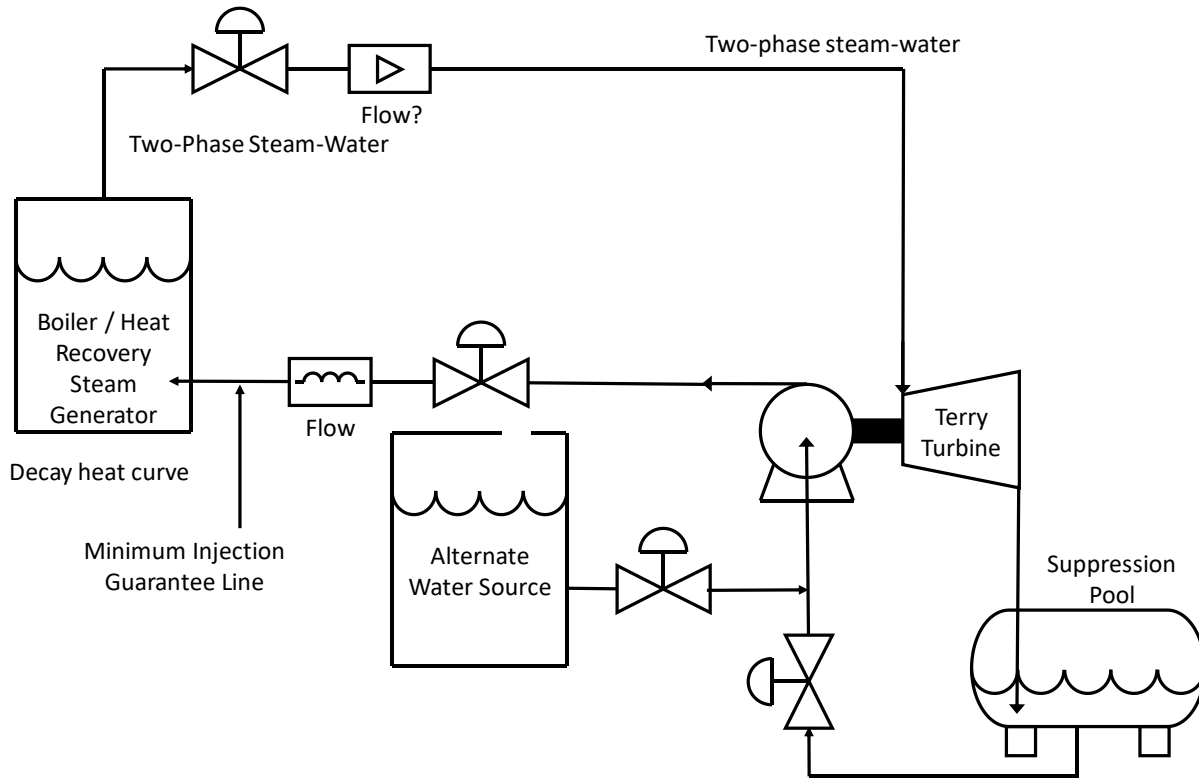
Figure 3.2: Full-Scale Analog System

The full-scale full-analog system presents several notable challenges. It is likely to be prohibitively expensive and the most costly of the options presented here. Test facilities may reject the idea entirely, as it could entail significant risk to the facility's boiler system and personnel. Facilities, even willing, may lack the resources to conduct the testing in this mode. If time and funding are not limiting factors, it would be possible to construct the full steam facility, including the boiler, or conceivably contract with a steam-operated power plant that is in the process of shutting down.

In addition to the challenge of finding a willing facility, there are physics hurdles involved. While overfilling a boiler/heat recovery steam generator system would likely produce a reasonable analog to spillover from a BWR RPV into the main steam line, it is not guaranteed; there may be behavior differences when compared to filling water above the steam separators and dryers in a BWR. More importantly, measuring the flow of a two-phase mixture can be very difficult, and many instruments will only accept limited ranges of wetness. To get accurate measurements, the steam and water flows could be separated and measured separately, but this would disturb the spillover performance and any oscillatory behavior would be affected.

3.2.1.2. Steam Line Injection Design

An adjustment to the full-analog system from Section 3.2.1.1 offers several remedies to the challenges presented by that system. This alternative is illustrated in Figure 3.3. Here, the pump output is not directly tied to the feedwater system of the boiler, but is

instead injected into the steamflow by a desuperheater system and possibly a mixing vessel of the type illustrated in Section 3.2.1.3 or 3.2.2.3.
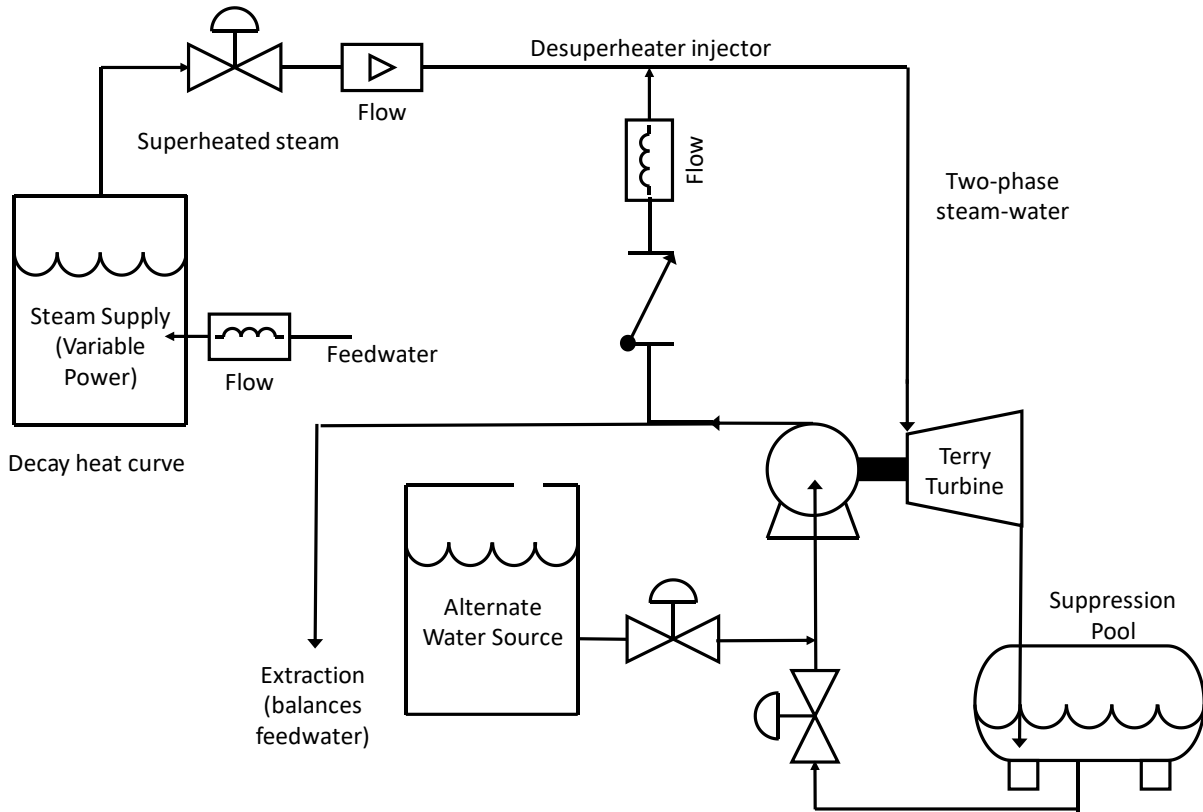
Figure 3.3: Full-Scale System with Water Injection Into the Steam Line

The decoupling of the boiler feedwater from the output of the pump eliminates much of the risk to the boiler from system operations. In addition, flow measurement is greatly improved as there is little need to measure the flow of a two-phase mixture. Each single-phase stream can be independently measured and fully characterized upstream of the mixing point.

Preferably, the system would regulate boiler power but allow the steam pressure to arrive at a natural value for the given conditions. The system would also extract from the pump outlet an equivalent amount of water to the feedwater to the boiler. This would require a good control system, but would maintain the proper mass balance between pump flow and turbine flow. The time-averaged flow through the pump minus a small amount diverted for cooling should match the time-averaged flow through the turbine.

3.2.1.3. Low-Pressure Air Design

While the best analog for a full-scale system would use medium or high-pressure steam as the driving fluid, much of the same insight can be gained by using air instead. Such a setup should be feasible at a commercial testing facility as well as in some university settings. Texas A&M University, in their Turbomachinery Lab, has shown success in

operating a full-scale GS-2 turbine adjusted to operate as a GS-1 with air and water injection. Their operating experience with the Milestone 3 and 4 systems and familiarity with the testing program from prior testing would provide significant benefits. The full-scale air-water system, shown in Figure 3.4, would be a modification of the existing test facility.
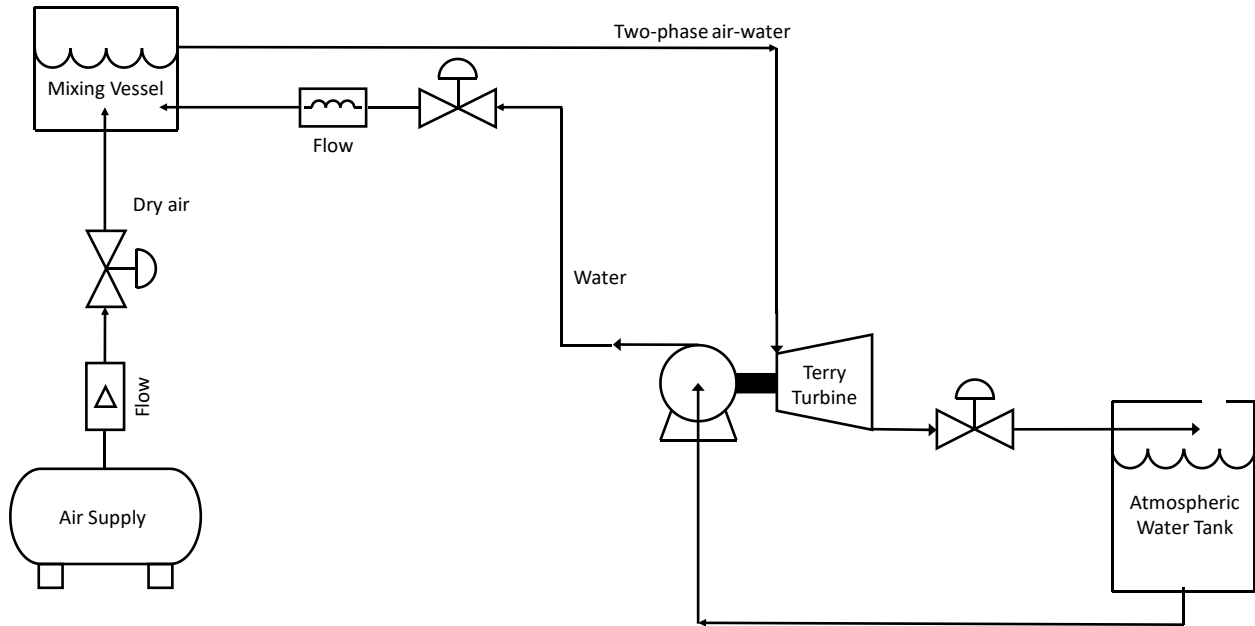
Figure 3.4: Full-Scale Air-Water System

Here, the inclusion of a mixing vessel and the pump would be the main departures from the previous testing at TAMU. The air supply would be set to maintain a desired pressure while the pump attached to the turbine would draw water from an atmospheric tank and direct the flow into a mixing vessel, which would be able to run at all regularly obtainable pressures in the lab. The air and water would both flow into the vessel, and a large drain on the side would be piped to the turbine inlet. This is intended to mimic the spillover effects into the main steam line from an overfilled BWR RPV.

This option is expected to be less expensive than full-scale steam testing at a commercial facility, though it may be more expensive than a small-scale facility, as the full-scale pump still needs refurbishment work. However, it does introduce certain distortions. Phase change effects, which may be especially important in nozzles, will be eliminated in the water-air system, which may result in different flow regimes entering the turbine. A potential modification of this concept is to divert some of the water flow so that the mass flow through the turbine and pump will be balanced. Barring any unexpected phenomena, the scaling rules developed from the work in Milestones 3-5 should be adequate to address the distortions introduced here.

3.2.2. Scaled Designs

Scaled testing would utilize a Terry ZS-1 turbine. At this scale, testing could be accomplished by a commercial testing facility or a university research laboratory. TAMU can conduct low-pressure air testing in the turbomachinery laboratory and low-pressure steam testing in the NHTS Laboratory. While the system would be scaled down from the full-scale system, it is expected that the scaling rules developed as one of the outcomes of the work in Milestones 3, 4, and 5 would be more than sufficient to address this issue.

3.2.2.1. Extended Milestone 4-Style Testing

Proof-of-concept testing for uncontrolled feedback will be performed as part of the Milestone 4 scaled turbine testing efforts [2]. This testing will occur in the NHTS Laboratory; a simplified diagram of the arrangement is shown in Figure 3.5. Here, steam is provided by setting the steam generator to a constant power and maintaining its water level via separate feedwater. The steam control valve is maintained in a fixed mostly-open state during the test.

Water will be drawn from the lab's suppression chamber, which also collects and condenses the exhaust from the turbine. Its pressure and temperature can be shifted to explore different turbine backpressure and pump suction conditions. The water drawn through the turbine-driven pump will be injected into the steam line downstream of the steamflow measurement point, and the flows and thermodynamic conditions of both the water and steam will be known. The resulting two-phase steam-water mixture will be directed into the turbine inlet. The faster the turbine runs, the more water will be injected into the steam line, thereby degrading the turbine's performance. If an overspeed trip is not triggered as time progresses, the test is expected to either move toward a stable steady state or to a state of consistent oscillations.
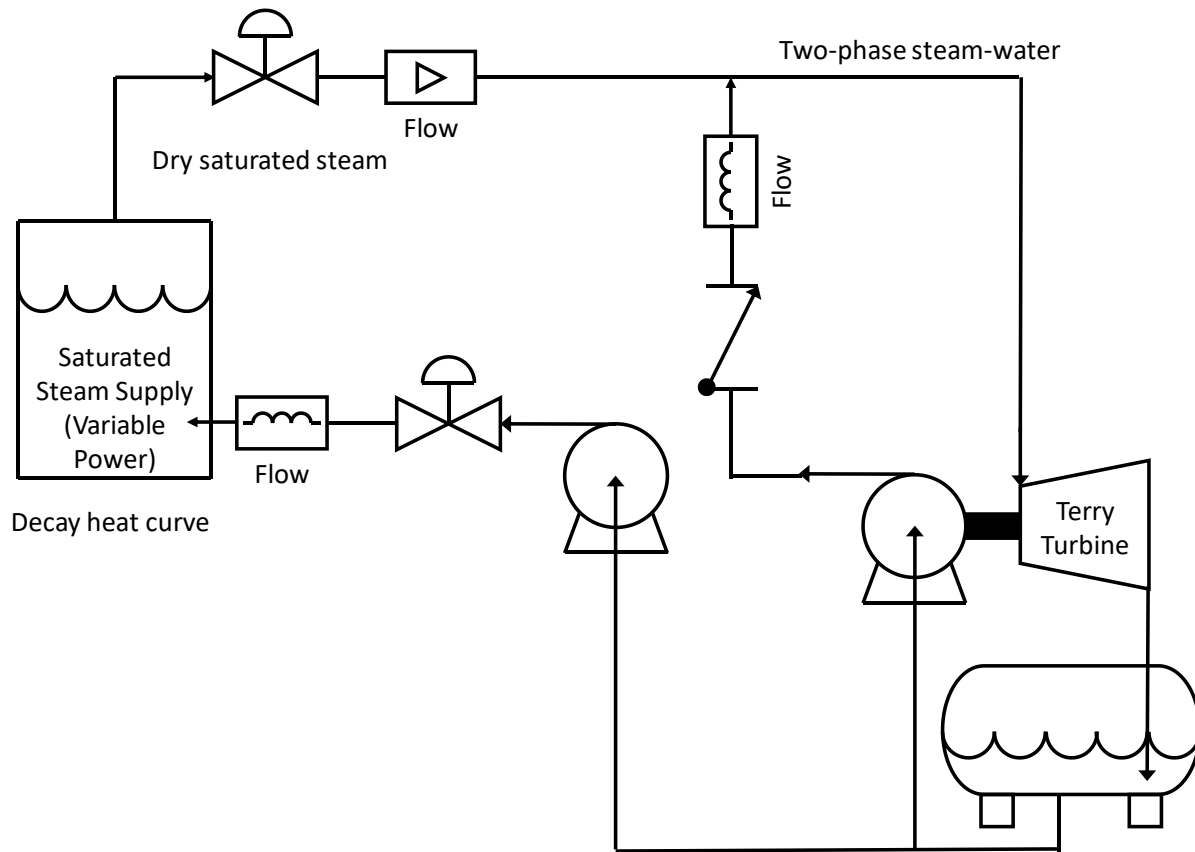
Figure 3.5: Milestone 4 Uncontrolled Feedback ZS-1 Configuration

This design has a mass imbalance distortion, since more mass will flow to the turbine than flows through the attached pump. The mass of the dry steam will be provided by a separate pump, so the turbine loading will be less than if the attached pump provided the full mass flow.

Under the auspices of Milestone 4, only a limited number of tests will be run. Under Milestone 6, the same facility in the same configuration can be leveraged with a much-expanded set of test matrices. The NHTS facility can be modified to use either of its two pumps with little to no construction or expense.

3.2.2.2. Mass-Balanced ZS-1 Testing

The approach utilized in Milestone 4 testing and detailed in Section 3.2.2.1 can be improved to remove the mass imbalance distortion. With some modifications to the existing system, the full complement of time-averaged flow through the ZS-1 turbine will be matched by the attached pump; this is depicted in Figure 3.6.
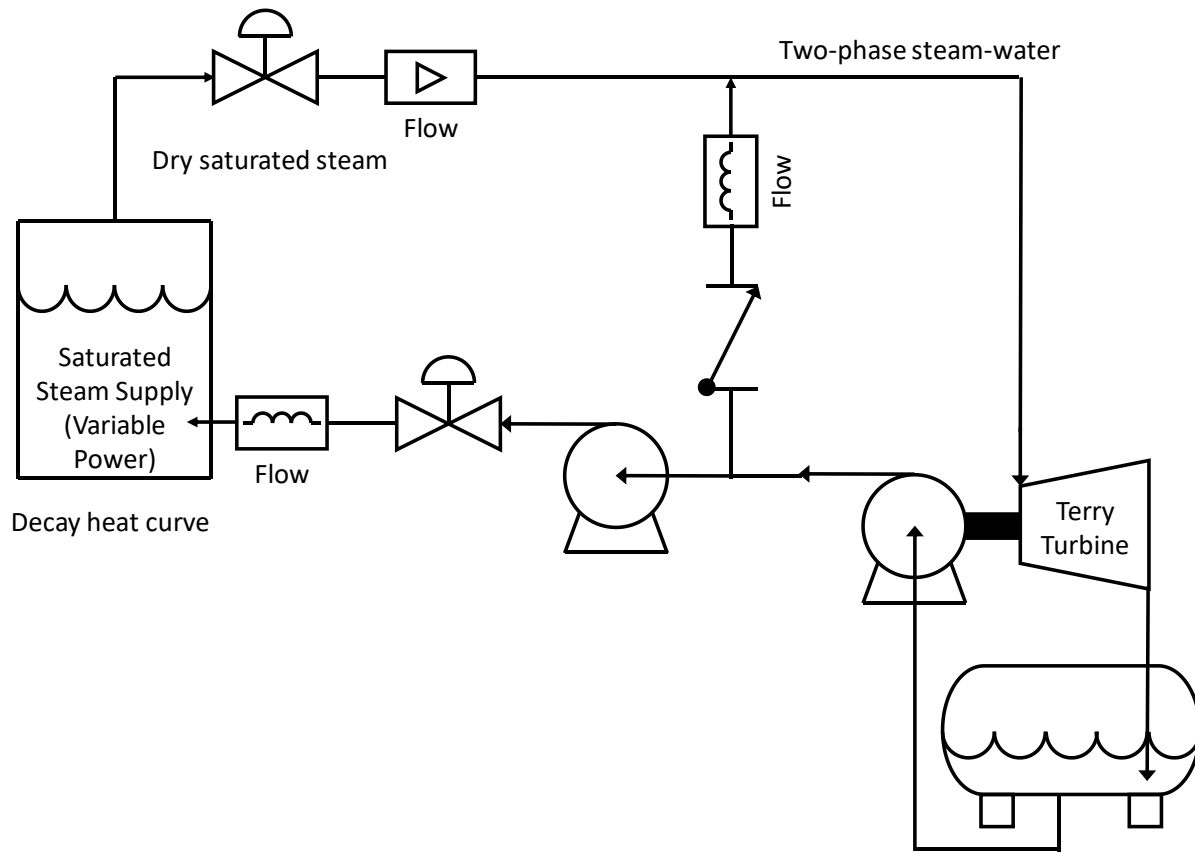
Figure 3.6: A Mass-Balanced Approach

The pump attached to the turbine draws water from the suppression chamber. Downstream of the pump, the flow is divided into a feedwater portion and the remainder is directed into the steam line. The feedwater portion flows through an additional booster pump and regulating valve to precisely control the flow into the steam generator. The portion of flow from the turbine-driven pump that is in excess of the boiler's feedwater needs will be redirected, maintaining the correct feedwater flow. The redirected portion is injected into the Main Steam Line, creating the two-phase steam-water flow that enters the turbine. Though slight transient mass flow imbalances are possible, the flow entering the turbine will match the pump flow when averaged over time.

If the operating point of the turbine-driven pump results in insufficient feedwater flow, the feedwater booster pump will draw additional water through the turbine-driven pump to compensate. Should the pressure in the line between the pumps fall below that of the main steam line, a check valve in the water injection line will close and prevent steam ingress into the feedwater booster pump suction. This state is equivalent to an underfilling state in a full-scale BWR on RCIC, except that here feedwater is guaranteed to the steam generator. In a plant, an underfilling state this could lead to uncovering of the fuel. This state is not a self-regulating RCIC mode, and therefore is not here

considered a significant distortion; instead, the state will be recorded as non-self-regulating.

This approach largely leverages existing equipment, installation, and expertise. As it does require some modification to the system installed at the NHTS lab, there would be additional time and equipment costs beyond those of Section 3.2.2.1. However, those costs are expected to be small.

3.2.2.3. Mixing Tank-Based Injection

An overall mass-balanced design can still allow for transient imbalances that may occur in full-scale systems. A modification to the Milestone 4 setup detailed in Section 3.2.2.1, as shown in Figure 3.7, can achieve this.
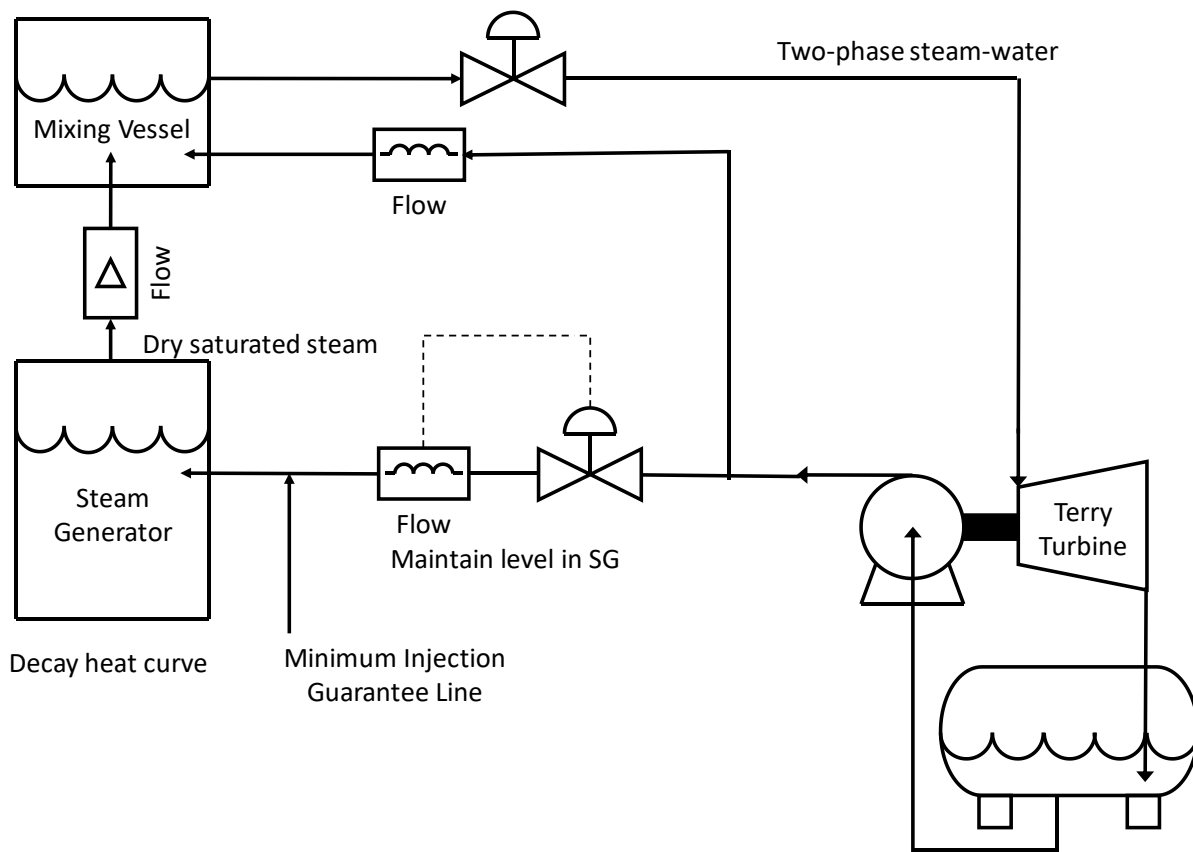
Figure 3.7: Mass-Balanced Approach with a Mixing Vessel

Under normal conditions with this design, the turbine-driven pump on average provides the complete feedwater flow to the steam generator and any excess is directed to a mixing vessel in the Main Steam Line. The feedwater quantity is regulated by a control valve in the feedwater line; care must be taken to avoid excessive pressure losses in the line and through a full-open feedwater valve as well as elsewhere in the system. The concept in Section 3.2.2.2 avoids this potential issue by use of a booster pump.

The mixing vessel provides a potential improvement to the system over other designs, as it allows for the steam and water to flow into the downstream steam line in a more discontinuous manner than simple direct injection of water into the steam line. As the water level in the vessel rises, it may spill over into the steam line as intermittent slugs or plugs, which may be a better analog for an overfilled reactor spilling water to the main steam line than a continuous stream.

3.2.2.4. Scaled Low-Pressure Air Design

The scaled low-pressure air design would be largely identical to the design of the full-scale low-pressure air design detailed in Section 3.2.1.3. However, the components themselves would be smaller; e.g., instead of a full-scale Terry GS turbopump skid, a ZS-1skid would be employed along with an appropriately-sized pump. Their interconnections would be the same, and this arrangement was shown in Figure 3.4.

3.2.2.5. Scaled Low-Power Steam Design with Containment Response

At TAMU in the Department of Nuclear Engineering, undergraduate students in their senior year are placed in 3-5 person teams and, over the course of a full academic year, complete an integrated design challenge. One such senior design team in the Class of 2019 was issued a challenge to design an experimental facility to perform scaled Milestone 6 testing. The design was required to make use of both the Heavy Liquid Metal Test (HELMET) facility heat source and Surtsey containment facilities.

The HELMET system belongs to Argonne National Laboratory and can provide controlled heating power up to 119 kW. It was originally designed to operate with liquid lead for high-temperature applications [21], but can be adapted to boil water as well. It uses seven 17-kW cartridge heaters arranged in a tubular vessel.

The Surtsey facility at SNL was built to explore direct containment heating and approximates a one tenth linear scale of a pressurized water reactor (PWR) containment. It is a pressure vessel into which experiments would be installed and operated [22], allowing for large-scale replication of in-containment structures. Its major component is a vertically-oriented 3-m diameter by 12-m tall pressure vessel.

Here, the HELMET boiler would be assembled inside the Surtsey vessel. In addition, an analog to a BWR suppression pool would be included either as an interior structure or as an exterior vessel connected to the Surtsey vessel in the manner similar to a BWR with the Mark I containment design. A Terry ZS-1 turbopump would be installed outside the Surtsey containment and piped to both the HELMET boiler and the suppression pool analog. A diagram of this arrangement, as developed by the senior design team, is shown in Figure 3.8 [23].
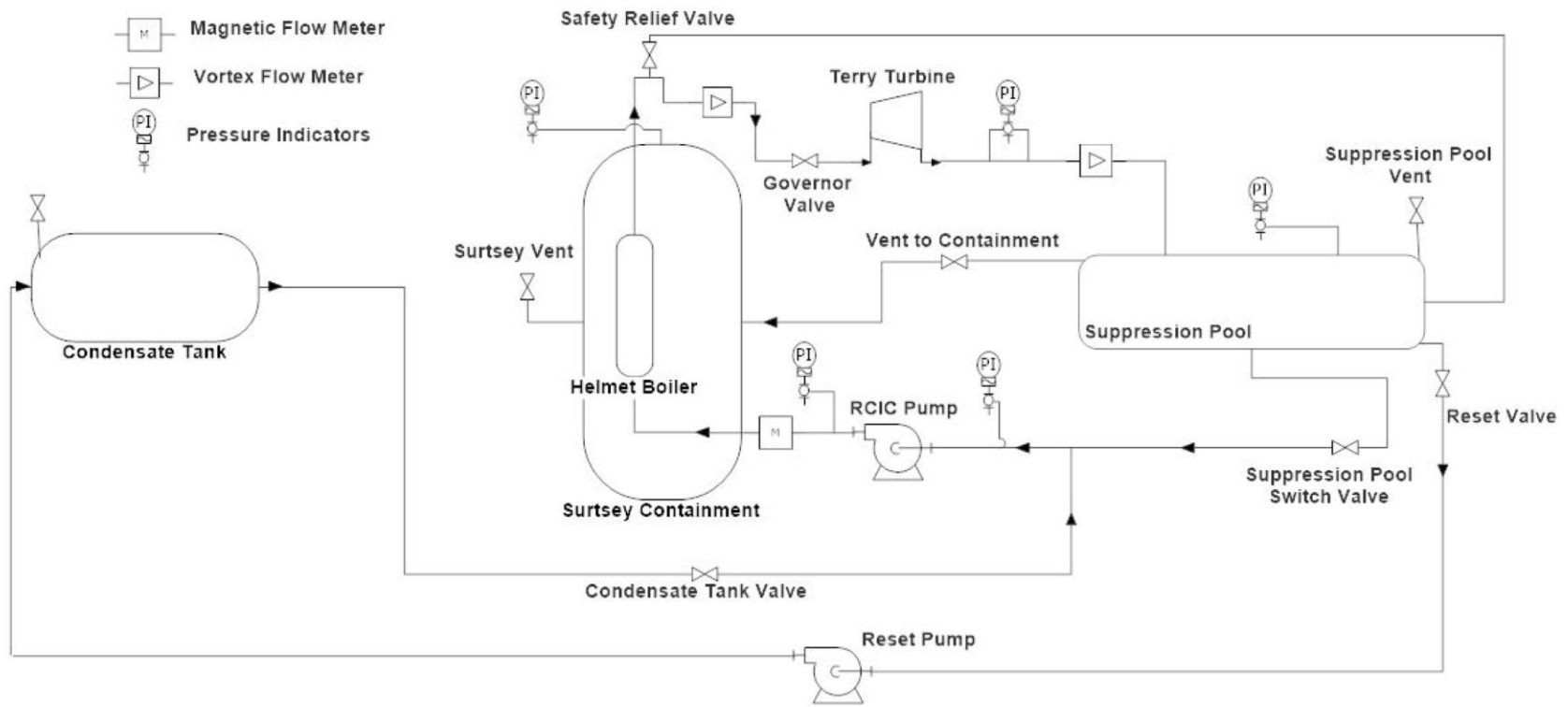
Figure 3.8: Surtsey and HELMET-based System [23] Allowing for Containment Response

This design considers the exploration of drawing RCIC suction from both the condensate storage tank (CST) as well as the suppression pool. Therefore, it could investigate the effects of source switchover. In addition, the effects on the wetwell and drywell volumes can be considered. However, it is limited by the low power of the Surtsey heaters. At 119 kW, it is only about three fourths of the power of the NHTS steam generator and thus will not be able to supply as much steam to the turbine, thereby limiting it to lower operating pressures.

3.3. Preliminary Considerations and Commentary On Proposed Configurations

The experimental designs presented here are only intended for integral investigation of the uncontrolled/self-regulating feedback mode, and in most cases are intended to fully replicate Fukushima Daiichi Unit 2. Should other tests fall to Milestone 6 or additional tests proposed, they might require additional designs. The recommendations and commentary here are preliminary and not binding or final.

Of the two full-scale steam systems proposed, the method of injecting water into the steam line rather than the boiler is believed to be more amenable to the needs of the project. It is expected to not only cost less but to provide better data. In addition, should related testing be desirable, that design appears to be more flexible as the boiler has more operational freedom; it is not tied to the pump response. However, it is still expected to be costly when compared to scaled testing.

The scaled steam tests are essentially variants of each other. They are expected to be much less costly than full-scale steam tests. The exception to this could be the design using HELMET and Surtsey to achieve integral containment responses, as it would require significant assembly in a national lab setting.

The quickest and cheapest option would be to leverage the existing TAMU facility from Milestone 4 proof-of-concept tests without significant modification as described in Section 3.2.2.1. However, as both of the improvements detailed in Sections 3.2.2.2 and 3.2.2.3 are not expected to introduce burdensome financial or timing issues, either of those is thought to better fulfill the needs of the program as they both reduce the distortions present in the proof-of-concept system.

The concepts in Sections 3.2.2.2 and 3.2.2.3 are very similar, and it may be possible to hybridize them. Of the two, Section 3.2.2.2 is thought to be slightly easier to implement on the existing system. The other option, Section 3.2.2.3, will require the procurement of an additional pressure vessel and therefore will require more time and funding; however, the mixing vessel may prove a better analog to the behavior of an overfilled BWR RPV than the current spritzer-style water injection system in the steam line. There are potential drawbacks in this approach as operators would have a slight reduction in direct control of the system and the mixing vessel may introduce dynamics that are difficult to characterize.

Air testing may provide interesting insights into system behavior. However, for scaled testing, steam is the preferred fluid. Full-scale air testing, however, may provide reasonable full-scale performance at a reasonable price. To address concerns that the

use of air instead of steam would provide an incomplete assessment of system performance, this full-scale air testing could be performed in parallel with scaled steam testing.

3.4.   Milestone 6 Development Progress

Milestone 6 is at a very early stage in development. Completion of Milestone 4's proof-of-concept testing is crucial for the full development of Milestone 6, and Milestone 5 should be developed into a final form in order for the TTEXOB consortium to fully determine its needs from Milestone 6 testing. Milestones 3 and 4 are nearing completion and Milestone 5 has yet to be finalized. Therefore, some testing conceptualization can be performed, but there may be considerable adjustments in the program's needs that will alter the design and test criteria.

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4.   MILESTONE 7 PROGRESS – SYSTEM-LEVEL MODELING AND SIMULATION

Airflow testing was performed at Texas A&M University (TAMU) for the GS-2 Terry turbine in FY19 [5]. The GS-2 Terry turbine has a larger diameter (24 inches) than the ZS-1 Terry turbine (18 inches) modeled in FY18 [19, 24]. A MELCOR model was made for the TAMU airflow testing of the GS-2 Terry turbine during FY19 and the results are compared to the experimental data in Section 4.1. A major insight gained during modeling of the GS-2 Terry turbine is that the windage loss/turbine torque coefficients determined through modeling of the ZS-1 could be applied to the GS-2 model and return reasonable results, which suggests that these coefficients do not scale with turbine size as was assumed previously. The TAMU airflow tests were modeled in MELCOR 2.2 revision 12925.

Additional RCIC system-level modeling performed in FY19 included modeling of the Fukushima Daiichi Unit 2 accident. A MELCOR model of the Fukushima Daiichi Unit 2 reactor core, reactor vessel, containment, reactor building, and RCIC turbine/pump was used to model the accident sequence. The current best-estimate model results shown in Section 4.2 are an improvement over the results obtained during FY17 [18], as shown by an improvement in the predicted boiler pressure compared to the recorded data from the accident. There are many unknowns in the RCIC modeling such as the losses associated with the RCIC turbine wheel and the effect of turbine size on the RCIC operation. These unknowns can be investigated by additional modeling of existing experiments. These Fukushima Daiichi Unit 2 analyses were modeled in MELCOR 2.2 revision 11932. The model itself is described in a previous progress report [18].

4.1.   TAMU Terry GS-2 Turbine Airflow Modeling

In FY18, system-level Terry turbine modeling was performed for airflow testing on a ZS-1 Terry turbine at TAMU using MELCOR [19]. The MELCOR modeling of the ZS-1 Terry turbine found that losses associated with the RCIC turbine wheel, such as friction and wheel windage, may be larger than anticipated and important to modeling the RCIC turbine in Fukushima Daiichi Unit 2 [19]. Another important modeling insight was that the RCIC turbine could develop the same power at different speeds, depending on the flow conditions.

Airflow testing was performed at TAMU for the GS-2 Terry turbine in FY19 [5]. All U.S. RCIC applications use a G turbine frame size [24], which has 24" nominal diameter Terry turbine wheel and is larger than the 18" ZS-1 turbine wheel previously modeled. The GS-1 frame has 5 steam nozzles on the lower-half where the GS-2 frame has 10 steam nozzles in total, with nozzles on the upper and lower halves [24]. Airflow tests were conducted with a GS-2 Terry turbine; however, the upper bank of nozzles were blocked off, which essentially converted the GS-2 turbine into a GS-1 turbine [5].

4.1.1.   Description of Experiment

Figure 4.1 shows the testing configuration used for the TAMU GS-2 airflow tests [5]. The airflow tests were the only ones modeled during FY19; however, additional experiments were performed with this configuration, such as two-phase (air and water)

testing [5]. The goal of these experiments was to characterize turbine performance as a function of airflow and speed. Dynamometer loading was used to control the turbine speed for different speed and flow conditions. Once the turbine was at the desired speed and at steady-state, data was recorded. The air and air-water tests were performed for turbine inlet pressures of approximately 138 to 483 kPa (20 to 70 psia) [5]. For the FY19 modeling, only the air tests at approximately 345 kPa (50 psia) were modeled due to time constraints. Additional testing such as governor valve and trip/throttle testing were also performed as part of the FY19 experimental work scope [5].

Figure 4.2 shows the turbine mechanical power versus speed, colored by the approximate turbine inlet pressure, for the GS-2 airflow tests. Data was collected for the airflow tests at turbine speeds between 380 and 3601 rpm. Figure 4.2 illustrates that the GS-2 turbine can reach the same power at two different speeds.

Figure 4.3 shows the measured turbine inlet pressures versus the airflow through the steam nozzles for the GS-2 turbine. The relationship is linear and not parabolic, which indicates that the flow is choked instead of friction-restricted. Choked flow is a limiting flow condition where further decreasing the downstream pressure will not affect the flow conditions in the nozzle [1]. It is convenient for modeling the GS-2 turbine/nozzles as the mass flow rate is independent of downstream pressure, and only depends on the upstream flow conditions. The odd features in the plots for 345 kPa is the result of using multiple sets of tests with somewhat different inlet air temperatures.
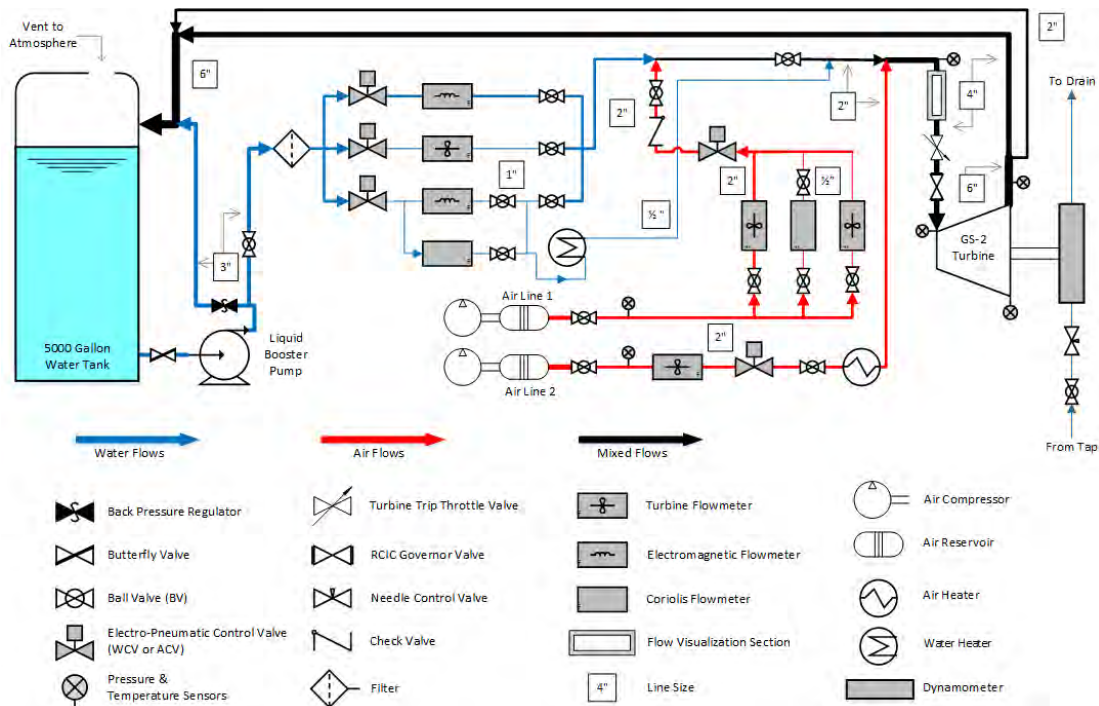

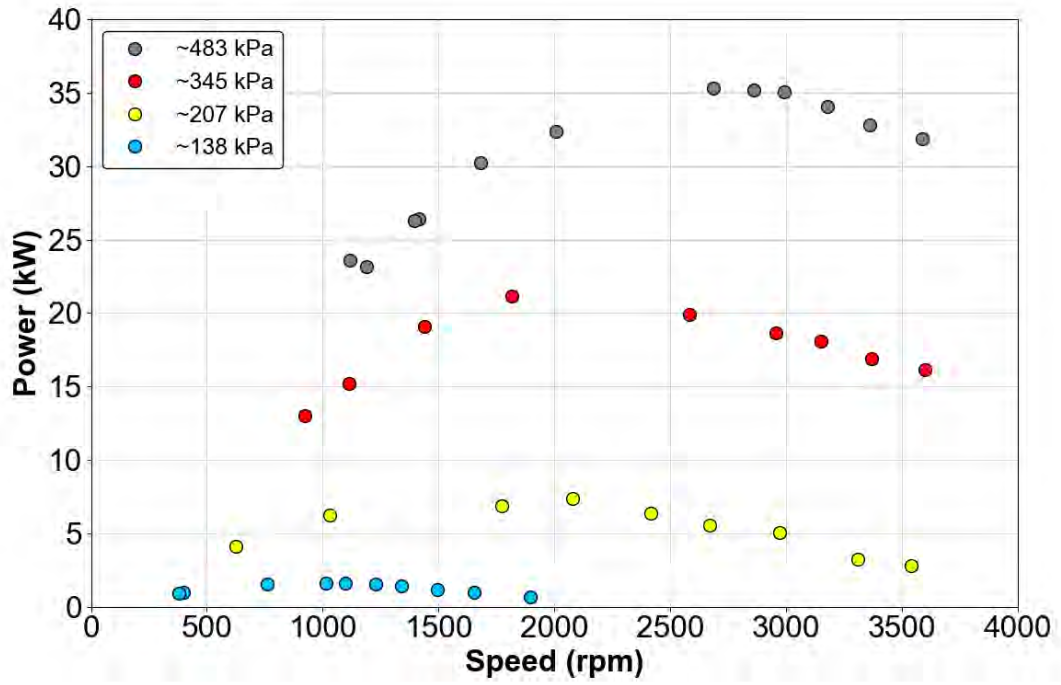**Figure 4.1: Experimental Configuration of GS-2 Air-Based Tests [5]**

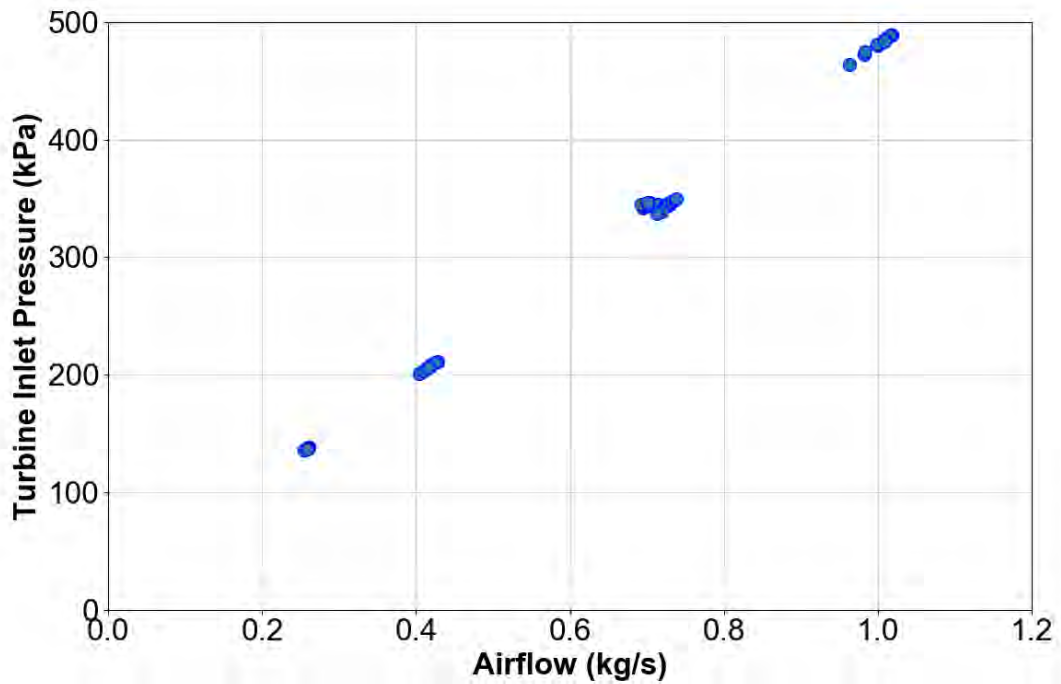**Figure 4.2: Measured GS-2 Power vs. Speed (colored by inlet pressure)**

Figure 4.3: Measured GS-2 Turbine Inlet Pressure vs. Airflow [5]

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4.1.2. *Description of MELCOR Modeling of the TAMU GS-2 Airflow Experiments*

A visual representation of the MELCOR modeling of the GS-2 airflow tests is shown in Figure 4.4. MELCOR modeling was performed for the airflow tests at approximately 345 kPa (50 psia). For a given flow condition, the air tank pressure and temperature were set according to the data and the air tank valve open fraction was adjusted to match the model with the experimental mass flow rate. The peak resistive torque developed by the dynamometer and the peak turbine speed were specified in the RCIC turbine equations. The model was brought slowly up from zero speed to the specified turbine speed (or to peak model turbine speed if the model speed was smaller than the experimental value). The model's peak turbine power was compared to recorded values from the experiment. As the GS-2 airflow tests have choked flow, the flow paths downstream of the turbine could be simplified. In future modeling, these flow paths will be represented by flow paths and control volumes that capture the downstream piping configuration from the turbine exhaust to the environment.

The raw torque developed by the turbine and windage losses were represented by Eq. (4.1) and (4.2) in the model. The raw turbine torque and windage loss equations had the following form, respectively:

$$Turbine\ torque_{raw} = r \times \dot{m} \times c_{torque} \times [(V_{in} - V_{out})\cos(\alpha) - 2r\omega] \qquad (4.1)$$

And

$$Windage\ Loss = c_{windage} \times \omega^2 \qquad (4.2)$$

where 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), 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. Additional explanation of these equations and modeling information are contained in the ZS-1 modeling documentation [19]. The two coefficients were set to match the reported net turbine torque at a given turbine speed and nozzle flow condition. More information is given on this in Section 4.1.3.

The GS-2 airflow modeling is similar to the previous ZS-1 modeling [19] with the following key differences:

- Turbine diameter: ZS-1 is 18" in diameter, while GS-2 is 24" in diameter, and

- Number of Nozzles: ZS-1 uses one nozzle, while the GS-2 model uses 5 nozzles.
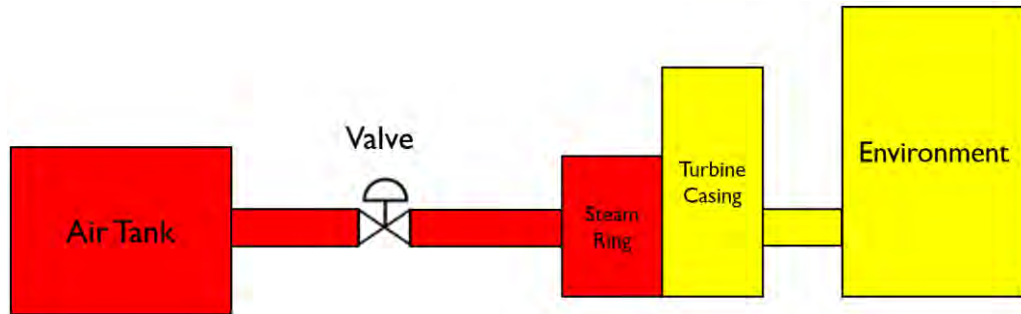
Figure 4.4: MELCOR Representation of GS-2 Air Test Experiment

4.1.3. *MELCOR Results*

MELCOR results for the GS-2 airflow test with turbine conditions 345 kPa, 1818 rpm, and 0.714 kg/s are shown in Figure 4.5 and Figure 4.6. These conditions resulted in a net turbine torque of 111 N-m and a corresponding 21.1 kW of turbine power. The raw torque and windage loss coefficients were calibrated to match the reported turbine speed (Figure 4.5) and power (Figure 4.6) for the selected mass flow rate and turbine inlet pressure. The coefficients were determined through calibration to be c_{torque} = 2.53 and $c_{windage}$ = 3.07×10^{-7}. This specific test was chosen for calibration as 1818 rpm is where the RCIC turbine operates at peak efficiency for the inlet pressure ~345 kPa air tests (see Figure 4.2).

Figure 4.6 shows the turbine power. The windage losses are not significant for this specific test, which is different than previously observed during the ZS-1 modeling [19]. There are a few potential explanations. First, there are likely multiple coefficients pairs that will yield the same speed/torque; a different coefficient pair may be more appropriate for the GS-2 modeling. Secondly, windage losses scale by turbine speed squared. Figure 4.7 shows that the windage losses for a higher speed GS-2 air test simulation at 346 kPa, 3601 rpm, and 0.703 kg/s flow conditions are much higher than for the 1818 rpm simulation. The ZS-1 model chosen for illustration in the FY18 report was at higher speed (2507 rpm) and lower power (~3.9 kW), which may have led to windage losses (~0.8 kW) appearing significant for those specific flow conditions [19].

One of the most interesting insights is seen when applying the calibrated torque and windage loss coefficients from the smaller ZS-1 to the larger GS-2. Figure 4.8 shows a comparison of the TAMU GS-2 airflow data (inlet pressure ~345 kPa tests) in red, the GS-2 model results for the ~345 kPa air tests using the ZS-1 coefficients for raw torque and windage losses in green, and the GS-2 model results for the ~345 kPa air tests using the GS-2 coefficients for raw torque and windage losses (obtained from the 1818 rpm, 345 kPa airflow test) in blue. The coefficients used are in Table 4.1. Even though the two turbines are different sizes, the coefficient values are very close.

Table 4.1: ZS-1 and GS-2 calibrated coefficients used in Figure 4.8

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

Overall, the GS-2 coefficient results match the power/speed trends recorded by the experiments at the different flow conditions. The 1818 rpm point is anticipated to match the data as the coefficients were calibrated to its value. At higher speeds, the GS-2 predicted power values are higher than the measured data except for at 3601 rpm, which very closely matches the data. Future modeling of the GS-2 air tests should include determining the calibrated coefficients for the remaining airflow tests to see how the values compare to the 345 kPa, 1818 rpm calibration point. This would give some information about the sensitivity of these coefficients to the flow conditions.

The ZS-1 coefficient results follow the same trends as the GS-2 coefficient results and the data. At higher speeds, the ZS-1 coefficients perform nearly as well as the GS-2 determined coefficients. This has large impacts for RCIC turbine modeling as this might indicate that the torque and windage loss coefficients do not scale with turbine size (as previously assumed) and may only be dependent on the fluid density. This would indicate that the effects of the turbine size on the RCIC performance are captured by the model in other ways, such as the RCIC turbine governing equations. Additional airflow tests should be modeled to determine if this is true for different air flow conditions. Two-phase air-water data was collected for the GS-2 turbine [5] and modeling these flow conditions would help better understand the scaling of the coefficients based on fluid density.
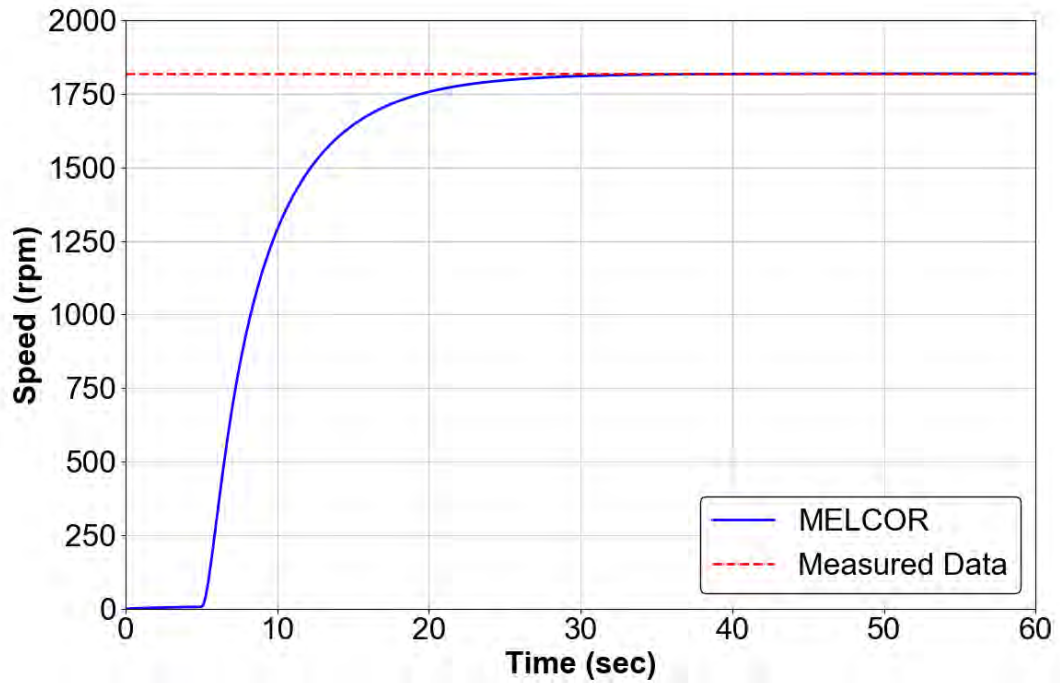
Figure 4.5: Measured GS-2 Speed vs. MELCOR Speed History for TAMU Airflow Test at 345 kPa and 1818 rpm
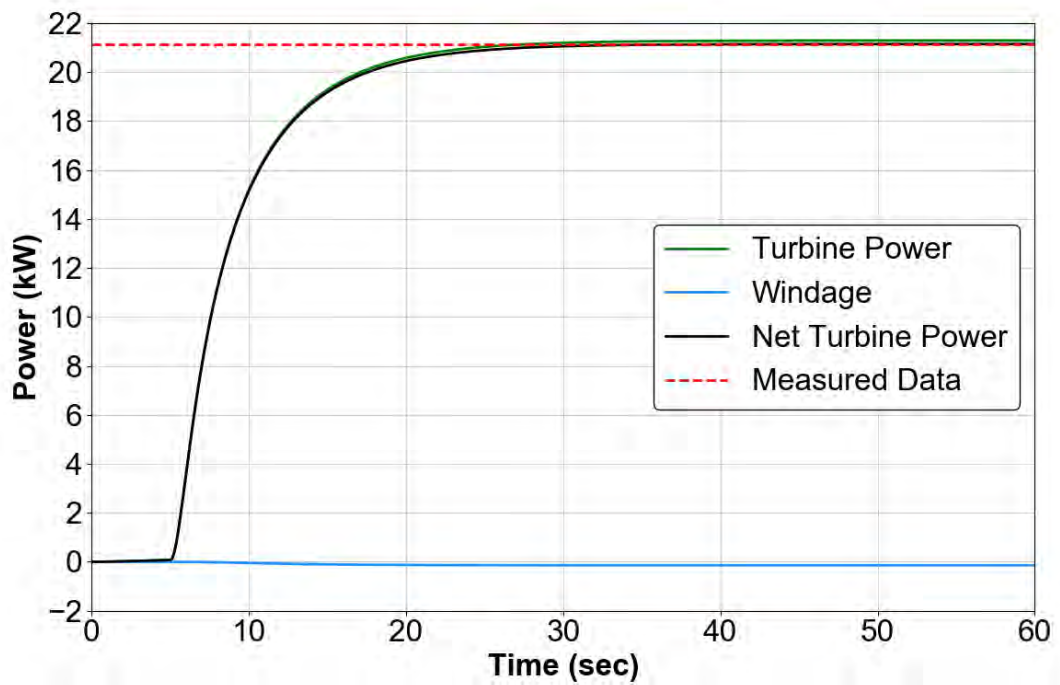

Figure 4.6: Measured GS-2 power vs. MELCOR Power History for TAMU Airflow Test at 345 kPa and 1818 rpm

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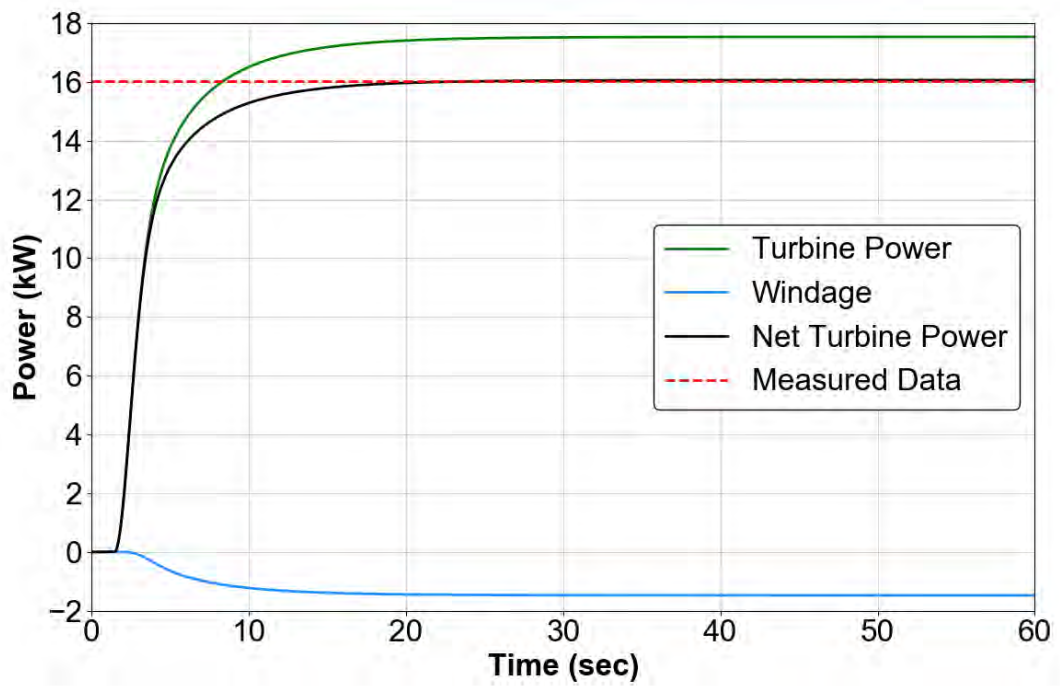
Figure 4.7: Measured GS-2 power vs. MELCOR Power History for TAMU Airflow Test at 346 kPa and 3601 rpm
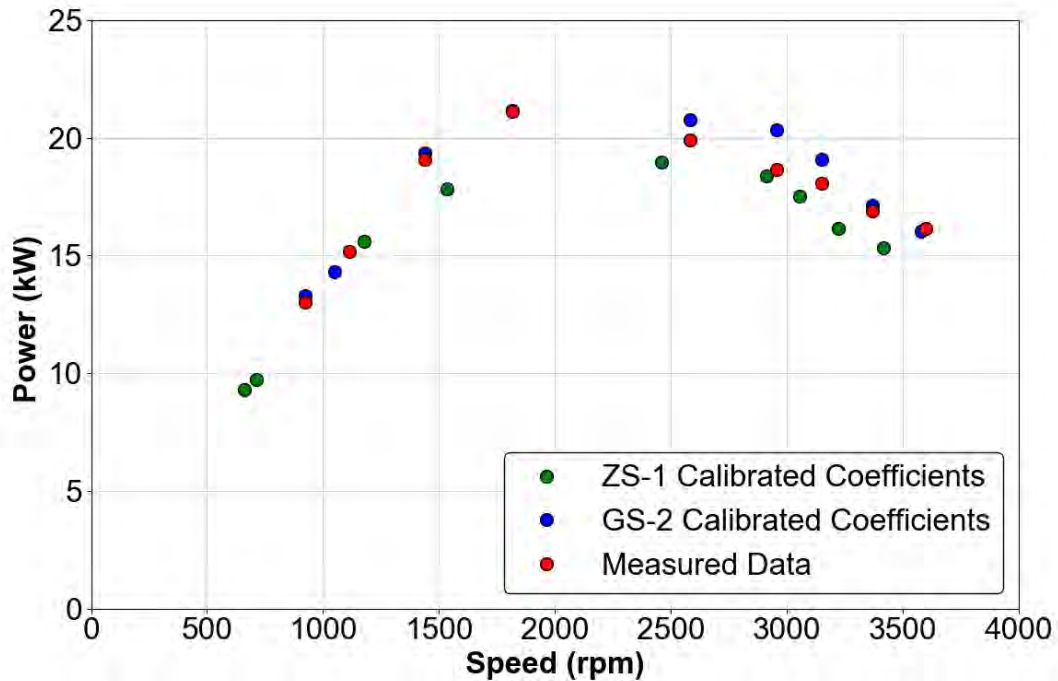
Figure 4.8: Power vs. Speed using the ZS-1 and GS-2 Calibrated Coefficients for Windage Loss and Raw Torque (Table 4.1) Compared to the Measured GS-2 Power for the Air Tests Performed at Turbine Inlet Pressure ~345 kPa

4.1.4. *Terry GS-2 Turbine Modeling Conclusions*

The following were identified as major modeling unknowns for the GS-2 airflow MELCOR modeling:

- Turbine size scaling and

- The coefficients associated with torque and losses.

These unknowns are discussed in further detail below with recommendations for their resolution.

Turbine Size Scaling

The turbine radius is currently captured in the RCIC turbine representation by the equation for the raw torque. Modeling was performed during FY18 on the smaller ZS-1 turbine, and when modeling later initiated for the GS-2 turbine, it was uncertain how the turbine size would affect the model RCIC equations. The turbine size may scale the coefficients associated with raw torque and windage losses, however it is difficult to determine as these quantities were not directly measured during the experiments. The modeling of the GS-2 airflow tests showed that coefficients did not seem to scale

significantly with size (compared to the smaller ZS-1). However, it is important to emphasize that this conclusion needs to be validated by additional modeling of different inlet pressures and flow conditions. Additional modeling of the GS-2 and ZS-1 airflow tests are needed to determine if the coefficients do not scale according to RCIC turbine size.

The Coefficients Associated with Torque and Losses

As mentioned previously, the coefficients associated with torque and losses are unknown and affect the RCIC turbine performance. The windage losses are scaled by the turbine speed squared, which can make the windage losses significant for high turbine speeds. The raw turbine torque scales directly by the torque coefficient, which makes it important to have a good estimate for this value. These values are determined by trial and error or calibration. A potential issue is introduced as neither raw torque or windages losses are reported in the data, only net torque/power, which is a combination of the two terms. There may be many pairs of coefficients that can be used to match the data for the net torque and speed in the GS-2 turbine. Additionally, it is likely that the coefficients will scale depending on fluid density or other operating conditions. These coefficients are important to predicting the performance of the RCIC turbine. Their uncertainty can be addressed by additional modeling of the remaining GS-2 airflow tests. The uncertainty due to fluid density can be addressed by also modeling air-water or steam tests.

Overall Conclusions

The GS-2 airflow Terry turbine test data and modeling showed that it is possible for a Terry turbine to develop the same power for two different turbine speeds while flowing air. This was also seen with the ZS-1 experimentation and modeling. This has large implications for RCIC operations and may help predict how a RCIC turbine would perform in a station black-out scenario. Additionally, the coefficients that scale the RCIC turbine raw torque and windage losses did not seem to change significantly when determined for the larger GS-2 turbine and compared to those determined for the ZS-1 turbine, for the specific air tests modeled. This may imply that for air, these coefficients are not scaled by size, however this needs to be validated by modeling additional GS-2 and ZS-1 airflow tests over a wider range of RCIC turbine boundary conditions. Modeling the GS-2 air-water or steam tests would help determine how the coefficients scale according to fluid density.

4.2. Best-Estimate Fukushima Daiichi Unit 2 Simulation

This section presents the current best-estimate results obtained during FY19 of the MELCOR modeling of Fukushima Daiichi Unit 2, focusing on the RCIC response. Modeling of Fukushima Daiichi Unit 2 was previously performed during FY17 [18]. The FY17 model results did not track the recorded pressure in the accident especially well; however, it was anticipated that by addressing several model deficiencies, the boiler pressure curve could be brought into better agreement with the recorded data [18]. This section includes a description of the best-estimate model and shows the updated results for Fukushima Daiichi Unit 2. The updated results match the boiler pressure recorded data more closely than the previous model.

4.2.1. Description of MELCOR Modeling of Fukushima Daiichi Unit 2

The MELCOR modeling of Fukushima Daiichi Unit 2 RCIC response was previously described in other documentation in 2018 [18] and uses detailed representations of the reactor, drywell, and wetwell and employs a mechanistic representation of a RCIC turbine/pump [26]. A representation of the control volume nodalization of the reactor vessel with the RCIC turbine/pump is shown in Figure 4.9. While the current best-estimate model from FY19 is based on the FY17 model, it has some key differences from the previous modeling.

First is the inclusion of windage loss acting on the RCIC turbine. The windage loss term was incorporated as modeling of the ZS-1 TAMU airflow tests showed that windage losses may be significant in determining the total parasitic losses in the Terry turbine, which influences total turbine performance [19].

Another key difference in modeling Fukushima Daiichi Unit 2 was the reduction of the heat transfer efficiency of the interaction of the feedwater in the downcomer and the steam standpipes. During previous modeling, the steel wrapper separating the steam standpipes and the feedwater was assumed to not have a significant adverse effect on the heat transfer mechanism. This assumption was changed for the current modeling and is discussed in more detail in Section 4.2.3.2.

Additionally, some other unknowns were resolved such as the RCIC turbine nozzle size, the governor valve wide open position, and correcting model errors such as overpredicting condensation of steam and subcooled water in the steam dome/lines. Addressing various model uncertainties and other shortcomings seen in the previous model improved the current best-estimate Fukushima Daiichi Unit 2 prediction of the boiler pressure curve.
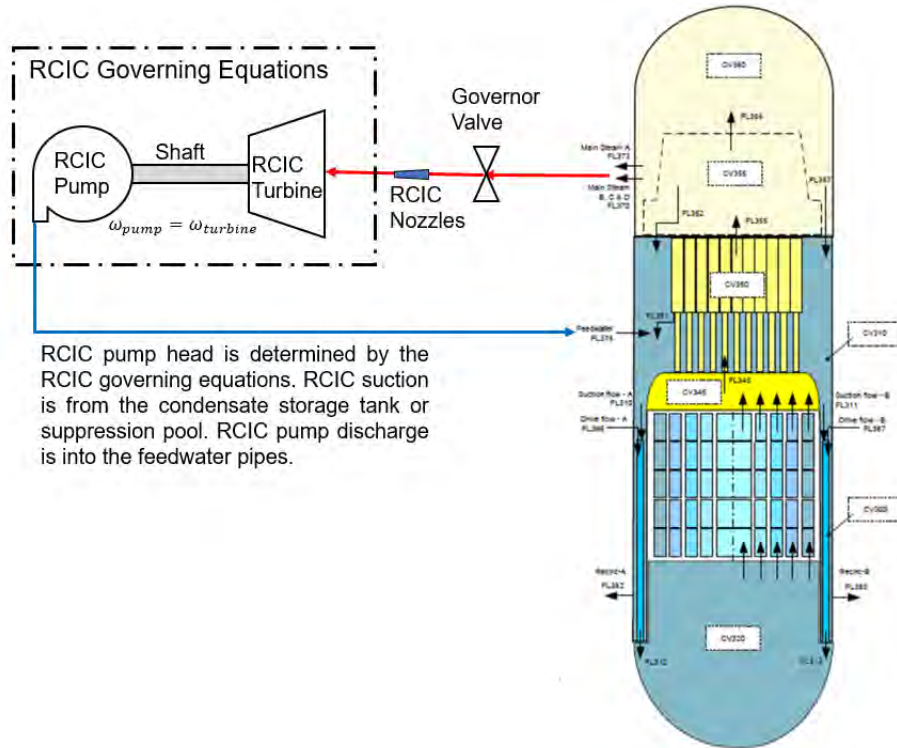
Figure 4.9: RPV Nodalization in MELCOR model

4.2.2. MELCOR Results

This section shows the current best-estimate MELCOR modeling results of Fukushima Daiichi Unit 2. RCIC managed to maintain cooling to the RPV for nearly 3 days (~67 hours) after losing back-up power in Fukushima Daiichi Unit 2 [13]. The MELCOR modeling results show that RCIC was able to self-regulate the water and pressure levels in the RPV and the cooling capacity of the water inflow.

Figure 4.10 shows the Fukushima Daiichi Unit 2 model boiler pressure response with the recorded pressure data. The FY17 results are included in Figure 4.10 for comparison. The FY17 modeling included two different nozzle sizes since the nozzle size was unknown at the time of modeling. The FY19 modeling used a nozzle size of 0.5 inches. The decrease in pressure at 1+ hour is caused by the loss of back-up power and opening of the RCIC turbine control valve, which causes a large increase in RCIC flow. The following increase in pressure is caused by water entering the RCIC turbine nozzle jet after the overflow of the RPV and flooding of the Main Steam Lines. The RCIC system operated concurrently with automatic cycling of the safety relief valves, which results in the observed fluctuations in pressure and turbine speed (Figure 4.11) from about 1.5 to 3.4 hours. The gradual pressure drop starting at approximately 5 hours may be attributed to a leak in a safety relief value (SRV), which may have failed to reseat properly [13].
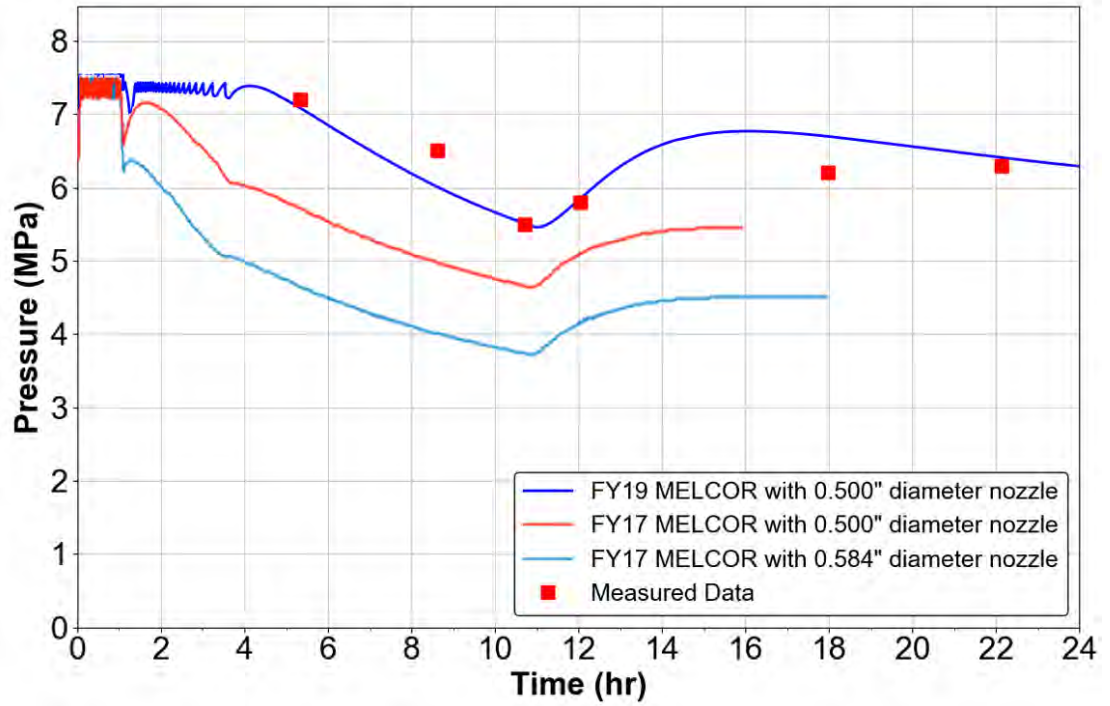
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Figure 4.10: Fukushima Daiichi Unit 2 Reactor Pressure Response With FY17 [18] and FY19 Results
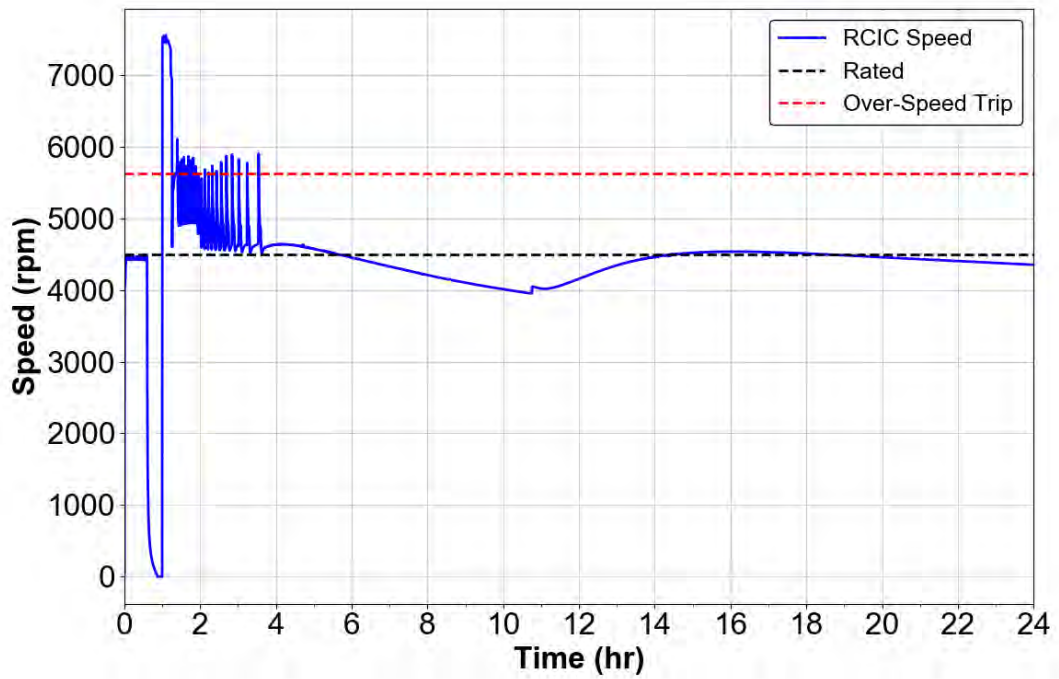

Figure 4.11: Simulated Fukushima Daiichi Unit 2 RCIC Speed

The system switches pump suction sources from the condensate storage tank to the warmer suppression pool at ~11 hours (assumed time). The rise in boiler pressure is a result of warmer water from the suppression pool being introduced into the RPV which has a lower relative cooling capacity, leading to more RCIC flow as the system self-compensates to provide additional volume of water to cool the core. These same observations were made during the modeling in 2017 [18], however several improvements have been made to the MELCOR modeling that bring the current simulation response into closer agreement with the measured pressure data. The current best-estimate results better predict the boiler pressure levels than the FY17 modeling, including capturing the pressure inflection at ~11 hours.

The current best-estimate model makes an important assumption regarding the heat transfer between the water in the downcomer and the steam standpipes. Previous analyses assumed that the wrapper surrounding the standpipes had a minimal effect on the heat transfer between the standpipes and the downcomer region feedwater. However, this assumption was revisited after reviewing the reactor vessel geometry. For the current modeling, it was assumed that the wrapper had a significant adverse effect on the heat transfer by preventing the feedwater from interacting with the steam standpipes. This was incorporated into the MELCOR modeling by reducing the heat transfer efficiency/communication between the surfaces by reducing the associated heat transfer coefficients. This greatly improved the MELCOR boiler pressure curve.
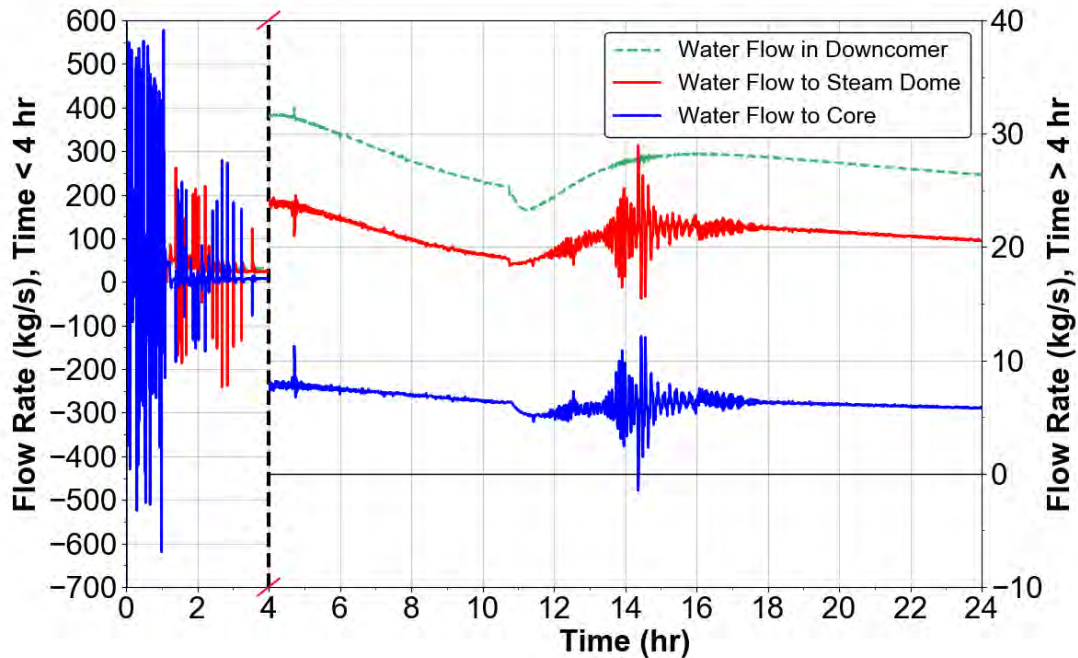

Figure 4.12: Simulated Fukushima Daiichi Unit 2 Water Flow. Vertical Dashed Line Indicates Where Plot Scaling Changes

The current best-estimate MELCOR modeling water flow response is shown in Figure 4.12. The water flows represented in the figure are single-phase (liquid water). The plot has a different scale starting at four hours, as early model fluctuations make it difficult to interpret the plot at later times. The MELCOR model nodalized the downcomer region into upper and lower control volumes. The lower downcomer region is connected to the core in the model by a flow path representing the jet pumps. The model predicts that most of the feedwater did not enter the core by flowing from the upper to the lower region but instead flowed from the upper downcomer region into the steam dome, which overflowed into the steam lines. Because the majority of the water enters the Main Steam Line, water injection into the RCIC turbine leads to reduced RCIC turbine performance. Figure 4.13 shows the effective number of RCIC turbine nozzles that are flowing steam or water. In MELCOR, the phases are separated by default, leading to water pooling in the bottom of the steam ring. This results in the higher elevated nozzles flowing steam while the submerged lower nozzles flow water.
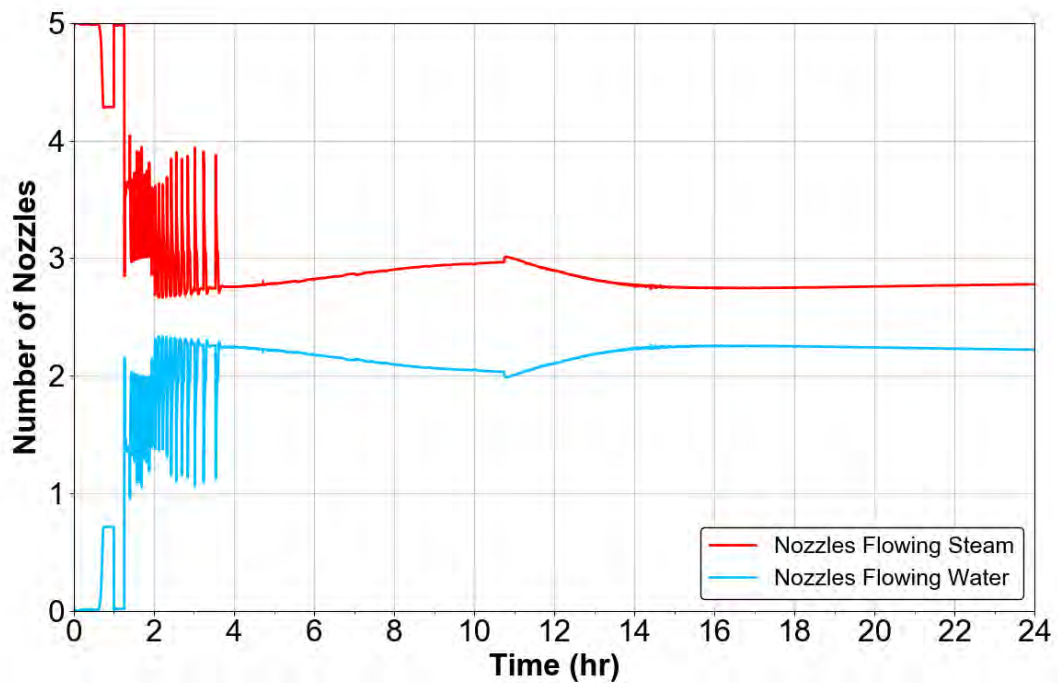
Figure 4.13: Simulated Fukushima Daiichi Unit 2 Nozzle Phase Distribution

Figure 4.14 shows the nozzle steam and water jet velocities through the RCIC turbine steam nozzles compared to the turbine wheel tangential velocity. The figure shows that the water jetting through the steam nozzles moves at a slower velocity than the steam jets entering/leaving the buckets. This results in the water jet acting as drag on the wheel as the jet is slow relative to the turbine wheel, which impedes the wheel motion. The water jet applies a resistive 'slap' torque to the wheel when the back of the wheel buckets impact and deflect the incoming water jet.

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Figure 4.14: Simulated Fukushima Daiichi Unit 2 Nozzle Jet Velocity

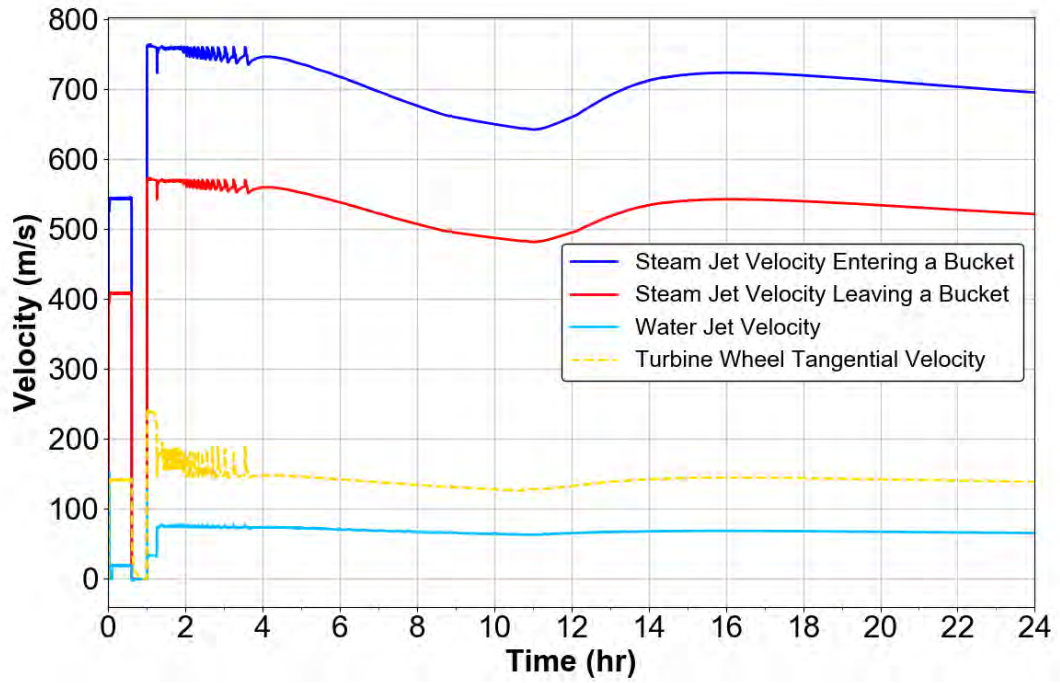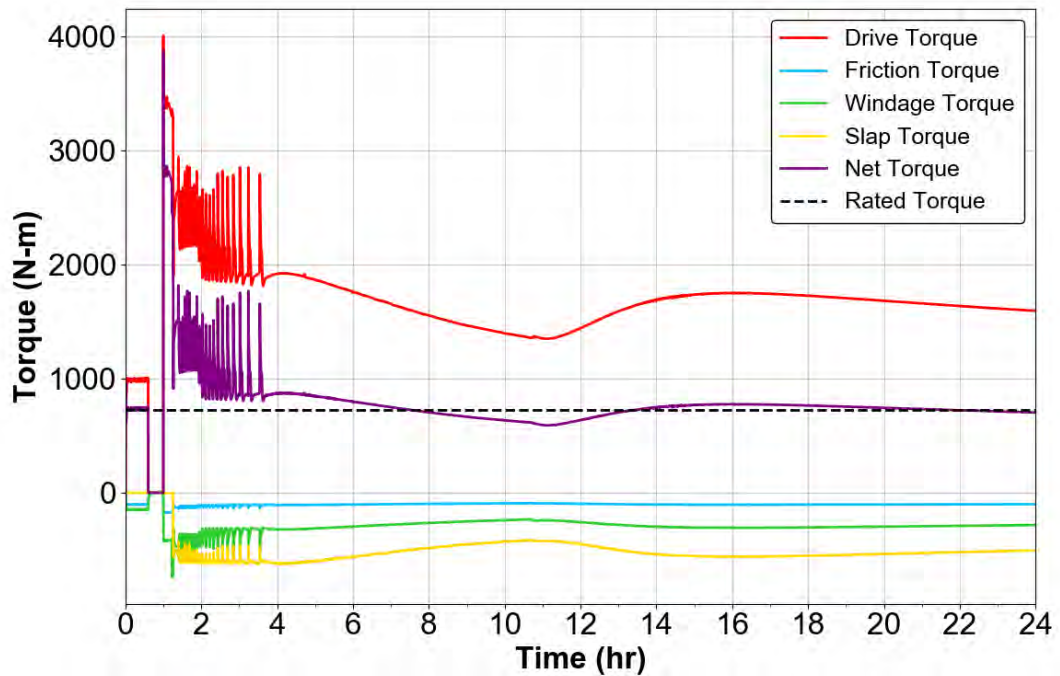**Figure 4.15: Simulated Fukushima Daiichi Unit 2 RCIC Torque**

Figure 4.15 shows the torque acting on the RCIC turbine wheel. The drive torque is the combined torque from the inflows of water and steam that drives the turbine wheel. The modeled water jet impedes the wheel motion, which results in the water driven component of the drive torque equaling zero. The bearing, windage, and 'slap' torques act as resistive torques that impede the motion of the turbine wheel. The 'slap' torque is caused by the drag on the wheel caused by the water jet, and the plot indicates that it is significant. During the ZS-1 airflow tests modeling [19], turbine windage losses were shown to be important. Figure 4.15 shows that the predicted windage and 'slap' torques are both greater than the predicted friction torque. Their inclusion is important for the RCIC modeling as it accurately predicts a reduced efficiency of the RCIC turbine.

Figure 4.16 shows the power developed by the RCIC turbine and the hydraulic power developed by the RCIC pump. The hydraulic power is less than the power developed by the RCIC turbine, which shows the inefficiency in pumping. The fluctuations in power starting at one hour are due to the start of water injection into the turbine and the cycling of the SRV. These fluctuations correspond to fluctuations in turbine speed in Figure 4.11. The MELCOR modeling ignored the over-speed trip, which allowed the RCIC model to continue operating.
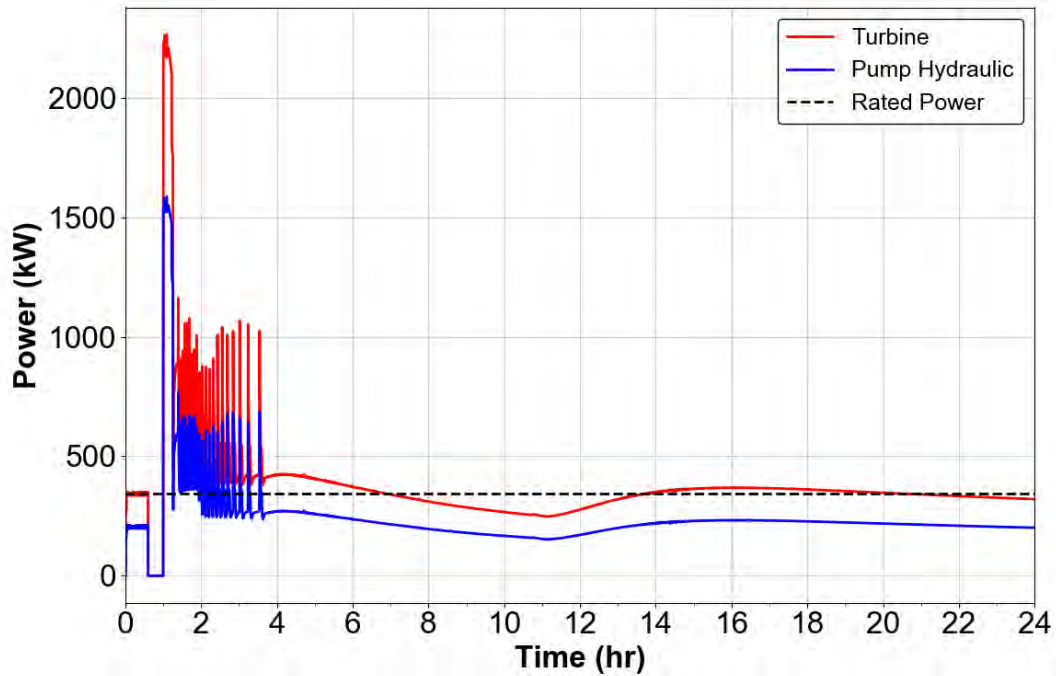
Figure 4.16: Simulated Fukushima Daiichi Unit 2 RCIC Power

Interestingly, the RCIC turbine model predicted turbine power exceeds or matches the rated power early in the operation and at 14 to 20 hours. The turbine would most likely not exceed or match the rated power once water injection into the RCIC turbine begins since this would lead to decreased turbine performance. The overprediction of model turbine power is likely due to modeling uncertainty. The change in power inflection at

about 11 hours corresponds to the assumed time the system switched to the hotter suppression pool, which results in more power being needed to pump an increased volume of water to cool the reactor core.

4.2.3.   *Systems-Level Modeling Conclusions*

The following were identified in FY17 [18] as major modeling unknowns for the Fukushima Daiichi Unit 2 MELCOR modeling:

- Phase separation in a RCIC turbine steam ring and RCIC self-regulation,

- Size of RCIC turbine nozzles,

- Benefit of reversing chambers,

- Jet velocity profile entering and exiting a turbine wheel bucket,

- Resistive torque associated with a water jet,

- Impact on turbine performance of water residing in a turbine casing,

- Possible RCIC recirculation to the CST,

- Unexplained RCIC lack of over-speed, and

- RCIC turbine governor valve wide-open position.

As these model unknowns and their potential resolution have been addressed at length in other documentation [18], they will not be discussed in this report. Since FY17, the following unknowns have been addressed in part: size of the RCIC turbine nozzle, resistive torque associated with a water jet, and RCIC turbine governor valve wide open position. The resolution of these is discussed in Section 4.2.3.1.

During the current Fukushima Daiichi Unit 2 modeling, additional modeling unknowns were identified that should be resolved for better modeling of Fukushima Daiichi Unit 2. These are: the effect of the steel wrapper on heat transfer in BWR modeling, the presence of feedwater in the steam lines, and the windage losses in the RCIC turbine. These are discussed in Section 4.2.3.2.

4.2.3.1.   Addressed System Level Unknown Quantities

The following system level unknowns identified in FY17 [18] were addressed in the FY18 and FY19 MELCOR RCIC modeling.

Size and Number of the RCIC Turbine Nozzles

The size and the number of the RCIC turbine nozzles for Fukushima Daiichi Unit 2, which had been unknown quantities, were ascertained prior to running the current best-estimate models for Fukushima Daiichi Unit 2. The size and numbers of nozzles in the Fukushima Daiichi Unit 2 RCIC turbine were obtained from personal communications with GE, the BWR Owner's Group, and TEPCO with SNL. All relayed the same

information about nozzle sizing and number. These values were incorporated into the current best-estimate model.

Resistive Torque Associated With a Water Jet

The resistive torque associated with RCIC turbine nozzles flowing water was partially resolved. This was done by incorporating the resistive torque equations that were modeled with the ZS-1 TAMU MELCOR models into the Fukushima Daiichi Unit 2 model. The associated coefficients were determined through an iterative trial and error process to yield results that matched the measured boiler pressure curves.

RCIC Turbine Governor Valve Wide Open Position

The governor value open position/withdrawal limit imposed on the turbine governor valve stem was determined by incorporating an appropriate range from [24]. The EG-type governor used in RCIC turbines has a nominal governor valve stem stroke between 0.625" and 0.875" [24]. For the MELCOR modeling, a midrange value was used for the governor valve full-open position. It is important to note, however, that the governor valve withdrawal limit is different for every plant, so this value needs to be adjusted to reflect the range of the specific plant during modeling.

4.2.3.2. Additional System Level Unknown Quantities

The following system level modeling unknowns were identified during the FY19 modeling efforts.

The Effect of the Steel Wrapper on Heat Transfer in BWR Modeling

The effect of the steel wrapper on heat transfer in BWR modeling is an important modeling unknown that should be investigated. The Fukushima Daiichi Unit 2 MELCOR modeling showed better conformity with measured pressure data when the steel wrapper separating the steam standpipes and the downcomer feedwater was assumed to have a non-negligible effect on the heat transfer mechanism. The steel wrapper may create a physical barrier that deflects the assumed flow path of the feedwater from flowing up into the steam standpipes. Previous modeling assumed that the steel wrapper didn't significantly alter the feedwater flow path; however, inspection of the BWR geometry showed that it is likely that the feedwater does not have much interaction with the steam standpipes (as was previously assumed), which would reduce the heat transfer mechanism efficiency. Applying a reduction in the associated heat transfer coefficients resulted in the predicted boiler pressure curve better matching the Fukushima Daiichi Unit 2 data. The effect of the wrapper limiting the heat transfer mechanisms of the standpipes and the feedwater is sometimes not considered during BWR modeling, so this insight warrants additional investigation. This could be performed by a close look at the geometry and additional modeling that focuses on the effects the wrapper has on the fluid flow paths and the heat transfer at the standpipes.

The Quantity of Water In the Steam Lines

The RCIC turbine begins to ingest water at one hour in the Fukushima Daiichi Unit 2 event sequence, following the loss of backup power and flooding of the Main Steam Lines. The current best-estimate simulation predicts that most of the feedwater in

Fukushima Daiichi Unit 2 went to the steam dome (and flooded the MSL) rather than the core, leading to the RCIC turbine nozzles flowing a two-phase mixture (steam and liquid water). As discussed previously, the water injection to the RCIC turbine results in the RCIC turbine wheel slowing down and a reduction of power. The MELCOR modeling of Fukushima Daiichi Unit 2 predicts that the majority of the feedwater enters the Main Steam Lines instead of flowing from the upper to the lower downcomer, which exits into the core. This can be seen in Figure 4.12. The unknown quantity of water entering the steam lines affects turbine performance and can be addressed with additional modeling.

Additionally, MELCOR separates the steam and water phases by default. As a result, water pools at the bottom of the steam ring with a steam atmosphere developing higher in the steam ring. It is currently unknown if this modeling assumption is valid for Fukushima Daiichi Unit 2.

The Windage Losses of the RCIC Turbine

Modeling of the ZS-1 and GS-2 TAMU airflow tests showed that windage losses were not negligible while modeling RCIC turbines [19]. The windage losses were proportional to the square of the RCIC turbine wheel angular velocity. The windage loss term contains a scaling coefficient. The scaling coefficient was calibrated for the ZS-1 airflow modeling to match the recorded experimental data for net torque and power for a single experiment [19]. Windage loss was incorporated in the current Fukushima Daiichi Unit 2 modeling, however it was uncertain how to apply the windage loss coefficient from the smaller ZS-1 turbine flowing air to a larger GS-1 turbine flowing a mixture of steam and water, which is representative of the Fukushima Daiichi Unit 2 RCIC turbine.

Modeling during FY19 of the GS-2 TAMU airflow tests (Section 4.1) showed that the same windage loss coefficient obtained from the ZS-1 modeling could be applied to the GS-2 RCIC turbine and return good predictions of the speed and power curves for turbine inlet pressure ~345 kPa boundary conditions, which suggested that the scaling of the turbine size was captured in other modeling aspects and didn't need to be reflected in the windage loss coefficient. However, it was noted that additional modeling over a wider range of flow conditions is needed to support this conclusion. Also, it is uncertain how the windage loss coefficient is affected by the flow density. The steam and water mixture density will likely scale the windage loss coefficient, which was originally obtained during airflow modeling. As the TAMU airflow test modeling and the Fukushima Daiichi Unit 2 RCIC modeling both show, the windage losses are not negligible and the windage loss coefficient directly scales the calculated windage loss, making this unknown model parameter important to modeling the Fukushima Unit 2 RCIC.

The GS-2 TAMU water and air tests and future steam tests should be modeled to gain a better understanding of how the windage loss coefficient scales with different flow densities, as it is currently unknown how the windage loss changes with fluid density.

Overall Conclusions

The FY19 MELCOR modeling of Fukushima Daiichi Unit 2 is an improvement over the previous best-estimate modeling in FY17 as reflected by an improved prediction of the boiler pressure curve. The current best-estimate modeling addressed some of the model unknowns identified in FY17 to improve model results and used information gained from the FY18 and FY19 modeling of the ZS-1 and GS-2 TAMU airflow experiments to update the current best-estimate model. However, there are still modeling improvements that could improve the MELCOR model results of Fukushima Daiichi Unit 2 and better predict the overall RCIC performance.

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5. SUMMARY

Experimental efforts at Texas A&M University under Milestone 3 and 4 of the TTEXOB program are ongoing in FY19 and nearing completion anticipated in early to mid FY2020. The results of these tests will be used in the further refinement of Milestone 5 and 6 efforts as well as in the modeling efforts belonging to Milestone 7.

The details of Milestone 5 testing continue to evolve with insights from the Milestone 3 and 4 efforts as well as discussions with test facilities and within the TTEXOB. Site visits to commercial test facilities have occurred as part of these development and site selection efforts.

The testing under Milestone 5 is grouped into six areas, five of which have had specific test matrices developed. These tests will occur largely at the low end of the RCIC operational pressure range to below the pressure range, and will explore certain adverse conditions which may be possible under some Beyond Design-Basis Events. In comparison with Milestone 4 turbine profiling, which generally involves quick tests at steady-state, these tests are intended to be much longer in duration (hours to days instead of seconds to minutes).

Milestone 6 efforts have begun in a limited manner. Discussions within the TTEXOB have led to the development of several potential design concepts that could be used to accomplish the current Milestone 6 testing goals. These designs range from scaled test loops that could be operated almost as add-on testing to Milestone 4 to full-scale analogs of the RCIC system. Crucial to further development efforts are the results of the proof-of-concept testing that will be performed under Milestone 4.

Modeling and simulation efforts fall under Milestone 7. The modeling efforts in FY19 have produced insights and improvements in modeling both a Terry GS-series turbine as well as insights into reactor overfill scenarios. Data taken from the Milestone 4 GS-2 air testing at TAMU has been used to improve the parameters used in the model to produce the turbine's output. Of note were the windage and loss coefficients developed from the GS-2 test data; the losses were similar to the prior ZS-1 data, suggesting that the scale differences between the GS and ZS turbines are of limited significance. In addition, the effects of water jets as a resistive torque in the turbine have been developed. While further development in this arena is recommended (exploring the effects of fluid density on loss terms), these efforts have improved the turbine model.

The improved Terry turbine modeling has been applied to the Fukushima Daichi Unit 2 simulations. In addition, certain assumptions regarding heat transfer within the reactor pressure vessel have been revisited. This led to improvements in the simulated RPV pressure response. In the reactor overfill scenario, it has demonstrated a potential for the excess feedwater to bypass much of the core and be redirected to the Main Steam Line, where it is consumed by the downstream equipment. Here, it results in degradation of the mechanical power developed by the RCIC turbine.

While there remain some modeling unknowns identified, the current FY19 efforts have addressed in whole or in part several while at the same time identifying new model unknowns. These are anticipated to be addressed in future modeling efforts.

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