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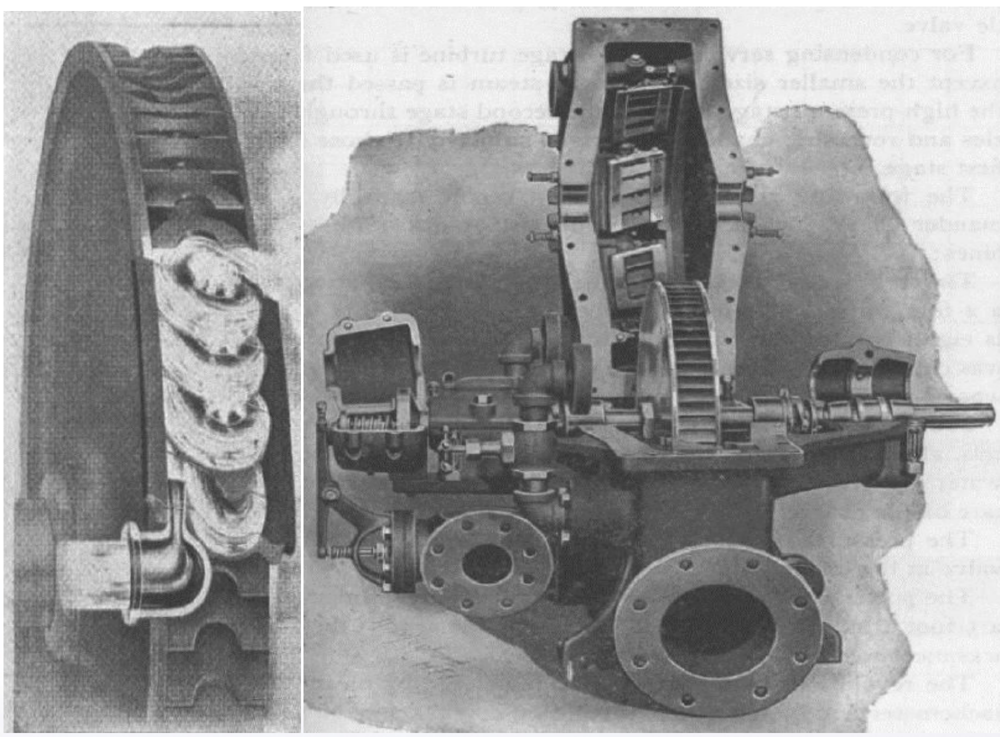
Terry Turbopump Expanded Operating Band Full-Scale Component and Basic Science Detailed Test Plan –Revision 2

Matt Solom, Kyle Ross, Jeff Cardoni, and Douglas Osborn



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Abstract

This document details the milestone approach to define the true operating limitations (margins) of the Terry turbopump systems used in the nuclear industry for Milestone 3 (full-scale component experiments) and Milestone 4 (Terry turbopump basic science experiments) efforts. The overall multinational-sponsored program creates the technical basis to: (1) reduce and defer additional utility costs, (2) simplify plant operations, and (3) provide a better understanding of the true margin which could reduce overall risk of operations.

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1F2	Fukushima Daiichi Unit 2
BDBE	Beyond Design Basis Event
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owner's Group
CNO	Chief Nuclear Officer
DBA	Design Basis Accident
DOE	U.S. Department of Energy
DOE-NE	U.S. Department of Energy's Office of Nuclear Energy
EOC	Executive Oversight Committee
EOP	Emergency Operating Procedure
EPG	Emergency Procedure Guidance
EPRI	Electric Power Research Institute
ExOB	Expanded Operating Band
HPCI	High Pressure Coolant Injection
IAE	Institute of Applied Energy
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
LWRS	Light Water Reactor Sustainability
METI	Government of Japan's Ministry of Economy, Trade, and Industry
NEI	Nuclear Energy Institute
NEUP	Nuclear Energy University Programs
NHTS	Nuclear Heat Transfer Systems
NRC	U.S. Nuclear Regulatory Commission
NSIAC	Nuclear Strategic Issues Advisory Committee
TTExOB	Terry Turbine Expanded Operating Band Committee
Turbo-TAG	Nuclear Grade Terry Turbopump Advisory Group
PIM	Pooled Inventory Management
PM	Program Manager
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
PWROG	Pressurized Water Reactor Owner's Group
QA	Quality Assurance
RCIC	Reactor Core Isolation Cooling
RHR	Residual Heat Removal
RSMC	Risk Management Subcommittee
RST	Reactor Safety Technologies
RPV	Reactor Pressure Vessel
SAG	Severe Accident Guidance
SG	Steam Generator
SNL	Sandia National Laboratories
TAMU	Texas A&M University
TDAFW	Turbine Driven Auxiliary Feedwater
TTUG	Terry Turbine User Group

1. Executive Summary of Overall Program

This document details the milestone approach to define the true operating limitations (margins) of the Terry turbopump systems (i.e. reactor core isolation cooling – RCIC and turbine driven auxiliary feedwater – TDAFW) used in the nuclear industry[1] for Milestone 3 (full-scale component experiments) and Milestone 4 (Terry turbopump basic science experiments) experimental and modeling efforts. The overall program's cost benefit to fleet operations and the potential for cost savings are significant[2] and may exceed the direct cost to perform this effort. The overall program details can be found in the Sandia Letter Report, "*Terry Turbopump Expanded Operating Band Summary of Program Plan – Revision 1*."[3] The overall multinational-sponsored program creates the technical basis to:

- Reduce and defer additional utility costs (e.g., associated with post-Fukushima actions),
- Simplify plant operations (e.g., provide guidance to operators for expanded Terry turbopump operations), and
- Provide a better understanding of the true margin which could reduce overall risk of operations.

The overall experimental program in particular:

- Protects utility assets by using the Terry turbopump under a broader range of conditions,
- Delays or prevents the need to use the less preferred 'non-reactor grade water' sources required during FLEX events,
- Extends the interval between preventive maintenance actions,
- Provides an avenue for qualification of obsolescent parts,
    - RCIC/TDAFW controls
- Provides a potential to avoid adverse regulatory actions, and
- Specifically, for boiling water reactors (BWRs):
    - Extends the time to get residual heat removal (RHR) system back online,
    - Extend the time for reactor pressure vessel (RPV) depressurization, and
    - Reduces outage time.

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1 Terry Turbine systems provide the transition between installed plant equipment and FLEX.

2 ~$450 million in deferred costs to preclude a unit from implementing FLEX, and ~$675 million in deferred costs for fleet-wide obsolescent control system parts (i.e., preclude switching over to digital control systems).

3 Severe Accident Analysis Department, "Terry Turbopump Expanded Operating Band Summary of Program Plan – Revision 1," SAND2017-5562, Sandia National Laboratories, Albuquerque, NM, May 2017.

This first-of-a-kind Terry turbopump experimental and modeling approach includes project plan development, first principles analytical modeling, full-scale component testing and modeling, basic scientific Terry turbopump testing and modeling, and full-scale integral system testing and modeling. The project plan includes checks and balances (milestone-based hold points) to ensure test suite expectations are met and the project remains within scope and predetermined expenditures as the program progresses to minimize programmatic risk.

First principles and initial scope modeling for feasibility funded by the U.S. Department of Energy (DOE) and the Institute of Applied Energy (IAE) in Japan has been performed. Additionally, modeling insights, scope discussions, and value assessments with industry stakeholders (domestic and international) have been completed to form the basis of this project plan.

An expert technical advisory group of engineers from the BWR Owners' Group (BWROG), Pressurized Water Reactor Owners Group (PWROG), Electric Power Research Institute (EPRI), DOE, Japan (IAE), GE-Hitachi (GEH) and Nuclear Energy Institute (NEI) has identified multiple benefits as direct value to the utilities from this program. This technical advisory group will also provide feedback and recommendations to the Nuclear Strategic Issues Advisory Committee (NSIAC) for US Industry programmatic decisions.

1.1 Overall Program Problem Statement

Prior to the accidents at Fukushima Daiichi, assumptions and modeling of the performance of Terry turbopumps are based mostly on generic vendor operational limits. The operational limits themselves were based on the now-obsolete guidance in the standard NEMA SM23 *Steam Turbine for Mechanical Drive Service;* the guidance was established for turbines intended to deliver reliable service 24 hours a day, 365 days a year with little or no maintenance. However, the RCIC/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 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 observation from Fukushima Daiichi Unit 2 (1F2) shows that RCIC function was affected but not terminated by uncontrolled steam line flooding, and in fact provided coolant injection for nearly three days[4,5,6,7].

Use of conservative assumptions regarding equipment functioning as found in PRA applications limits the anticipated mitigation options considered for normal and emergency operations.

4 Gauntt R., et. al., "Fukushima Daiichi Accident Study (Status as of April 2012)," SAND2012-6173, Sandia National Laboratories, Albuquerque, NM, August 2012.

5 Ross, K., et. al., "Modeling of the Reactor Core Isolation Cooling Response to Beyond Design Basis Operations – Phase 1," SAND2015-10662, Sandia National Laboratories, Albuquerque, NM, December 2015.

6 http://www.tepco.co.jp/nu/fukushima-np/images/handouts_120312_02-j.pdf

7 http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_120312_04-e.pdf

Improved understanding for expanded operations of Terry turbopumps can be realized through a combined and iterative process of advanced modeling methods with full-scale experimental testing.

Hypothesis

The Terry turbopump (RCIC/TDAFW) system has the capability to operate long-term (days) over an extended range of steam pressures (75 to 1205 psig – design range is 150 psig to the lowest safety relief valve / safety valve setpoint), varied steam quality (100% to 0% - current is 100%), and increased lube oil temperature conditions (215^{o}F to above 300^{o}F – current is 160^{o}F) with limited to no active control features.

Basis for Hypothesis

The events at Fukushima Daiichi, qualitative analysis, and experience in other industries demonstrate the Terry turbopump has significant additional operating flexibility than credited and currently being used in plant operations. In particular, operating experience is indicating 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 (events such as Fukushima and other types of BDBE) with minimal cost to the fleet of plants (e.g. 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 indicate 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; see Footnotes 4 and 5 for references.

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 of reliable and rugged performance under a broad range of operating conditions. It is commonly known within other commercial industries the Terry turbopump can run with water ingestion into the turbine; see Footnote 5 for reference.

Additionally, experience within the nuclear industry reflects the robustness of this systems. The turbine and pump have injected into the RPV/SG for extended times in response to rare events and are tested quarterly at both 150 and 1000 psig. In addition, a turbine qualification test was run at extreme conditions including ingestion of a large slug of water with no loss of function or damage to the turbine[8].

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8 Terry Corp., "Terry Wheel Water Slug Test – Sales Aid Memo #12," Terry Corp. Engineering Library Log No. 20106, March 1, 1973.

1.2 Overall Program Expectations

Overarching question to be address for each milestone is,

> "Given the differences exhibited between the modeling and the test data and with extrapolated simulation performance, do the current system models for RCIC/TDAFW operation provide adequate confidence in the proposed RCIC/TDAFW operation outside of the normal operational band?"

The level of '*adequate confidence*' will be decided by the nuclear grade Terry turbopump advisory group (Turbo-TAG) with input from the BWROG and PWROG. High-level organizational relationships can be found in the Project's Charter[9]. Generally, the advancing milestones reduce uncertainty and increase confidence in the plans for extended operation and may be needed to fully confirm planned operations. Based on the modeling and testing results, insights, and before the summary reports are completed, the Turbo-TAG will ensure the following tasks and expectations for each of the milestones are met:

Milestone 2 – Principles & Phenomenology

- Assess the efforts needed to complete Milestones 3 & 4,
- Assess the efforts needed to scope an existing full-scale test facility for Milestone 5,
- Conduct an initial scope of the development of a detailed experimental plan, and initial cost estimates for the Milestone 5, and
- Conduct an initial scope of the development of a detailed experimental plan, and initial cost estimates for Milestone 6

Milestone 3 – Full-Scale Separate-Effect Component Experiments[10]

- The test results will reduce the uncertainty in specific model parameters that cannot be explicitly addressed in the Milestone 4 testing and associated modeling, and

- These efforts benefit advancing with the selection of a full-scale test facility; inform the development of a detailed full-scale experimental plan, and further refinements on the cost estimates for the Milestone 5 & 6 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
7. Evaluate the results for Turbo-TAG expectations and '*adequate confidence*'

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9 International TTExOB Initiative Charter – Version 5.3, July 14, 2017.

10 Efforts are to be conducted in parallel with Milestone 4 and will inform modeling efforts for Milestones 4-6.

Milestone 4 – Terry Turbopump Basic Science Experiments

- The test results will reduce the uncertainty in specific model parameters for integrated components/system, and

- These efforts benefit advancing with the selection of an integral full-scale test facility; inform the development of a detailed integral full-scale experimental plan, and further refinements on the cost estimates for the Milestone 5 & 6 efforts.

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

- These test results will reduce the uncertainty in specific model parameters, and

- These efforts inform the development of a detailed integral full-scale experimental plan, and further refinements on the cost estimates for the Milestone 6 efforts.

Milestone 6 – Integrated Full-Scale Experiments Replicating 1F2 Self-Regulating Feedback

- These test results will reduce the uncertainty in specific model parameters

Milestone 7 is an integration of the Milestone 3-6 modeling efforts.

Based on the results of the determinations for each milestone, the Turbo-TAG will make recommendations within a summary report to the funding organizations: NSIAC, DOE, and METI (Government of Japan's Ministry of Economy, Trade, and Industry). At the conclusion of performance of work for each set of milestones, a 'hold point' period of 3-6 weeks will be allocated for the funding organizations to review the program progress and associated funding. Since the milestones are setup such that each can be considered an 'off ramp,' full funding for the next milestone will be determined upon agreement from the funding organizations.

Certain preplanning tasks will be accomplished to ensure proper alignment within the flow of the overall program. Associated costs are incorporated within the milestone cost estimates, but are not specifically called out for each milestone. Additionally, certain individualized efforts will be funded independently of the funding parties' overarching agreement. These efforts are uniquely dependent on funding to meet a specific organization's priorities (e.g., DOE's NEUP funding of efforts useful for Milestone 4 tasks when the overall program was focused on Milestone 2).

1.3 Summary of Milestone 3 and Milestone 4

For the Milestone 3, Full-Scale Component Experiments, the components under investigation will be GS-series Terry turbine nozzles, governor valves, trip/throttle valves, and lubrication oil and bearing performance. The Milestone 3 efforts are divided into four areas of experiments:

1. Free jet testing,
2. GS-series governor valve and trip/throttle valve testing,
3. Lube oil testing, and
4. Bearing tests.

Flow visualization results from the free jet testing will benefit detailed computation efforts discussed in Section 4.1.1, since the impulse of the steam jet has a first-order influence on the turbine wheel velocity. The governor valve and trip/throttle valve testing will provide insights into steam flow vs. stem position for flow coefficients (C_v). The lube oil and bearing testing will provide insights into long-term operations for full-scale testing.

The Milestone 4, Terry Turbopump Basic Science Experiments, are intended to provide information which will allow for the overall effort to better design, scale, and model the full-scale testing (i.e., Milestone 5 & 6), if the Turbo-TAG determines it is necessary to proceed to these subsequent milestones. The Milestone 4 efforts are divided into three areas of experiments:

1. Z-1 Terry turbopump testing,
2. Full-scale (GS-series) testing technique confirmation, and
3. Initial scoping of Fukushima Unit 2 uncontrolled feedback with a Z-1 Terry turbopump.

The Z-1 and GS-series Terry turbopump tests will provide data for modeling efforts discussed in Section 4.1.2, provide initial operational/field data on GEH's incipient failure equipment, 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 & 6 full-scale tests. The initial scoping of uncontrolled feedback with a Z-1 Terry turbopump will also provide confirmation that 1F2 observations are potentially applicable across all Terry turbopump models.

The modeling efforts for Milestone 3 and Milestone 4 are specific to system-level modeling (e.g., SAMPSON, RELAP, and MELCOR) as well as detailed computations (e.g., CFD), and will be parallel efforts with their associated experimental phase. These modeling aspects are to be integrated and iterated with the Milestone 3 and Milestone 4 experimental efforts and are further discussed in Section 4.

Figure 1.1 and Figure 1.2 show the overall work flow of the Milestone 3 & 4 efforts for each quarter of the 2-year performance period. Additionally, a Gantt chart is provided for each section so the reader can better understand the integrated test plan. The subsequent sections provide a more detailed discussion of each experimental and modeling effort. The discussions are such that the later testing has less stringent test requirements; the key details for much of the later testing rely on the results from testing conducted earlier in this program, and will be further developed as the information becomes available.

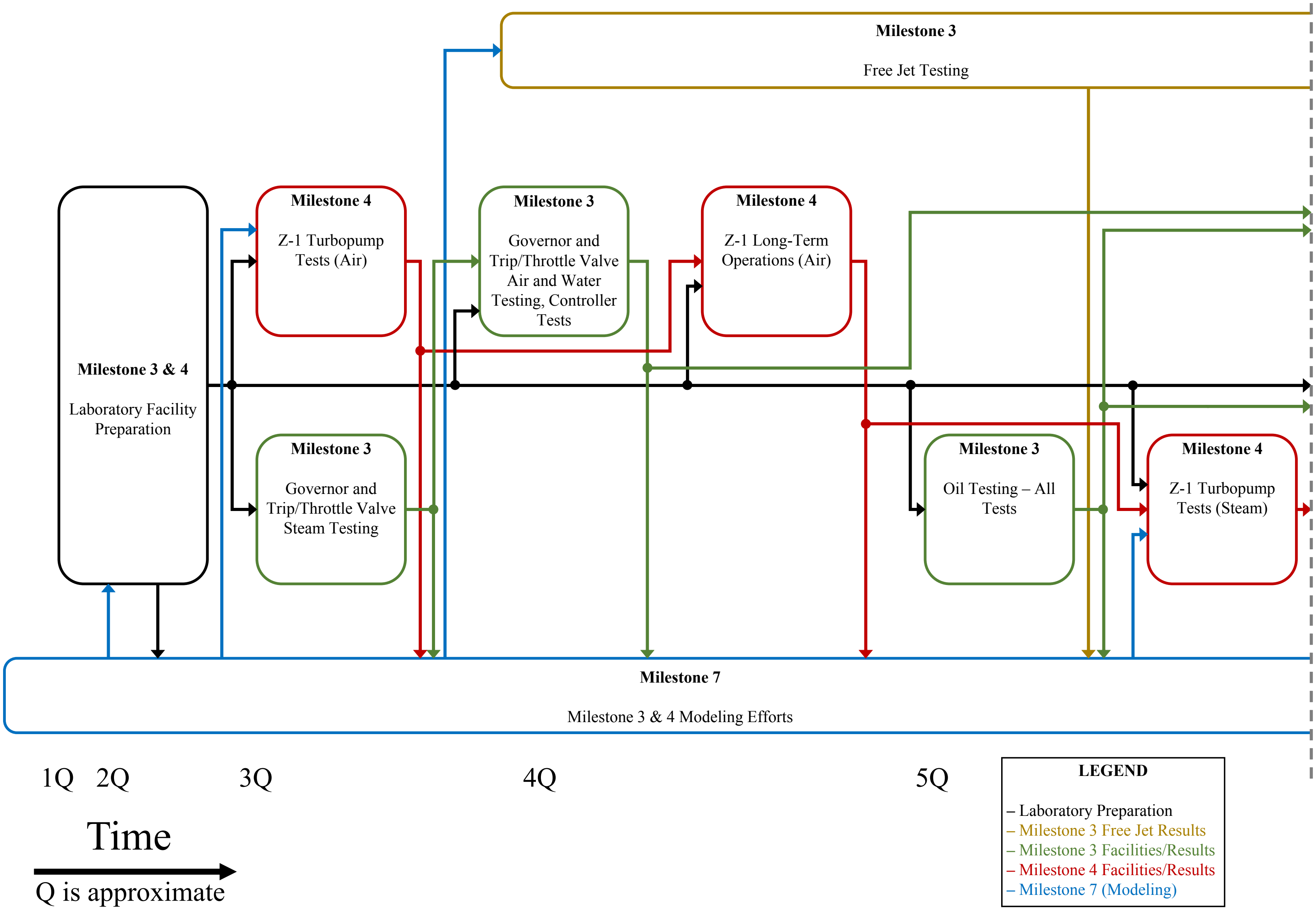

Figure 1.1 Milestone 3 & 4 Experimental and Modeling Flow Chart Quarter 1-5

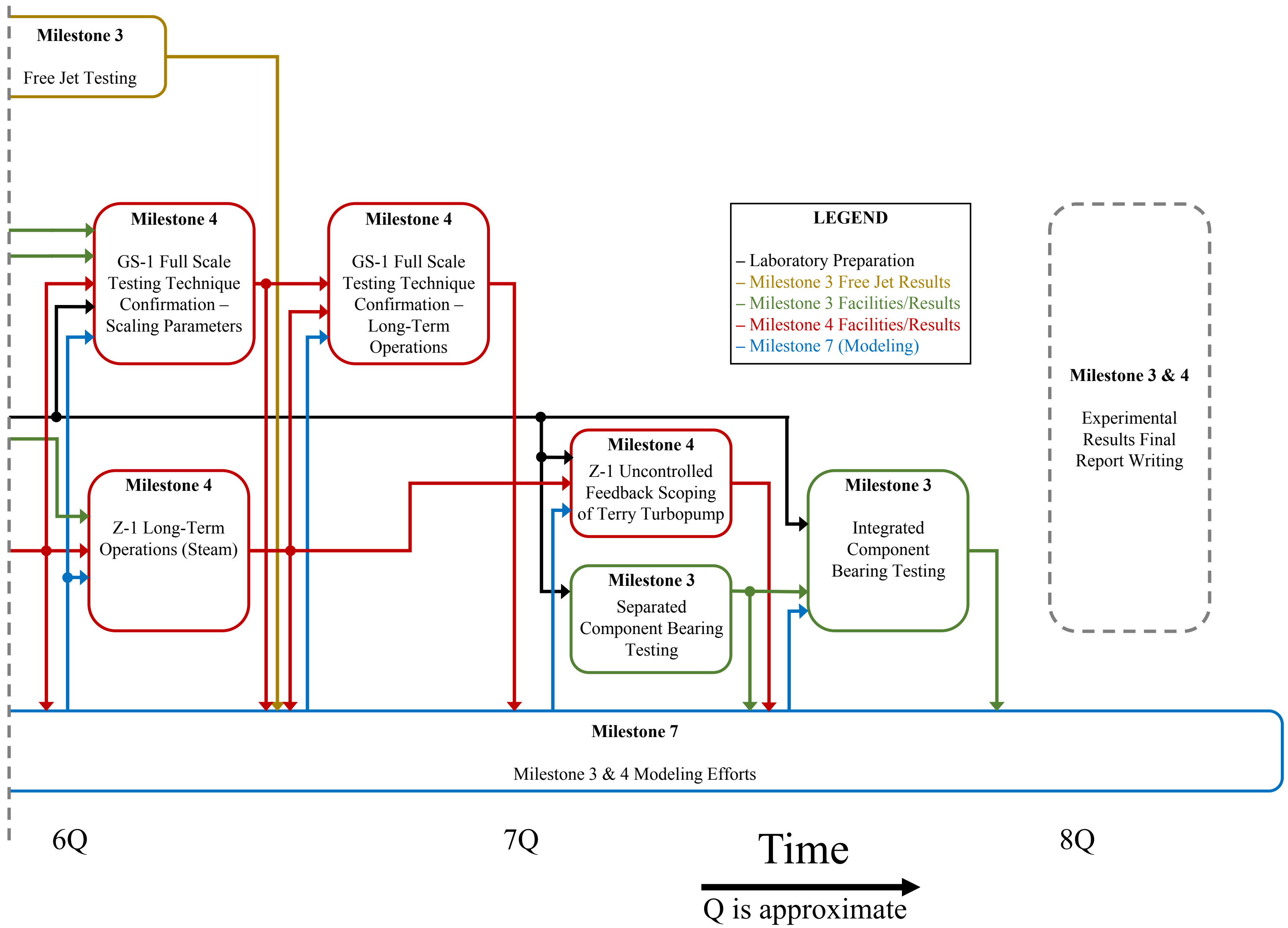

Figure 1.2 Milestone 3 & 4 Experimental and Modeling Flow Chart Quarter 6-8

2. Milestone 3 – Full-Scale Component Experiments

As efforts for Milestone 2 (Principles & Phenomenology) neared completion in 2016, the Turbo-TAG in conjunction with Sandia National Laboratories (SNL) and Idaho National Laboratory (INL) identified a suite of component experiments that could inform the later efforts of the program. Milestone 3 is intended to provide information which will allow for the overall effort to better design, scale, and model the full-scale steam testing (i.e., Milestone 5 & 6).

These experiments are intended to be conducted at low pressures and flow rates such that a university or small research facility could conduct the work within an achievable timeframe for use in the later milestones. Additionally, these efforts will be conducted in parallel with Milestone 4 efforts (see Section 3).

Texas A&M University (TAMU) has been identified by the Turbo-TAG as the suitable location for this effort. Component testing will be performed at TAMU under the guidance of Prof. Karen Vierow Kirkland (TAMU), Matthew Solom (SNL), and Nobuyoshi Tsuzuki (IAE). The TAMU Nuclear Heat Transfer System (NHTS) facility includes a 157 kW_e steam generator, a simulated RCIC pump, and a 1400-gallon suppression chamber. TAMU currently has a DOE-funded Nuclear Energy University Programs (NEUP) project entitled "Multi-phase Model Development to Assess RCIC System Capabilities under Severe Accident Conditions." The project goal is to provide analysis methods for evaluation of RCIC system turbomachinery performance under multiphase conditions. Figure 2.1 shows the NHTS facility with the suppression pool in the foreground and the steam generator in the background.

Additional facilities at TAMU include high-capacity, high-pressure air and water supplies at the Turbomachinery Laboratory. An example of an air test configuration for a Z-1 Terry turbine is provided in Figure 2.2, which can be conducted at the TAMU Turbomachinery Laboratory.

In this effort, the components under investigation will be GS-series Terry turbine nozzles, governor valves, trip/throttle valves, lubrication oil, and bearings. These examinations will yield component characteristics (e.g., C_v curves for valves) as well as the behavior in long-term operations. These efforts will allow dynamic responses to off-normal conditions to be better understood at the component level, allow for improved incorporation into models, and inform certain abnormal/emergency condition procedures; the measured C_v profiles and resulting guidance, for example, will allow operators to more confidently open and adjust the trip/throttle valve on the Terry turbine to the correct position as part of the blackstart emergency operations.

At certain times during testing, the industry collaborators will provide direct, on-site support to TAMU personnel. These industry personnel will assist TAMU with such tasks as the installation, operation, and training for the GS-series Terry turbopump and valve efforts.

Appendix A provides a comment/resolution discussion beyond the discussions provided in this section.

Figure 2.1 Nuclear Heat Transfer System Facility

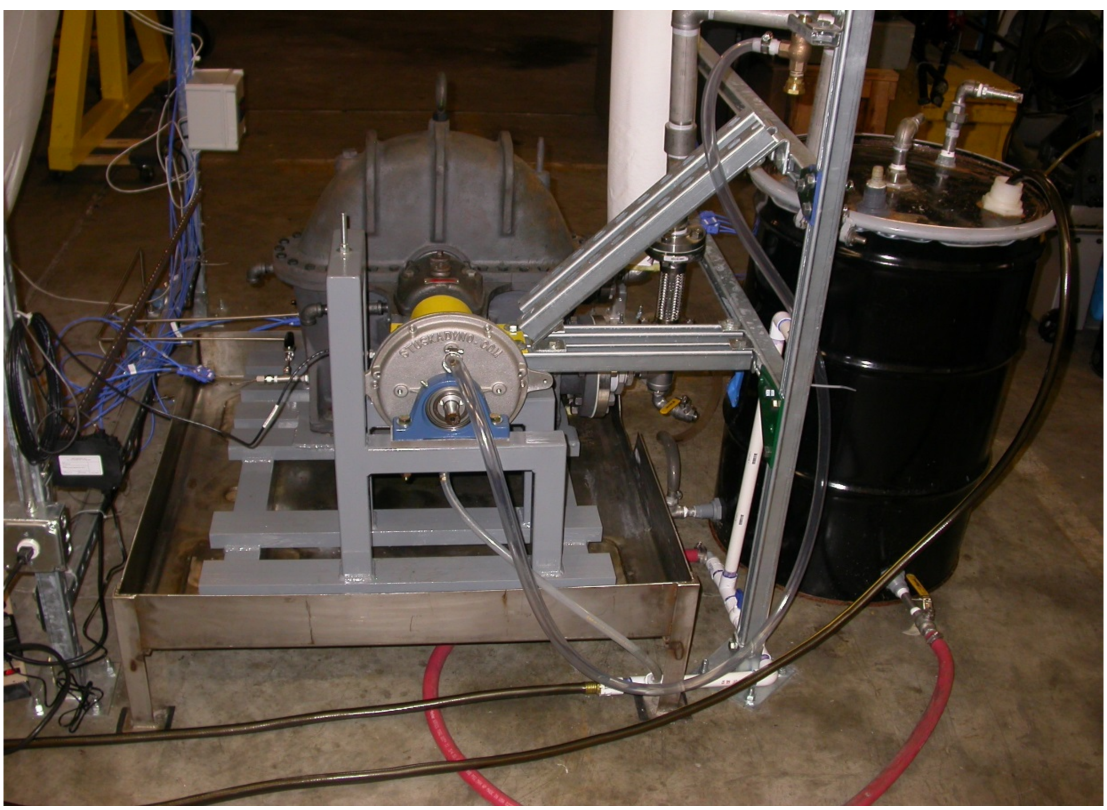

Figure 2.2 Example of Z-1 Terry Turbine Air Test Configuration

2.1 Test Suite

Full-scale component testing is to be divided into four areas of experiments:

1. Free jet testing,
2. GS-series governor valve and trip/throttle valve testing,
3. Lube oil testing, and
4. Bearing tests.

Flow visualization results from the free jet testing will benefit detailed computation efforts discussed in Section 4.1.1, since the impulse of the steam jet has a first-order influence on the turbine wheel velocity. The governor valve and trip/throttle valve testing will provide insights into steam flow vs. stem position for flow coefficients (C_v). The lube oil and bearing testing will provide insights into long-term operations for full-scale testing. The objectives for each of these experimental areas will be discussed in detail in the subsequent subsections.

Test Suite Expectations:

The expectations for the Milestone 3 efforts are the following:

- The test results will reduce the uncertainty in specific model parameters that cannot be explicitly addressed in the Milestone 4 testing and associated modeling, and

- These efforts benefit advancing with the selection of a full-scale test facility; inform the development of a detailed full-scale experimental plan, and further refinements on the cost estimates for the Milestone 5 & 6 efforts.

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

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

Quality Assurance of Experiments:

The quality assurance (QA) requirements for this effort shall abide by established TAMU QA levels of rigor to include the following:

- Peer review of test setup and procedures prior to commencement of testing,
- Calibration of instrumentation with proper records, and
- Data acquisition system documentation trail which abides by an established standard
    - A second or third order NIST standard

The specific QA processes will be determined by the Turbo-TAG and the Terry Turbine Expanded Operating Band Committee (TTExOB) in coordination with TAMU, and will be fully documented.[11] Additional QA requirements through the DOE-NE Light Water Reactor Sustainability (LWRS) Program will be applied whenever applicable.[12]

2.1.1 Free Jet Tests

The free jet experiments are to be conducted by Prof. Yassin Hassan at TAMU's Thermal-Hydraulic Research Laboratory. The objective of these tests is to develop a body of knowledge regarding the realistic outcomes of two-phase flow past a GS-series Terry turbine nozzle. Figure 2.3 shows an example (particle image velocimetry experiment) of TAMU's capabilities for the experimental study of turbulent mixing for free jet testing. Corresponding and supporting objectives are as follows:

- Provide an experimental basis for improved computational fluid dynamic (CFD) modeling efforts discussed in Section 4.1.1 for correlated air-water and steam-water inlet conditions into the nozzle of a GS-series Terry turbine, which in turn will provide information on steam-water nozzle coefficient data.

- Provide nozzle coefficient data and a technical basis for improved system modeling efforts discussed in Section 4.1 for steam-water inlet conditions into the nozzle of a GS-series Terry turbine under beyond design basis event (BDBE) conditions.

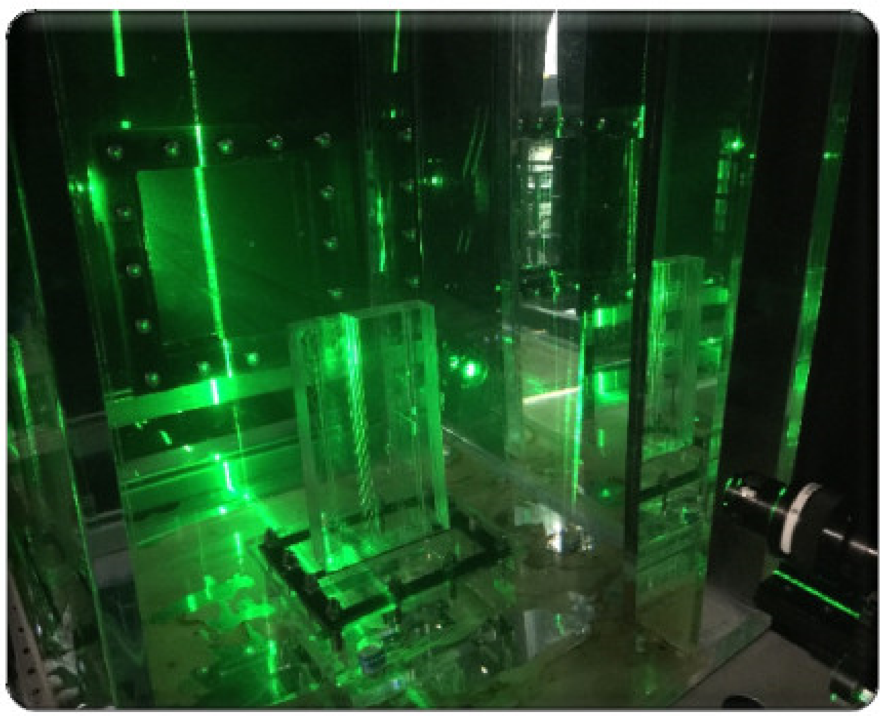

Figure 2.3 Particle Image Velocimetry Experiment

[11] The working draft of the Milestone 3 & 4 QA document for TAMU is: Kirkland, K., "Quality Assurance Plan for RCIC Testing at Texas A&M University," August 2017.

[12] Light Water Reactor Sustainability Program, "Quality Assurance Program Description," INL/MIS-10-19844 Revision 2, U.S. Department of Energy, July 2016.

Motivation:

For most U.S. and Japan BWRs and PWRs, the RCIC or TDAFW)system, respectively, is driven by a Terry impulse turbine, and thus the development of a steam momentum jet by the nozzles is of key significance in accurately modeling and understanding the principal operation of the system. There are important mechanisms involved in the nozzle flow that have a first-order influence on Terry turbine performance, especially for BDBE conditions, which cannot be readily assessed using system-modeling techniques or CFD.[13] A dedicated literature review, system analysis, and CFD evaluation has already been completed.[14] These previous modeling efforts have made considerable progress in advancing the state-of-the-art knowledge of the Terry turbine operation and provide some of the details of Terry turbine nozzle flow. Nonetheless, unanswered questions remain concerning key aspects of nozzle flow during BDBE conditions. Additionally, there is a scarcity of available data for nozzle flow of a Terry turbine even under saturated steam conditions. Thus, these tests will serve to expand the available data for modeling validation and verification.

The current physical understanding for the behavior of the nozzles in a Terry turbine is insufficient for the development of accurate models to predict turbine performance. Given that the nozzles drive the turbine wheel, and therefore all attached equipment, when the nozzle behavior is unknown, the behavior of the system cannot be predicted with a high confidence of certainty in system models. The nozzle behavior data collected in these tests will clarify the nozzle behavior in off-normal conditions, and therefore allow much-improved modeling and a better understanding of overall system behavior.

Nozzle inlet flow with high liquid content is believed to degrade the momentum jet developed by the nozzles, and the subsequent torque imparted on the turbine; this is also a particularly challenging state for most existing analytical tools.[15] Therefore, experimental examination of the jet produced by a free nozzle under various conditions is of invaluable importance for enhancing the modeling (i.e., the steam velocity exiting the nozzle is a first-order effect on the turbine performance) and understanding of RCIC/TDAFW system. Assessment of key nozzle phenomena is facilitated by examining a free jet separate from the turbine wheel. The space between the nozzles, turbine casing wall, and buckets is only on the order of 1 cm or less, which would restrict a thorough analysis in the Milestone 4 integral system experiments. Furthermore, the fundamental behavior in a supersonic nozzle is (largely) unaffected by downstream structures such as the buckets, and hence free-stream nozzle experiments would allow for insights into the actual performance of the Terry turbine nozzles. Such measurements would increase the

[13] SNL, "Terry Turbopump Analytical Modeling Efforts in Fiscal Year 2017 – Progress Report," Sandia Letter Report, SNL, September 2017.

[14] Ross, K., J. Cardoni, "RCIC Governing Equation Scoping Studies for Severe Accidents," 16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics – NURETH-16, Chicago, IL, September 2015.

[15] The behavior of a two-phase water-steam mixture undergoing rapid expansion and acceleration through a supersonic nozzle (the Terry turbine nozzles are converging-diverging) is a complicated flow problem even for modern computational tools. During normal operation the ingress of steam or predominately steam flow into the nozzles produces a two-phase flow problem consisting of several simultaneous phenomena including compressible flow, two-phase mass and heat transfer, non-equilibrium thermodynamics, supersonic velocities, and potentially shock formation (i.e. condensation and pressure discontinuities). The introduction of high liquid content under off-normal conditions yields flashing, which further complicates the modeling, and may temporarily disrupt/degrade the momentum jet that drives the turbine.

knowledge of the jet velocity, jet formation, and two-phase composition of fluid exiting the nozzles. This information is essential for calculating the quantitative changes in jet momentum (and subsequent turbine torque) during off-normal conditions. In addition, analysis of the collected data will be able to determine the discharge coefficient of the nozzle.

Test Parameters:

The free jet test measurements will be coordinated with the CFD and system modeling efforts discussed in Section 4.1.1. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Single-phase and two-phase properties
- Mass flow rate
- Exit velocity at nozzle exit
    - As function of pressure, liquid content, and flow regime,
    - Vapor velocity is of most concern, and
    - If possible, 1 cm from nozzle exit, 2 cm, and 3 cm
- Observations of liquid flashing and consequent disturbance of steam jet formation
    - As function of nozzle inlet conditions

Test Requirements:

Standalone testing will be conducted on a single GS-series Terry turbine nozzle (i.e., flow testing outside of a Terry turbine) with the following fluids and fluid states:

- Room air up to compressor maximum pressure
- Room air up to compressor maximum pressure with metered water injection
- If possible, saturated steam up to maximum laboratory boiler pressure
- If possible, saturated steam up to maximum laboratory boiler pressure with metered saturated water injection
- If possible, water at temperatures increasingly greater than saturation temperature at atmospheric pressure

The jet flow fields will be characterized by flow visualization techniques to clarify features such as the jet length and width and two-phase configuration. This will inform calculation efforts of steam-water inlet conditions into the Terry turbine. Particle Image Velocimetry (see Figure 2.4) and possibly ultrasonic techniques will be employed. In addition, the use of pressure-indicating paint will be considered. TAMU's Thermal-Hydraulic Research Laboratory has the equipment and expertise with both techniques for air and air-water. This includes a 20,000 fps high speed camera facility, 3-D printing of test materials, and PIV-capable lasers; use of a SNL high speed camera greater than that of TAMU will be considered. TAMU will also attempt the same techniques with steam and steam-water conditions, if possible. A proposed test matrix for the free jet tests can be seen in Table 2.1. Various jet velocities will be applied to this test matrix.

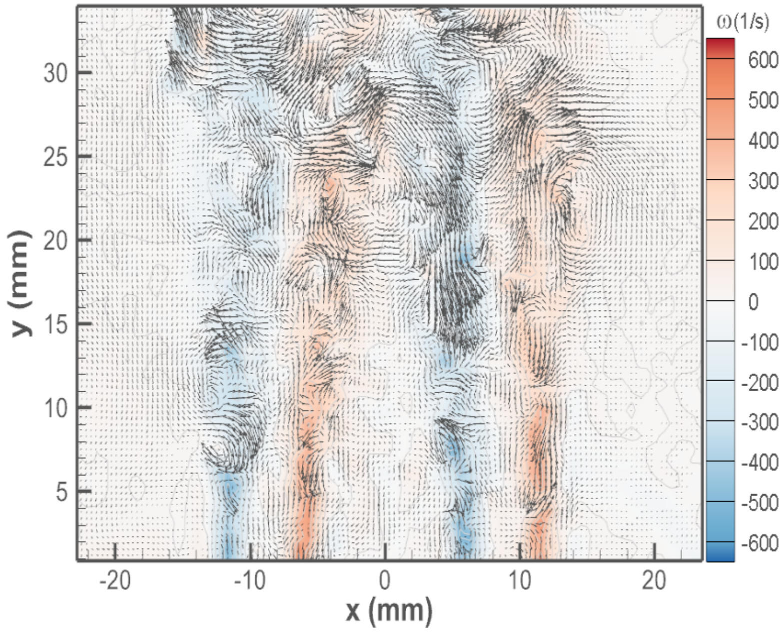

Figure 2.4 An Example of Fluctuating Velocity Fields and Vortices of Jets at t = 5ms

Table 2.1 Free Jet Test Matrix

Nozzle diameter		8 mm	
Spacing to Wall		10 mm	
Nozzle Angle		45 ~ 90°	
Gas Mass Fraction	**40 psi**	**30 psi**	**20 psi**
100% (Air*)	x	x	x
90%	x	x	x
80%	x	x	x
70%	x	x	x
60%	x	x	x
50%	x	x	x
40%	x	x	x
30%	x	x	x
20%	x	x	x
10%	x	x	x
5%	x	x	x
1%	x	x	x
0% (Water)	x	x	x

* Will attempt steam testing should visualization techniques permit

The nozzle flow characterization apparatus will be designed such that the free-form flow profile of a jet flowing from a Terry nozzle can be characterized. In addition, a wall or plate can be installed in the flow path of the fluid exiting the nozzle. It will have the ability to be positioned at different distances from the nozzle outlet and aligned at different angles to the outlet. The flow from the nozzle will apply a force on the plate, which will be recorded; this measured force will aid model developers in developing a semi-mechanistic model of the torque applied to a Terry wheel, especially under two-phase conditions.

In regards to flow visualization for air and air-water conditions, the Thermal-Hydraulic Research Laboratory has service air at 40 psi. For the steam and steam-water conditions, the lab has a boiler with an operating pressure of 100 psi. The following are the proposed tasks to meet the test requirements:

- Facility design
- Identification of test quality metrics,
- Selection of nozzle angles relative to a curved fixed surface (i.e., a moving turbine blade),
    - Adjustments of several spacing distances between the nozzle and the fixed surface
- Test execution with several flow rates and temperatures for air and air-water conditions,
    - If possible, similar tests using steam and steam-water conditions
- Data analysis, and
- Final report.

2.1.2 Governor and Trip/Throttle Valve Tests

The governor and trip/throttle valve experiments are to be conducted by Prof. Gerald Morrison at TAMU's Turbomachinery Laboratory for the air and air-water tests. The steam and steam-water tests are to be conducted by Prof. Karen Vierow Kirkland at TAMU's NHTS facility. The objective of these tests is to develop a body of knowledge regarding the realistic outcomes of GS-series Terry turbine governor valve and trip/throttle valve behavior under low steam pressure operations. This set of behavior can be described by the valve flow coefficient (C_v) and related curves; C_v is an empirical engineering parameter used to describe valve capacity, and depends on the collective contributions of the size, shape/geometry, and other physical characteristics of the valve. Corresponding and supporting objectives are as follows:

- Provide an experimental basis for improved modeling efforts discussed in Section 4.1.1 for the governor valve and trip/throttle valve flow coefficient (C_v) in GS-series Terry turbines.

- Provide the technical basis for the minimum voltage required to operate the electronic controls for RCIC/TDAFW response during BDBE conditions.

- Provide the technical basis for blackstart of the RCIC/TDAFW pump during BDBE conditions

<u>Motivation:</u>

The RCIC/TDAFW system uses an electro-hydraulic feedback control system that adjusts the governor valve to manage turbine speed and system output. In order to more fully understand and predict system behavior, the flow response characteristics of the governor and trip/throttle valves should be better understood, especially near key operating positions. Without applicable flow coefficient (C_v vs. position) curves, the dynamic response of the system can be difficult or impossible to correctly predict as interfacing conditions change.[16] In addition, certain abnormal/emergency operating procedures can be facilitated with a better understanding of the valves; for example, a known 'minimum' position for the trip/throttle valve based on the valve's flow coefficient (C_v) can help operators avoid turbine overspeed trips during blackstart operations. Not only would this knowledge promote more rapid starting times, it will limit the need for operators to 'hunt' for the correct valve position and thus reduce operator dose for startup of RCIC. Better information can also assist in determining optimal controller parameters as well as avoiding problems with transient responses.

Specifically, the C_v is needed as a function of stem position. The C_v information can be measured by experiment or determined through CFD calculations. Detailed drawings of the valves will be needed if using CFD. Note in theory, C_v need only be measured or CFD-determined for the situation of a valve flowing simply liquid water for relationships which could allow application of the measured/CFD-determined C_v characteristics of a valve flowing water to the characteristics of the same valve flowing saturated, wet, or superheated steam as well as flowing air. In theory, these curves can be developed by application of CFD modeling rather than experimental testing. However, the ability to do so here is limited by two main factors (reference Footnote 16):

- The valves under consideration have relatively complicated geometries, and
- Even with accurate CAD models the C_v cannot be determined for less than 20% opening.

Laboratory testing has been standardized and is straightforward to conduct, and is therefore the preferential method for determining the valve characteristics.

Test Parameters:

The governor valve and trip/throttle valve test measurements will be integrated with the CFD and system modeling efforts discussed in Section 4.1; further the minimum voltage for electronic control under BDBE conditions, and desired blackstart valve positions will be identified. The minimum sets of parameters that are needed to meet the objectives are the following:

- Flow and pressure drop data vs. valve position for water
    - GS-2 governor valve and trip/throttle valve
    - GS-1 governor valve and trip/throttle valve
- Flow and pressure drop data vs. valve position for air
    - GS-2 governor valve and trip/throttle valve
    - GS-1 governor valve and trip/throttle valve
- Choked flow and pressure data vs valve position for water
    - GS-2 governor valve and trip/throttle valve
    - GS-1 governor valve and trip/throttle valve
- Flow and pressure drop data vs. valve position for low-pressure dry, saturated steam
    - GS-2 governor valve and trip/throttle valve
    - GS-1 governor valve and trip/throttle valve

[16] SNL, "Terry Turbopump Analytical Modeling Efforts in Fiscal Year 2017 – Progress Report," Sandia Letter Report, SNL, September 2017.

- Voltage vs. operability of controller
    - GS-2 governor valve
    - GS-1 governor valve
- Peak current/amperage draw of controller vs. operating voltage
    - GS-2 governor valve
    - GS-1 governor valve

Test Requirements:
Both types of governor valves and trip/throttle valves for a GS-series Terry turbine will be acquired. A GS-1 Terry turbine has 2.5-inch valves and a GS-2 Terry turbine has 3-inch valves. Prior to obtaining these valves, TAMU will ensure that they have a test facility that can deliver enough flow for the selected govenor and trip/throttle valves. These tests will include the following:

- The governor valve flow coefficient (C_v), recovery (F_L), and pressure differential ratio factor (x_T) vs. position curves will be obtained from standards-compliant measurements of the flow and the pressure drop through the valve for air and water (as applicable), and for verification where possible with low-pressure steam.

- The trip/throttle valve flow coefficient (C_v), recovery (F_L), and pressure differential ratio factor (x_T) vs. position curves will be obtained from standards-compliant measurements of the flow and the pressure drop through the valve for air and water (as applicable), and for verification where possible with low-pressure steam.

- The minimum voltage required to operate the electronic controls for the governor valve will be tested.

Standardized testing for valve performance characteristics, especially the valve flow coefficient (C_v) and liquid pressure recovery factor (F_L), has been established by IEC 60534-2-3 and mirrored by ANSI/ISA 75.02.01,[17] with the 2015 revision being current.[18] In accordance with the guidance in the standard, full C_v, F_L, and x_T curves for each GS-series Terry turbine governor and trip/throttle valve shall be established. Points in the curves shall be taken for valve stroke positions at 10% intervals from fully closed (0%) to fully-opened (100%), with additional points taken at smaller intervals in the 'near-closed' region. These data sets, along with the formulation provided in IEC 60534-2-1 / ANSI/ISA 75.01.01 and various industry guidance, should be sufficient to predict the behavior of the valves under varying conditions.

As directed by the standard, the primary test fluid will be water (incompressible) for C_v and F_L; standard-compliant air (compressible) testing shall be performed as well to determine x_T. If time

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[17] American National Standards Institute/International Society of Automation, "Control Valve Capacity Test Procedures," ANSI/ISA-75.02.01-2008 (IEC 60534-2-3 Mod), https://www.isa.org/store/ansi/isa-750201-2008-iec-60534-2-3-mod-control-valve-capacity-test-procedures/118220, *accessed: 11/10/2016*.

[18] International Electrotechnical Commission, "Industrial-process control valves – Part 2-3: Flow capacity – Test procedures," IEC 60534-2-3:2015, https://webstore.iec.ch/publication/23942, *accessed: 6/2/2016*

permits, additional data will be taken with low-pressure (<100 psia) saturated steam (outside the bounds of the standard) strictly for comparison and model verification.

For each fluid and valve position, C_v data will be collected at three distinct flowrates/pressure drops as per the standard. Before adjusting the valve position, F_L or x_T (as appropriate) will be determined by measuring the maximum/choked flow at sufficient upstream pressure. A recommended test matrix for these valve characterization tests is given in Table 2.2; the actual range of steam tests performed will depend upon the limits of the laboratory equipment as well as the need for particular ranges as determined by the expert judgment of the Turbo-TAG and experimental personnel.

Table 2.2 Valve Profiling Test Matrix

A: Air W: Water S: Steam			
Open	**C_v Tests**	**F_L Tests**	**x_T Tests**
0%	A,W Leakage		
2.5%	A,W,S	W	A,S
5%	A,W,S	W	A,S
7.5%	A,W,S	W	A,S
10%	A,W,S	W	A,S
12.5%	A,W,S	W	A,S
15%	A,W,S	W	A,S
17.5%*	A,W,S	W	A,S
20%*	A,W,S	W	A,S
25%*	A,W,S	W	A,S
30%	A,W	W	A
40%	A,W	W	A
50%	A,W	W	A
60%	A,W	W	A
70%	A,W	W	A
80%	A,W	W	A
90%	A,W	W	A
100%	A,W	W	A

* Will acquire steam data up to test facility limits

Governor and trip/throttle valve flow coefficient profiles

- Standards-compliant testing will be performed on governor and trip/throttle valves to develop complete C_v, F_L, and x_T curves
    - Air and water testing will be conducted at the TAMU Turbomachinery Lab under the guidance of Prof. Gerald Morrison

- Where sufficient steam flow is available, limited low-pressure saturated steam testing will be performed to verify applicability of IEC 60534-2-1 / ANSI/ISA 75.01.01 saturated steam calculations

    - Low pressure steam testing will be conducted at the TAMU NHTS Lab under the guidance of Prof. Karen Vierow Kirkland
    - Saturated steam, which is the material the valves normally regulate, is outside the bounds of the standards for testing purposes; its investigation here is strictly as a verification measure

- If funding and schedule permit, limited two-phase testing will be performed to verify applicability of IEC 60534-2-1 / ANSI/ISA 75.01.01 two-phase calculations
    - Air/water at the TAMU Turbomachinery Lab
    - Low pressure steam/water at the TAMU NHTS Lab

Specific to the trip/throttle valves, not only will the valve stem position be recorded, but the number of turns of the handwheel to arrive at the position shall be noted as well; however, this may differ for valves from different manufacturers. This collection of curves will permit operators to more accurately predict the correct position vs. number of turns for the valve in advance of manual throttling operations before personnel enter the room. While this is especially useful in blackstart operations, it is also helpful for any other direct, manual control operation (e.g., during maintenance runs).

Additionally, to ensure best direct benefit of RCIC blackstart for a high success rate with the least amount of time at the RCIC pump (minimize dose) and minimize the number of times the operator will need to go back for adjustments, the following will also be conducted for the trip/throttle valve:

- Development of an analytical model to inform blackstart and maintenance operating procedures (Section 4.1.1).

- A survey for the US and Japan BWR fleet on how they conduct blackstart RCIC during maintenance; this may not currently be recorded for each unit, so it is possible this will be knowledge based information.

- A survey of the US and Japan BWR fleet on the number of turns of the handwheel that cause the turbine to trip on overspeed; this may not currently be recorded for each unit, so it is possible this will be knowledge based information.

So long as sufficient power is delivered to the electro-hydraulic controller for the turbine, manual control of the turbine via the trip/throttle valve should not be necessary. To determine the bounds of controller operability, the electrical components of the system will be subjected to operability tests to determine the minimum bounding supply voltage and necessary current for both continuing and startup operations. The system will be subjected to a voltage descending from the nominal operating voltage at intervals which the signals will be manipulated such that the controller should attempt to maintain governor valve position, opening the valve, or closing the valve. The voltage across the electric coil, which provides the interface between the electric and hydraulic side, will be monitored both for correct value and for stability, and the current draw for the supply will be noted. The system will also be tested for minimum startup supply voltage, in increments increasing from zero in a similar manner. The Turbo-TAG has determined that the turbine controller electronics testing is 'low priority,' and therefore can be limited or deferred without affecting the success of the overall test program. A test matrix for this is given in Table 2.3.

Table 2.3 Controller Operability Test Matrix

Fraction of Nominal Operating Voltage	Maintain Valve Position	Open Valve	Close Valve
Decreasing Supply Voltage			
100%	x	x	x
90%	x	x	x
80%	x	x	x
70%	x	x	x
60%	x	x	x
50%	x	x	x
40%	x	x	x
30%	x	x	x
20%	x	x	x
10%*	x	x	x
Increasing Supply Voltage			
0%	x	x	x
10%	x	x	x
20%	x	x	x
30%	x	x	x
40%	x	x	x
50%	x	x	x
60%	x	x	x
70%	x	x	x
80%	x	x	x
90%*	x	x	x

* Will conduct tests only through the supply voltages that establish full bounds of controller operability

Minimum voltage for control operations

- Operability of the governor controller with slowly decreasing voltage from normal
    - Ability to cause opening/closing of governor at full and partial/slow rates
    - Ability to maintain governor valve position
    - Peak current draw for operation vs. voltage
    - Power-off/shutdown voltage

- Operability of governor controller with slowly increasing voltage from zero
    - Ability to cause opening/closing of governor at full and partial/slow rates
    - Ability to maintain governor valve position
    - Peak current draw for operation vs voltage
    - Stable power-on voltage

2.1.3 Oil Tests

The oil experiments are to be conducted by Prof. Karen Vierow Kirkland at a TAMU experimental facility. The objective of these tests is to develop a body of knowledge regarding the realistic performance of GS-series Terry turbopump lubrication oil behavior under BDBE conditions. Corresponding and supporting objectives are as follows:

- Provide an experimental basis for expanding the lube oil temperature range in a GS-series Terry turbopump.
- Provide the technical basis for various GS-series Terry turbopump lube oil performance under long-term operations of RCIC/TDAFW during BDBE conditions.

Motivation:

The recommended oil for a Terry turbopump is an ISO-V32 light grade turbine oil. Past tests were run at 390°F for one week.[19] These tests (using medium-weight V46 DTE) showed a slight decrease in viscosity, although the oil's ability to lubricate was not affected. Several plants use Mobil DTE Light V32 (some plants may also use Mobil DTE 797); although there are turbine lube oils that have demonstrated less degradation at high temperatures than Mobil DTE.

Currently, the most agreed upon hypothesis for the 1F2 RCIC failure after ~68 hours of unregulated operations is due to oil breakdown which led to ultimate bearing failure. Since the 1F2 RCIC pump is buried under meters of highly contaminated debris, this hypothesis cannot be verified. Under the current Fukushima Daiichi decommissioning efforts, the 1F2 RCIC pump room may not be accessible to inspection for about a decade.

Initially, a detailed literature survey will be conducted to evaluate the need for additional testing of lubrication oil types. Prior to any new testing, a literature survey will be used to determine the effects of aging, heating, and contamination for the oil types in use. It is likely that these effects are already well-understood and can be readily translated for application to Terry turbines. However, should additional testing be necessary, it will focus on expected BDBE conditions.

In addition to BDBE conditions, these oil tests will provide experimental evidence for the behavior/operability of the oil beyond the current authorized temperature limits.

Test Parameters:

The lube oil test measurements will be connected to expected BDBE conditions and realistic upper temperature limits. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Determine any change of oil properties and functions when heated up to 390°F
- Oil quality, which is best to deal with water, and increase current margin of oil

[19] TAMU correspondence with Mark Bergman of GEH, 2016

Test Requirements:
The to-be-specified Terry turbopump lubrication oil(s) will be acquired. These tests will include the following:

- Quantify the loss of inventory for oil(s) heated for several days under BDBE conditions and observe any changes in viscosity, acidity, and filter residue between pre-test and post-test measurements.
  - Conduct the test at the currently approved limit of 160°F
  - Conduct the test at specified intervals up to 310°F or severely degraded conditions
  - Conduct verification test at 390°F

- Quantify oil quality under various water mixtures for BDBE conditions and observe changes in viscosity, acidity, and filter residue between pre-test and post-test measurements
  - Conduct the test at the currently approved limit of 160°F
  - Conduct the test at specified intervals up to 310°F or severely degraded conditions
  - Conduct verification test at 390°F

In conjunction with the tests discussed in this section, consideration for the effects of oil wear, particle build up (crud), varnish, and other by products on the governor valve control system, in particular the exhaust gas recirculation valve, will be further investigated in tests conducted in Section 2.1.2 and Section 3.1.2.

TAMU will follow established ASTM standards for oil testing, where applicable. A degree of separation of effects will be considered. A sample of ISO-V32 turbine oil will be placed in a small enclosed vessel and maintained at specified temperatures for specified periods. One or two other oil types can also be considered based on industry expert recommendations. The temperatures will be 160°F, 180°F, etc..., 310°F as well as 390°F and compared with previous testing. Time periods will be 1 hour, 4 hours, 8 hours, 16 hours, 24 hours, 48 hours, 72 hours, and 168 hours. The oil will not be circulated or otherwise agitated, but rather will be left stagnant. Additional tests will bubble known quantities of air through the oil to facilitate/accelerate sludge and varnish formation. At the end of the period, the viscosity, turbidity, and pH will be examined both hot and at room temperature. In addition, the inventory shall be measured to determine loss, and the oil shall be passed through a filter to extract and characterize residue. Samples of the oil will be sent to offsite facilities for laboratory testing as well. These test parameters and post-test analyses will also be done for known oil/water mixtures. A test matrix detailing the specific variables is shown in Table 2.4.

Oil degradation under varied temperature ranges
- Known quantity of oil heated at atmospheric pressure on a hot plate for 1, 4, 8, 16, 24, 48, 72, and 168 hours without agitation and stagnant air.
  - Conduct the test at the currently approved limit of 160°F
  - Conduct the test at specified intervals up to 310°F or severely degraded conditions
  - Conduct verification test at 390 °F

- Known quantity of oil heated at atmospheric pressure on a hot plate for 1, 4, 8, 16, 24, 48, 72, and 168 hours with known air injection/bubbling.
    - Conduct the test at the currently approved limit of 160°F
    - Conduct the test at specified intervals up to 310°F or severely degraded conditions
    - Conduct verification test at 390°F

- Characterize the condition of the aged/degraded oil at hot conditions as well as post-cooldown

Table 2.4 Oil Characterization Test Matrix

x: No Air L: Low Air H: High Air				
Temperature, °F	**0% Wet**	**1% Wet**	**5% Wet**	**10% Wet****
160	x,L,H	x,L	x,L	x,L
180	x,L,H	x,L	x,L	x,L
250	x,L,H	x,L	x,L	x,L
270*	x,L,H	x,L	x	x
290	x,L,H	x,L	x	x
310	x,L,H	x,L	x	x
390	x	-	-	-

* High-temperature air-injected tests with water contamination will be performed if data indicate a need

** 10% Wetness test series is optional

<u>Oil/water quality under varied temperature ranges</u>

- Oil with a known quantity of water
    - 1% by mass water mixture
    - 5% by mass water mixture
    - 10% by mass water mixture (optional)

- Known quantity of oil/water heated at atmospheric pressure on a hot plate for 1, 4, 8, 16, 24, 48, 72, and 168 hours without agitation and stagnant air.
    - Conduct the test at the currently approved limit of 160 °F
    - Conduct the test at specified intervals up to 310°F or severely degraded conditions
    - Conduct verification test at 390°F

- Known quantity of oil/water heated at atmospheric pressure on a hot plate for 1, 4, 8, 16, 24, 48, 72, and 168 hours with known air injection/bubbling.
    - Conduct the test at the currently approved limit of 160 °F
    - Conduct the test at specified intervals up to 310°F or severely degraded conditions
    - Conduct verification test at 390°F

- Characterize the condition of the aged/degraded oil at hot conditions as well as post-cooldown

2.1.4 Terry Turbine Bearing Tests

The Terry turbine bearing experiments are to be conducted by Prof. Gerald Morrison at TAMU's Turbomachinery Laboratory and by Prof. Karen Vierow Kirkland at TAMU's NHTS facility. The objective of these tests is to develop a body of knowledge regarding the realistic performance of Z-1 Terry turbopump bearings with lubrication oil behavior under BDBE conditions. The corresponding and supporting objectives are as follows:

- Through correlations, provide an experimental basis for expanding the lube oil temperature range in a GS-series Terry turbopump.
- Through correlations, provide the technical basis for various GS-series Terry turbopump bearing performance under long-term operations of RCIC/TDAFW during BDBE conditions.
- May provide a technical basis for an incipient failure detector to be developed by GEH.

<u>Motivation:</u>

The recommended oil for a Terry turbopump is an ISO-V32 light grade turbine oil Past tests were run at 390 ^{o}F for one week.[20] These tests showed a slight decrease in viscosity, although the oil's ability to lubricate was not affected. However, these tests were not conducted under operating conditions with Terry turbopump bearings.

Currently, the most agreed upon hypothesis for the 1F2 RCIC failure after ~68 hours of unregulated operations was due to oil breakdown which lead to ultimate bearing failure. Since the 1F2 RCIC pump is buried under meters of highly contaminated debris, this hypothesis cannot be proved. Under the current Fukushima Daiichi decommissioning efforts, the 1F2 RCIC pump room may not be accessible to inspection for about a decade.

Since conducting a series of bearing tests with a nuclear grade GS-series Terry turbopump is not feasible, Z-1 Terry turbopump bearings will be tested in a volume of heated oil for incipient failure and may employ an incipient failure detector developed by GEH.

As with the lubrication oil tests discussed in Section 2.1.3, a sufficient body of knowledge may already exist to enable accurate prediction of bearing behavior in BDBE conditions; a literature survey will be conducted to precisely determine the exact extent of necessary testing before any is done. With known oil properties and bearing design data, CFD could be used to predict the stability of the oil wedge in the bearing as a function of temperature.

Of special interest to long-term BDBE operation are effects of such parameters as water contamination of the oil or heat degradation. In addition at high temperatures, consideration of bearing (Babbitt) material will be given.

[20] TAMU correspondence with Mark Bergman of GEH, 2016

Test Parameters:
The bearing test measurements need to be connected to expected BDBE conditions and realistic upper temperature limits. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Determine effects on bearings when previously heated oil is used in tests
- Consideration of the effects of elevated ambient temperature

Test Requirements:
These tests will be performed in conjunction with the heated oil tests described Section 2.1.3. To investigate bearing failure in the GS-series turbopump, lube oil which has been heated for several days to above the maximum operating temperature specified in Terry turbine maintenance manuals will be used. A Z-1 Terry turbopump and additional bearings will be acquired. These tests will include the following:

- Separate bearing testing of the GS-series Terry turbopump
    - Determine the degradation of GS-series turbine bearings when operated with heated oil for an extended period; observe conditions and potential failure between pre-test and post-test measurements.

- Z-1 integrated bearing testing
    - Quantify the degradation for bearings heated for several days under BDBE conditions and observe conditions and potential failure between pre-test and post-test measurements.

Since there is no known standard for inspecting bearing material, TAMU will use established guidelines for visual inspection. These visual inspections will also be conducted for not only lubricated bearing parts, but also for premature degradation of frictionless (ball) thrust bearings.

Separated component testing
Testing will involve both the lubrication oil and turbine bearings. A bearing for a GS-series Terry turbine shall be mounted with a shaft rotating at nominal turbine speeds; the shaft will be weighted to 100% and 150% of design loading for the bearing (the force needed to support the GS-series turbine shaft, wheel, etc.), and the bearing will be supplied with circulating lubrication oil for each test. The oil shall be supplied and maintained in a reservoir at the temperatures specified for the standalone oil tests; the tests shall be for similar periods, or until bearing failure. The same post-test characterization shall occur for the oil testing discussed in Section 2.1.3. Additionally, the bearings will be inspected, disassembled, and examined for wear/damage and material loss. The test matrix for the GS-turbine (separate-component) tests is given in Table 2.5.

If needed for the performance characterization of the GEH incipient failure detector, the facility will be operated with a bearing without active lubrication until failure.

Table 2.5 GS-Bearing Test Matrix

L: 72-hour S: 12-hour			
Temperature, °F	**Lo-Speed**	**Hi-Speed**	**Alternating**
160	L	S	S
180	L	L	L
250	L	S	S
290	-	S	-

Integrated component testing

A Z-1 turbine will be used for integrated testing of Z-1 bearings under varying conditions. The turbine, instead of being powered by steam, air, or water, will be connected to an electric motor and gearbox (a motoring dynamometer system), and will be driven at varying set speeds. In addition, the lubrication oil and overall turbine/pump bearing temperatures will be controlled, as will certain degradation conditions such as water content. The torque transmitted to the turbine shaft will be monitored during the test to observe any changes in parasitic losses during operation and any bearing degradation. In addition, the GEH incipient failure detector may be deployed in these tests. The test matrix is shown in Table 2.6.

Table 2.6 Z-1 Integrated Bearing Test Matrix

L: 72-hour S: 12-hour			
Temperature, °F	**Lo-Speed**	**Hi-Speed**	**Alternating**
160	L	S	S
180	L	L	L
250	L	S	S
290	S	S	S

Bearing degradation under varied temperature ranges

- Pre-condition oil by heating to 325 ^{o}F for 3 days

- For a turbine with 'good' bearings, replace oil with the pre-conditioned oil and operate at high speed.
    - Inspect bearings and measure material loss.

- For turbine with 'good' bearings, replace oil with the pre-conditioned oil and operate at low speed.
    - Inspect bearings and measure material loss.

- For turbine with 'good' bearings, replace oil with the pre-conditioned oil and operate at alternating between low and high speed.
    - Inspect bearings and measure material loss.

2.1.5 Turbine Exhaust Line Purge Tests

In recent efforts,[21] a new issue has been identified. The steam exhaust line departing the Terry turbine in many BWRs and PWRs has a large rise in elevation, potentially trapping saturated liquid and therefore under two-phase conditions can increase the backpressure significantly. This would result not only from the two-phase flow resistance, but the additional gravity head in the vertical line as well; should the condensate drain line from the turbine exhaust be overwhelmed. Such may cause the turbine's efficiency to degrade beyond that of two-phase injection alone; especially if liquid is constantly fed through the turbine or otherwise maintained in the exhaust line. While the increase in backpressure resulting from the turbine exhaust line conditions is currently unknown, the efficiency and performance of Terry turbines is known to significantly degrade when the backpressure is increased from 25 to 50 psi.[22] As a result, this may play an important role in the uncontrolled self-regulation of the system.

It should be noted that this is not a water hammer issue, which is outside the bounds of this test program. Rather, it is an examination of the potential for greater than currently modeled backpressure on the turbine, which decreases its ability to extract kinetic energy from the steam flow.

The TAMU NHTS Laboratory has a counter-current flow limitation (CCFL, also known as "flooding") facility for steam/water and air/water that can be readily adapted to investigate the conditions under which (potentially wet) steam flow through the turbine would be able to purge its vertical exhaust line of residual liquid, and under which conditions liquid would remain in the line for the long-term.

Since this is a recently discovered issue, further discussion with the Turbo-TAG will determine the scope of these tests and associated modeling efforts.

2.2 Schedule & Deliverables

The expectation is for component testing to start in August 2017. A Terry turbopump supplier will give this project priority for purchasing refurbished Terry turbine components as they become available. Table 2.7 provides the schedule and duration for Milestone 3.

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[21] SNL, "Terry Turbopump Analytical Modeling Efforts in Fiscal Year 2017 – Progress Report," Sandia Letter Report, SNL, September 2017.

[22] Operational experience discussions with industry members attending the 2017 EPRI Terry Turbine User Group meeting in Skokie, IL.

Table 2.7 Milestone 3 Schedule

Schedule	
Free Jet Test facility preparation	2 months
Free Jet Test facility test execution	8 months
Free Jet Test Post-test modeling analysis (see Section 4.1.1)	4 months
Free Jet Test facility data analysis and report	2 months
Governor & Trip/Throttle Valves Test facility preparation	2 months
Governor & Trip/Throttle Valves Test facility test execution	4 months
Governor & Trip/Throttle Valves Test Post-test modeling analysis (see Section 4.1.1)	4 months
Governor & Trip/Throttle Valves Test facility data and analysis report	2 months
Oil Test facility preparation	2 months
Oil Test facility test execution	5 months
Oil Test facility data and analysis report	3 months
Bearing Test facility preparation	2 months
Bearing Test facility test execution	4 months
Bearing Test facility data and analysis report	3 months
Oil & Bearing Test Post-test modeling analysis (see Section 4.1.1)	3 months

Table 2.8 provides the deliverables and duration for Milestone 3 efforts.

Table 2.8 Milestone 3 Deliverables

Deliverables	Duration
Free Jet Test facility data and analysis report	2 months
Governor Valve Test facility data and analysis report	2 months
Trip/Throttle Test facility data and analysis report	3 months
Oil Test facility data and analysis report	3 months
Bearing Test facility data and analysis report	3 months

The Milestone 3 schedule for this effort is summarized as a Gantt chart shown in Table 2.9; dashed lines indicate the beginning/end of the calendar year. At the conclusion to performance of work for each set of milestones, a 'hold point' period of 3-6 weeks will be allocated for the funding organizations to review the program progress and associated funding.

Table 2.9 Milestone 3 Gantt Chart (1-26 months)

Terry Turbopump Expanded Operating Band Gantt Chart														
		Month (June 2017 = Month 1, January 2018 = Month 8, January 2019 = Month 20)												
Experimental Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Milestone 3 – Full-Scale Component Experiments														
NHTS Lab Facility Preparations	4 months		■	■			■							
Free Jet Test facility preparation	2 months					■	■							
Free Jet Test facility test execution	8 months					■	■	■	■					
Turbomachinery Lab Facility Preparations	1 month			■										
GS-series Governor & Trip/Throttle Valves Testing facility preparation	2 months			■	■									
Governor & Trip/Throttle Valves Testing facility test execution	4 months				■	■	■							
Oil Test facility preparation	2 months					■	■							
Oil Test facility test execution	5 months							■	■		■			
Bearing Test facility preparation	2 months									■				
Bearing Test facility test execution	4 months										■	■		
Report Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
TAMU Free Jet Test facility data analysis and report	2 months									■				
TAMU Governor & Trip/Throttle Valves Testing facility data and analysis report	3 months						■	■						
Oil Test facility data and analysis report	3 months											■	■	
Bearing Test facility data and analysis report	3 months												■	■
SNL & IAE experimental experts at TAMU	24 months	■	■	■	■	■	■	■	■	■	■	■	■	
Industry Staff input on experimental efforts	4 months			■	■									
Industry Contributions and Review of Milestone 3 reports	4 months										■			■

2.3 Scaling Factors & Test Limitations

Scaling analysis will be required for any separate-effects or integral testing performed at less than full-scale system conditions. Scaling of single components involves matching the relevant non-dimensional parameters between the model and the prototype for the component of interest. For single-phase components with natural convection, the Rayleigh number must be added to the list. For components with two-phase flow and boiling or condensation heat transfer, additional parameters must be added including the Jakob number, the Bond number, the Weber number, and others. In addition, geometrical parameters such as orientation (vertical or horizontal) become explicitly significant for two-phase thermal hydraulics. For transient behavior of thermal-hydraulic components, the scaling analysis of even a single component is significantly more complicated, and parameters related to heat conduction in the solid material must also be considered.

For complex multi-component multi-phase systems, such as nuclear steam supply systems, it is generally not possible to match all of the relevant non-dimensional parameters in subscale models. Thus, scaling analysis of these integrated systems typically requires the introduction of many additional non-dimensional (Pi or ð) groups. Therefore, compromises must be made and an assessment of the importance of scaling distortions must be performed.

3. Milestone 4 – Terry Turbopump Basic Science Experiments

As efforts for Milestone 2 (Principles & Phenomenology) neared completion in 2016, the Turbo-TAG in conjunction with SNL and INL identified a suite of component experiments that could inform the later efforts of the program. This milestone is intended to provide information which will allow for the overall effort to better design, scale, and model the full-scale testing (i.e., Milestone 5 & 6), if the Turbo-TAG determines it is necessary to proceed to the subsequent milestones.

These experiments are intended to be conducted at low pressures and flow rates such that a university or small research facility could conduct them within an achievable timeframe for the later phases. Additionally, these efforts will be conducted in parallel with Milestone 3 efforts (see Section 2).

TAMU has been identified by the Turbo-TAG as the suitable location for this effort. Scaled-testing will be performed at TAMU under the guidance of Prof. Karen Vierow Kirkland (TAMU), Matthew Solom (SNL), and Nobuyoshi Tsuzuki (IAE). The NHTS facility includes a 157 kW_e steam generator, a simulated RCIC pump, and a 1400-gallon suppression chamber. Additionally, the TAMU Turbomachinery Laboratory includes high-capacity, high-pressure air and water supplies. The air supply is sufficient not only to power a Z-1, but large enough to provide the powering of a GS-series Terry turbopump. TAMU currently has a DOE-funded NEUP project entitled “Multi-phase Model Development to Assess RCIC System Capabilities under Severe Accident Conditions;” the project goal is to provide analysis methods for evaluation of RCIC system turbomachinery performance under multiphase conditions.

At certain times during testing, the industry collaborators will provide direct, on-site support to TAMU personnel. These industry personnel will assist TAMU with such tasks as the installation, operation, and training for the GS-series Terry turbopump and valve efforts.

Appendix A provides a comment/resolution discussion beyond the discussions provided in this section.

3.1 Test Phases

The Terry turbopump basis science testing is to be divided into three areas of experiments:

1. Z-1 turbopump testing,
2. Full-scale testing technique confirmation, and
3. Initial scoping of Fukushima Unit 2 uncontrolled feedback.

The Z-1 and GS-series turbopump tests will provide data for modeling efforts discussed further in Section 4.1.2, provide initial data on GEH’s incipient failure equipment, 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 & 6 full-scale tests. The initial scoping of uncontrolled feedback with a Z-1 turbopump will also provide confirmation that 1F2 observations are potentially applicable across all Terry turbopump models.

The objectives for each of these experimental areas will be discussed in detail in the subsequent subsections.

Test Suite Expectations:
The expectations for the Milestone 4 efforts are the following:

- Experimental test results will reduce the uncertainty in specific model parameters,

- The tasks will provide scaled (steam, steam/water, air, and air/water) and full-scaled (air) data which can be directly implemented into fleet-wide RCIC/TDAFW guidance, and

- These efforts benefit advancing with the selection of a full-scale test facility, inform the development of a detailed full-scale experimental plan, and further refinements on the cost estimates for the Milestone 5 & 6 efforts.

To achieve these expectations, a generic technical approach for each test suite will be:

1. Model the planned test
2. Perform tests within specified test requirements
3. Analyze tests across the test requirements range
4. Compare model analyses to test results
5. Report differences and possible technical reasons
6. Extrapolate to full-scale conditions
7. Turbo-TAG evaluation of expectations and '*adequate confidence*'

Quality Assurance of Experiments:
The QA requirements for this effort shall abide by established TAMU QA levels of rigor to include the following:

- Scoping with peer review and documentation,
- Calibration of instrumentation with proper records, and
- Data acquisition system documentation trail which abides by an established standard
    - A second or third order NIST standard

The specific QA processes will be determined by the Turbo-TAG and the TTExOB in coordination with TAMU, and will be fully documented.[23] Additional QA requirements through the DOE-NE LWRS Program will be applied whenever applicable.[24]

3.1.1 Z-1 Turbopump Tests

The Z-1 Terry turbopump experiments are to be conducted by Prof. Gerald Morrison at TAMU's Turbomachinery Laboratory for the air and air-water tests. The steam and steam-water tests are

[23] The working draft of the Milestone 3 & 4 QA document for TAMU is: Kirkland, K., "Quality Assurance Plan for RCIC Testing at Texas A&M University," August 2017.

[24] Light Water Reactor Sustainability Program, "Quality Assurance Program Description," INL/MIS-10-19844 Revision 2, July 2016.

to be conducted by Prof. Karen Vierow Kirkland at TAMU's NHTS facility. The objective of these tests is to develop a body of knowledge regarding the realistic outcomes of Terry turbopump performance. Corresponding and supporting objectives are as follows:

- Provide an experimental basis for improved CFD and system level modeling efforts discussed in Section 4.1.2 for correlated air-water and steam-water inlet conditions into a Z-1 Terry turbine, which in turn will provide information on Terry pump performance data.

- Provide a technical basis for improved system modeling efforts discussed in Section 4.1.2 for steam-water inlet conditions into the nozzle of a GS-series Terry turbine under BDBE conditions.

Motivation:
The RCIC/TDAFW system is driven by a Terry impulse turbine, and thus the development of an experimentally based system level model to accurately understand the principal operation of the system is critical for BDBEs. There is a scarcity of available data for BDBE performance of a Terry turbopump for steam and steam-water conditions. Thus, these tests will serve to expand the available data for modeling validation and verification, while creating a basic scientific understanding of Terry turbopumps in a cost-effective manner without the potential of severely damaging a nuclear grade GS-series Terry turbopump.

These initial Z-1 turbopump tests will inform the experimental design and testing, and modeling efforts for the subsequent basis science tests (e.g., development of pump curves). For air and air-water testing, the availability of the TAMU Turbomachinery Lab's air compressor and a large water supply will enable testing with continuous air feed, or air-water feed, to at least 100 psi. The large-volume compressor allows for longer tests (tens of minutes) and with greater flow rates through the turbine. Additionally, for steam and steam-water testing, the current capabilities remain at up to 60 psia for a few minutes in the NHTS lab.

Test Parameters:
The Z-1 Terry turbopump test measurements will be connected to the CFD and system modeling efforts discussed in Section 4.1.2. A test matrix can be seen in Table 3.1. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Turbine steady-state response
  - Torque vs. speed for given steam pressure, quality, and flow
- Turbine step response
  - Time constant for step change in flow conditions
- Turbopump steady-state response
  - Pump output vs. backpressure for given steam pressure, quality, and flow
- Turbopump step response
  - Time constant for step change in flow conditions

Table 3.1 Z-1 Profiling Test Matrix

Vapor Mass Fraction (Quality)	Torque Curve	Turbine Step-Change	Turbopump Curve	Pump Step Change
100%	x	x	x	x
95%	x	x	x	x
90%	x	x	x	x
80%	x	x	x	x
70%	x	x	x	x
60%	x	x	x	x
50%	x	x	x	x
40%	x	x	x	x
30%	x	x	x	x
25%	x	x	x	x
20%	x	x	x	x
15%	x	x	x	x
10%	x	x	x	x
7.5%	x	x	x	x
5%	x	x	x	x
2.5%	x	x	x	x
0%	x	x	x	x

Steam: Inlet at 80-90, 70, 50, 30 psia

Air: Inlet at 110, 80-90, 70, 50, 30 psia

Test Requirements:

The Z-1 turbine will be connected to the analog RCIC/TDAFW pump to enable scaled integrated testing. The technical approach is as follows:

- Drive the Terry turbine through its RPM range resisted by a dynamometer
    - Measure turbine torque as a function of speed
        1. Determine the critical speed

- Drive the Terry turbine with an analog RCIC/TDAFW pump
    - Record flow rates (air-water or steam-water), pressure, and temperature
        1. Under steam and steam-water conditions
        2. Under air and air-water conditions
    - Generate turbopump horsepower curves from measured torque and speed
    - Generate turbopump efficiency curves by comparing turbopump horsepower to fluid flow rates and fluid state changes
        1. Use air, steam, steam/water, and air/water mixtures

- Drive the Terry turbine through a range of dynamic events
    - Measure turbine response as it reaches steady-state conditions

Drive Terry turbine with dynamometer
The initial Z-1 and dynamometer testbed will be identical to that used in the DOE NEUP project "Multi-phase Model Development to Assess RCIC System Capabilities under Severe Accident Conditions" for straightforward comparison and extension of the data sets. Characterized flows (pressure, temperature, quality/void fraction, mass flowrate) will be injected through the Z-1 for air, air/water, steam, and steam/water. Steady-state torque will be measured at a number of speeds to develop complete torque curves for specified inlet conditions. The two-phase testing will encompass the entire range of steam quality; saturated steam through saturated water, which is expected to produce some flashing in the nozzle. The air and air/water testing will have an expanded range for the data set, as greater pressure and continuous flow air sources will be available for it.

Terry turbine and RCIC/TDAFW analog
The turbopump testing will initially use the Z-1 turbine testbed from dynamometer testing; the dynamometer will be removed and replaced with a RCIC/TDAFW pump analog. Testing will be similar; known steam/air/water flows will be injected through the turbine. The pump will have a set differential pressures to overcome; the steady-state turbine speed and pump flow will then be measured.

Dynamic Response Curves:
Step-function response curves applicable to dynamic analyses can be produced. It is noted that true step-changes in process conditions are difficult to achieve; the detailed procedures will be such that the effects of non-instantaneity will be minimized in the final analysis. The Z-1 testbed can be set to provide constant motive fluid flow upon rapid opening of a gate/ball valve. Initially, the turbine, unloaded by a dynamometer or pump, will be stopped/at rest with no flow through it. Upon quickly opening the valve, a steady flow will be injected; the time response of the turbine speed will be monitored as it approaches steady-state. From the steady-state speed, the flow will then be suddenly cut off by closure of the supply valve, and the speed response during coast down will be monitored. By combining these step-function responses with the steady-state profiles, full dynamic response profiles can be developed for implementing into system models.

3.1.2 Full-Scale Testing Technique Confirmation
The full-scale testing technique confirmation experiments are to be conducted by Prof. Gerald Morrison at TAMU's Turbomachinery Laboratory for the air and air-water tests. The limited steam and steam-water tests are to be conducted by Prof. Karen Vierow Kirkland at TAMU's NHTS facility. The objective of these tests is to develop a body of knowledge regarding the realistic outcomes of GS-series Terry turbopump performance under Milestone 5 conditions but instead of steam, air will be used as the kinetic fluid. Corresponding and supporting objectives are as follows:

- Provide an experimental basis for improved CFD and system level modeling efforts discussed in Section 4.1.2 for Milestone 5 conditions with steam-to-air correlations for a Z-1 Terry turbopump, which in turn will provide information on air testing from GS-series Terry turbopump performance data.

- Provide a technical basis for improved system modeling efforts discussed in Section 4.1.2 with steam-to-air correlations for a Z-1 Terry turbopump, which in turn will provide information on air testing from GS-series Terry turbopump performance data under BDBE conditions.

- Provide confirmation of the test procedures proposed for the Milestone 5 efforts.

Motivation:
The RCIC/TDAFW system is driven by a Terry impulse turbine, and thus the development of an experimentally based system level model to accurately understand the principal operation of the system is critical for BDBEs. There is a scarcity of available data for BDBE performance of a Terry turbopump for saturated steam, low pressure long-term operating conditions. Thus, these air tests will serve to expand the available data for modeling validation and verification, while creating a basis for scientific understanding of a GS-series Terry turbopump in a cost-effective manner without the potential of severely damaging a nuclear grade Terry turbopump.

The initial Z-1 Terry turbopump tests discussed in Section 3.1.1 will inform the experimental design and testing, and modeling efforts for the subsequent basis science tests (e.g., bearing performance under BDBE conditions). At the TAMU Turbomachinery Lab, the large air compressor and water supply may be able to spin a full-scale GS-series turbine to power a RCIC/TDAFW pump. Initial estimations based on equipment specifications give promise that some level of integral full-scale testing can be done at TAMU. The ability to conduct both Z-1 testing and some level of integral full-scale GS-series turbine tests will enable benchmarking of the small-scale Z-1 turbine test data to the full-scale turbine test data. A swap of only the turbines on the test rig, with all other equipment the same, will enable a clean comparison of the two data sets. ***This comparison can resolve any scaling issues on the Z-1 Terry turbine data and enable definition of test procedures and protocols for the full-scale tests.***

Test Parameters:
The full-scale confirmatory test measurements will be connected to the CFD and system modeling efforts discussed in Section 4.1.2. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Evaluation of degradation for a Z-1 Terry turbopump due to long-term operation under various inlet conditions

- Evaluation of degradation for a GS-series Terry turbopump due to long-term operation under various inlet conditions

- Establishment of scaling parameters from a Z-1 Terry turbopump to a GS-series Terry turbopump

Test Requirements:
Air tests with a Z-1 Terry turbine will be connected to the analog RCIC/TDAFW pump to enable scaled integrated testing. Additionally, air tests with a nuclear grade GS-series Terry turbopump will be done with an integrated test. The technical approach is as follows:

- Long-term operations of a Z-1 Terry turbine with an analog RCIC/TDAFW pump
    - Characterization system tests will be conducted for 3 days
        1. Observe steady-state inlet conditions
        2. There is also a potential for 7 days and 10 days of continuous operation
        3. Thermal and vibrational performance will be monitored
    - Record bearing wear and lube oil performance
        1. There is also a potential to identify incipient failure
    - Record air flow rates, pressure, and temperature
    - Generate turbopump horsepower curves from measured torque and speed
    - Generate turbopump efficiency curves by comparing turbopump horsepower to fluid flow rates

- Short-Term (Scaling Parameter) operations of the GS-series Terry turbopump
    - Subset of Z-1 characterization tests, performed on GS-series turbopump
    - Drive the Terry turbine with RCIC/TDAFW pump
        1. Record flow rates (air-water), pressure, and temperature
            1. Vary air and air-water conditions
            2. Vary pump outlet conditions

- Long-term operations of the GS-series Terry turbopump
    - Characterization system tests will be conducted for 3 days
        1. Observe steady-state inlet conditions
        2. Observe steady turbine speed (governor enabled) conditions
        3. There is also a potential for 7 days and 10 days of continuous operation
        4. Thermal and vibrational performance will be monitored
    - Record bearing wear and lube oil performance
        1. There is also a potential to identify incipient failure
    - Record air flow rates, pressure, and temperature
    - Generate turbopump horsepower curves from measured torque and speed
    - Generate turbopump efficiency curves by comparing turbopump horsepower to fluid flow rates

Long-term operations of the Z-1 Terry turbine and RCIC/TDAFW analog

The Z-1 Terry turbine will be connected to a dynamometer and air tested for long-term operations. The inlet and outlet conditions (P, T, Flow) will be brought to steady-state along with the speed and torque. Then, with constant inlet and outlet conditions, the torque will be maintained at a constant value while the speed is allowed to drift. This response will be monitored continuously for 3-day and possibly up to 7-10 days of operation. Due to the long operating times necessary, only a limited number of tests will be run. The dynamometer will then be removed and replaced by the analog RCIC/TDAFW pump, and the tests repeated; a constant DP across the pump will be maintained in place of constant torque via a backpressure regulator. A test matrix for both the Z-1 Terry turbine tests discussed here and GS-series turbine long-term operations is given in Table 3.2.

Table 3.2 Long-Term Testing Test Matrix

System	Turbine (T) / Turbopump (P)	Ambient Temperature[1]	Cooling Temperature[2]	Fluid	Duration (days)
Z-1	T	Lab room temp.	Ambient air-cooled	Air	3
Z-1	T	180 ^{o}F	Ambient air-cooled	Steam	7
Z-1	T	Lab room temp.	Ambient air-cooled	Steam	3
Z-1	P	180 ^{o}F	Ambient air-cooled	Steam	3
GS-2	T	Lab room temp.	Lab room temp.	Air	3
GS-2	P	Lab room temp.	Lab room temp.	Air	3
GS-2	P	180 ^{o}F	180 ^{o}F	Air[3]	7

[1] The turbine skid will be placed in an insulated enclosure. The ambient air temperature inside the enclosure will be regulated.

[2] The GS-1 has an oil cooler. The coolant fluid is water and the water temperature will be controlled. The Z-1 does not have such a cooler.

[3] The air will be heated upstream of the turbine. The inlet air temperature will be determined during test preparation.

Short-term (Scaling Parameter) operations of the GS-series Terry turbopump
With the acquisition of a nuclear grade GS-series Terry turbopump skid, the air response profiling conducted for the Z-1 testbed in Section 3.1.1 will be performed on the GS-series turbopump skid. There is sufficient air but not sufficient steam for supplying a GS-series turbine at TAMU; steam testing will not be performed on the GS-series turbopump skid as part of Milestone 4 efforts. The test matrix for Z-1 characterization (Table 3.1) is also applicable for the GS-series turbine as well, with the exception of the steam tests.

Long-term operations of the GS-series Terry turbopump
With the experience obtained from the Z-1 Terry turbopump air testbed assembly, the long-term air operation tests will be repeated with the larger GS-series Terry turbopump skid (Table 3.2). Comparison of the GS-series and Z-1 Terry turbopump air test results will establish the necessary scaling factors to apply to the Z-1 Terry turbopump steam data to the full-scale plant systems; any anomalous behavioral differences between the Z-1 and the GS-series systems will be noted. The direct and scaled performance curves will then be incorporated into system models and plant simulators to better characterize the dynamic response of the RCIC/TDAFW system under low-pressure long-term operations.

3.1.3 Scoping of Terry Turbopump Uncontrolled Feedback

The Terry turbopump uncontrolled feedback experiments are to be conducted by Prof. Karen Vierow Kirkland at TAMU's NHTS facility. The objective of these tests is to develop a body of knowledge regarding the realistic outcomes of GS-series Terry turbopump performance under Milestone 6 conditions and potential recovery options using a Z-1 Terry turbine with an analog RCIC/TDAFW pump. Corresponding and supporting objectives are as follows:

- Provide an experimental basis for improved CFD and system level modeling efforts discussed in Section 4.1.2 for Milestone 6 conditions with a Z-1 Terry turbopump, which in turn will provide information on GS-series Terry turbopump performance data.

- Provide a technical basis for improved system modeling efforts discussed in Section 4.1.2 with a Z-1 Terry turbopump, which in turn will provide information on GS-series Terry turbopump performance data under BDBE conditions.

- Provide confirmation for the test procedures proposed for the Milestone 6 efforts.

Motivation:

The RCIC/TDAFW system is driven by a Terry impulse turbine, and thus the development of an experimentally based system level model to accurately understand the principal operation of the system is critical for BDBEs. There is a scarcity of available data for BDBE performance of a Terry turbopump for two-phase steam-water conditions at or near operating pressure for long-term BDBE operation conditions (e.g., 1F2 RCIC operated unregulated for ~68 hours). Thus, these tests will serve to expand the available data for modeling validation and verification, while creating a basic scientific understanding of Terry turbopumps in a cost-effective manner without the potential of severely damaging a nuclear grade GS-series Terry turbopump.

A series of scoping tests where the Z-1 Terry turbopump runs in an uncontrolled mode and returns water back to the steam generator will be attempted. These would be proof-of-concept tests where the governor valve position may be frozen in different positions to ascertain whether the valve can stick in a favorable open fraction which may have occurred in the 1F2 RCIC operations.

Another observation from the Fukushima accidents was the transition to seawater injection which took multiple tries to achieve and maintain injection. A transition from RCIC/TDAFW unregulated operations to FLEX could, in reality, take multiple attempts to achieve the desired outcome. Thus, scoping tests will be conducted to show how the transition from a self-regulating mode to FLEX mode can be enabled. This series of scoping tests will also consider 'failed' attempts at FLEX and whether it is feasible to allow the Terry turbopump to achieve a self-regulating mode prior to attempting another try at implementing FLEX.

These initial Z-1 turbopump tests will inform the experimental design and testing, and modeling efforts for Milestone 6 experiments (e.g., Terry turbine performance under two-phase self-regulating BDBE conditions).

Test Parameters:

These scaled confirmatory test measurements need to be connected to the CFD and system modeling efforts discussed in Section 4.1.2. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Pressure and temperature profiles of the varied two-phase inlet conditions into the governor valve and Z-1 Terry turbopump,

- Moisture quality of the two-phase inlet conditions into the governor valve and Z-1 Terry turbopump, and

- Pump performance curves under varied two-phase conditions.

Test Requirements:
The Z-1 turbine will be connected to the analog RCIC/TDAFW pump to enable scaled integrated testing. The technical approach is as follows:

- Uncontrolled two-phase operations of the Terry turbine with an analog RCIC/TDAFW pump feeding the steam generator
  - Characterization system tests will be conducted for 8-12 hours
    1. There is also a potential for 3 days of continuous operation
  - Simulated variance of the governor valve
    1. Identify 'favorable' valve open fractions
  - Record bearing wear and lube oil performance
    1. There is also a potential to identify incipient failure
  - Record flow rates (air-water or steam-water), pressure, and temperature
    1. Under steam-water conditions; preferred mode of testing
    2. Under air-water conditions, if steam-water cannot be achieved
  - Generate turbopump horsepower curves from measured torque and speed
  - Generate turbopump efficiency curves by comparing turbopump horsepower to fluid flow rates and fluid state changes
    1. Use air, steam, water, and steam/water mixtures

- Transition from uncontrolled self-regulating mode of the Terry turbine, with an analog RCIC/TDAFW pump feeding the steam generator, to a FLEX mode
  - Characterization system tests will be conducted for various options of transitioning from a self-regulating mode to a FLEX mode
    1. Consider scenarios where multiple attempts to transition from a self-regulating mode to a FLEX mode are required
  - Record flow rates (air-water or steam-water), pressure, and temperature
    1. Under steam-water conditions; preferred mode of testing
    2. Under air-water conditions, if steam-water cannot be achieved
  - Generate turbopump horsepower curves from measured torque and speed
  - Generate turbopump efficiency curves by comparing turbopump horsepower to fluid flow rates and fluid state changes
    1. Use air, steam, water, and steam/water mixtures

Uncontrolled two-phase operations of the Terry turbine
The Z-1 turbopump testbed will be set up with slight differences in interconnection to the steam facility. The steam generator will be supplied by its standard feedwater pump, which will draw from the same source as the RCIC/TDAFW pump analog. With a constant steam generator heater power and feedwater flow and temperature (i.e., constant steam supply), the steam line will have a water injection line connected to the inlet of the Z-1 turbine. When sufficient flow is available, the feedwater flowrate will be measured and the same flowrate will be extracted from

the RCIC/TDAFW pump analog outlet and directed back to the water source. The remaining water provided by the RCIC/TDAFW pump analog will be injected into the steam line. This potentially two-phase steam/water flow will then be directed to the turbine inlet; given sufficient time, negative feedback between the water injection and turbine speed is expected to develop and bring the system to a quasi-steady-state condition. A test matrix for the Z-1 turbine uncontrolled feedback operation is given in Table 3.3.

Once such quasi-steady-state conditions are seen to develop at multiple steam generator power levels, perturbations will be introduced (e.g., lowering of steam generator pressure similar to the trends seen at 1F2) to demonstrate the negative feedback and stable operation of the turbopump. Once demonstrated, control system theory will be applied to develop a full dynamic response model for a GS-series Terry turbopump in a 1F2 scenario.

Table 3.3 Uncontrolled Feedback Test Matrix

Governor Valve Stem Position	**Steam Pressure**	**Duration (hours)**
open	high	12
open	medium	72
open	low	12
75%*	medium	8
50%*	medium	8
Fail as-is**	medium	8

* Exact position will be determined with guidance from the Turbo-TAG and results of the Milestone 3 valve profiling

** Equivalent to estimated last good positioning by controller

Transition from uncontrolled self-regulating mode to a FLEX mode

The Z-1 turbopump testbed will be set up in the same manner as previously discussed for the *Uncontrolled two-phase operations of the Terry turbine*. The two-phase steam/water flow will then be directed to the turbine inlet. Given sufficient time, negative feedback between the water injection and turbine speed is expected to develop and bring the system to a quasi-steady-state condition. A test matrix for the Z-1 turbopump uncontrolled feedback to a FLEX mode of operation is given in Table 3.4. Detailed procedures for FLEX tests will be developed with input from Industry experts.

Once such quasi-steady-state conditions are seen to develop at multiple steam generator power levels, transitions from the Terry turbopump feedwater to another ‘FLEX’ feedwater source will be investigated to demonstrate transition scenarios. Once demonstrated for the Z-1 system, scaling effects and control system theory will be applied to develop a full dynamic response model for a GS-series Terry turbopump in a 1F2 scenario.

Table 3.4 Uncontrolled Feedback to FLEX Test Matrix

Governor Valve	**Steam Pressure**	**Number of FLEX Attempts**
open	high	1 to 3
open	medium	1 to 3
open	low	1 to 3

3.2 Schedule & Deliverables

The expectation is for Terry turbopump basic science testing to start in FY-17, with the start of facility preparations dependent upon the availability of refurbished Z-1 turbopump. Table 3.5 provides the schedule and duration for Milestone 4.

Table 3.5 Milestone 4 Schedule

Schedule	
Z-1 Turbopump Test facility preparation	6 months
Z-1 Turbopump Test facility test execution	6 months
Z-1 Turbopump Test Post-test modeling analysis (see Section 4.1.2)	4 months
Z-1 Turbopump Test facility data and analysis report	4 months
Full-Scale Technique Test facility preparation	2 months
Full-Scale Technique Test facility test execution	5 months
Full-Scale Technique Test Post-test modeling analysis (see Section 4.1.2)	3 months
Full-Scale Technique Test facility data and analysis report	4 months
Scoping Uncontrolled Feedback Test facility preparation	1 months
Scoping Uncontrolled Feedback Test facility test execution	3 months
Scoping Uncontrolled Feedback Test Post-test modeling analysis (see Section 4.1.2)	3 months
Scoping Uncontrolled Feedback Test facility data and analysis report	3 months

Table 3.6 provides the deliverables and duration for Milestone 4 efforts.

Table 3.6 Milestone 4 Deliverables

Deliverables	Duration
Z-1 Turbopump Test facility data and analysis report	4 months
Full-Scale Technique Test facility data and analysis report	4 months
Scoping Uncontrolled Feedback Test facility data and analysis report	3 months

The Milestone 4 schedule for this effort is summarized as a Gantt chart in Table 3.7; dashed lines indicate the beginning/end of the calendar year. At the conclusion to performance of work for each set of milestones, a 'hold point' period of 3-6 weeks will be allocated for the funding organizations to review the program progress and associated funding.

3.3 Scaling Factors & Test Limitations

Discussions in Section 2.3 are also applicable for the Milestone 4 efforts.

Table 3.7 Milestone 4 Gantt Chart (1-26 months)

Terry Turbopump Expanded Operating Band Gantt Chart														
		Month (June 2017 = Month 1, January 2018 = Month 8, January 2019 = Month 20)												
Experimental Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Milestone 4 – Terry Turbopump Basic Science Experiments														
NHTS Lab Facility Preparations	3 months													
Z-1 Turbopump Test facility preparation	6 months													
Z-1 Turbopump Test facility test execution	6 months													
Turbomachinery Lab Facility Preparations	1 month													
Full-Scale Technique Test facility preparation	2 months													
Full-Scale Technique Test facility test execution	5 months													
Scoping Uncontrolled Feedback Test facility preparation	1 months													
Scoping Uncontrolled Feedback Test facility test execution	3 months													
Report Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Z-1 Turbopump Test facility data and analysis report	4 months													
Full-Scale Technique Test facility data and analysis report	4 months													
Scoping Uncontrolled Feedback Test facility data and analysis report	3 months													
SNL & IAE experimental experts at TAMU	24 months													
Industry Staff input on experimental efforts	4 months													
Industry Contributions and Review of Milestone 3 reports	4 months													

4. Modeling Updates from Milestone 3 & 4 Data and Insights

The modeling efforts for Milestone 3 and Milestone 4 of the program are discussed within this section. This is to ensure that the experimental testing discussed in Sections 2 and 3 are stand-alone. By doing so, this section allows a more detailed discussion of the modeling efforts without detracting from the experimental efforts. The modeling and analyses discussed in this section are specific to system-level modeling (e.g., SAMPSON, RELAP, and MELCOR) as well as detailed computations (e.g., CFD), and will be parallel efforts with their associated experimental phase. When appropriate, the specific type of modeling is called out to better inform the reader.

These modeling aspects are to be integrated and iterated with the Milestone 3 and Milestone 4 efforts. Given that this part of the plan is for a two-year effort, the modeling effort has to be closely related to the testing discussed in Sections 2 and 3. The experimental research team will be kept abreast of all modeling efforts, assumptions, and limitations for the system models and the detailed computation models which inform the tests.

Appendix A provides a comment/resolution discussion beyond the discussions provided in this section.

Modeling Phases

The overall Milestone 7 modeling efforts discussed in the summary program plan are broken out to coincide with Milestone 2 and pre/post-testing for Milestones 3-6 of this effort. This section provides a detailed discussion only for the Milestone 3 and Milestone 4 modeling efforts. For a high-level discussion on each of the Milestone 3-6 experimental efforts and the associated Milestone 7 modeling/analysis efforts, refer to the *Terry Turbopump Expanded Operating Band Summary of Program Plan – Revision 1*.

Modeling Expectations:

The expectations for these Milestone 3 & 4 modeling efforts are following:

- In conjunction with the Milestone 3 & 4 experimental results, determine if there is sufficient confidence in the modeling results such that Milestone 5 & 6 are not necessary to meet the objectives of this program
    - This determination will be made by the technical advisory group (Turbo-TAG) discussed in the summary program plan

- Integrate an advanced Terry turbopump MELCOR system model into an existing nuclear power plant simulator for modeling confirmation and new procedure verification; Perry Nuclear Generating Station's simulator uses MELCOR.

- If deemed necessary to go beyond Milestone 3 & 4 efforts, the modeling results will reduce the uncertainty in specific full-scale parameters in Milestone 5 & 6 testing and associated modeling, and

- These efforts benefit advancing with the selection of a full-scale test facility; inform the development of a detailed full-scale experimental plan, and further refinements on the cost estimates for the Milestone 5 & 6 efforts.

Quality Assurance of Modeling:
The QA requirements for this effort shall abide by established TAMU and SNL QA levels of rigor for modeling to include the following:

- Independent peer review of the models,
- Appropriate documentation, and
- Models for review upon request from stakeholders

The specific QA processes will be determined by the Turbo-TAG in coordination with TAMU, and will be fully documented[25]. Additional QA requirements[26] through the LWRS Program will be applied whenever applicable.

Modeling Motivation:
In conjunction with the experimental data obtained from the efforts discussed in Section 2 and Section 3, the insights from these modeling efforts will inform the following:

- Fleet-wide or BWR/PWR-wide system impact analysis
    - Summary document
    - FLEX implementation guidance
    - RCIC/TDAFW blackstart procedural guidance
        - Recommendations to assist operators in knowing if the Terry turbine is operational (rolling) or not
        - Identify how to know if the Terry turbine is operational (rolling) if the room is dark

- Guidance on inputs for improved realism for operator training (simulator)
    - Improved relationship to actual plant parameters during drills, exercises, and simulator training
        - Integrate the advanced Terry turbine system models into the simulator
    - Recommendations of added failure modes to help 'stress' the operators
        - Feedback from simulator trainers

- Maintenance improvements/recommendations
    - Ensure fleet-wide consistency (e.g., 'at resistance on the valve')

[25] The working draft of the Milestone 3 and 4 QA document for TAMU is Kirkland, K. "Quality Assurance Plan for RCIC Testing at Texas A&M University," August 2017.

[26] Light Water Reactor Sustainability Program, "Quality Assurance Program Description," INL/MIS-10-19844 Revision 2, July 2016.

4.1.1 Milestone 3 Modeling – Full-Scale Component Experiments

The modeling is planned to inform the Milestone 3-6 experiments and Milestones 4-6 modeling with the following:

- Detailed pre-test computational modeling and analysis of specific full-scale component testing. Specifically, this modeling will inform Milestone 3 free jet testing (see Section 2.1.1) and governor and trip/throttle valve testing (see Section 2.1.2). This part of the modeling effort will be done using detailed computational modeling.

- Detailed post-test computational modeling and analysis of all executed Milestone 3 testing to inform Milestone 4-6 testing. This part of the modeling effort will be done using detailed computational modeling and system modeling.

- Identify insights to inform the Terry turbopump modeling in Milestone 4-6 from results of the testing with iterations to improve the modeling.

4.1.1.1 Free Jet Modeling Efforts

The pre-test and post-test Free Jet Modeling efforts will ultimately produce a predictive model for the behavior of Terry nozzles under single and two-phase conditions that can be reasonably integrated into a systems-level code. The Terry turbopump steam nozzles have a first order effect on system-level predictive modeling[27]. This endeavor will leverage existing and recent research[28,29], utilize any necessary computational (i.e., CFD) codes to produce simulated performance data, and integrate the data/experience from the experimental effort to produce an integrated model of a Terry turbopump steam nozzle with sufficient fidelity for use as a component within an improved Terry turbine system-level model.

4.1.1.2 Governor and Trip/Throttle Valve Modeling Efforts

The pre-test and post-test governor and trip/throttle valve modeling efforts will produce two types of models. The first is a computational (CFD) model of the valves that can be rapidly incorporated into a systems-level code, and will include the measured C_v, F_L, and x_T curves. The second is a system-level model for the experimental test rig as a validation model of the measured C_v, F_L, and x_T curves for that system-level code.

4.1.1.3 Oil Performance Modeling Efforts

CFD could be used to predict the stability of the oil wedge in the bearing as a function of temperature. The post-test oil performance modeling effort will produce models that can be

[27] SNL, "Terry Turbopump Analytical Modeling Efforts in Fiscal Year 2017 – Progress Report," Sandia Letter Report, SNL, September 2017.

[28] Beeny, Bradley A. Computational Multiphase Fluid Dynamics Analyses and Systems-Level Model Development for a Reactor Core Isolation Cooling System Terry Turbine. Ph.D. Dissertation, Texas A&M University. College Station, TX, 2017.

[29] K. Ross et. al., "Modeling of the Rector Core Isolation Cooling Response to Beyond Design Basis Operations – Phase 1," SAND2015-10662, Sandia National Laboratories, Albuquerque, NM, 2015.

inserted into systems-level code that will enable prediction of the state of degradation of oil in turbomachinery based on operational history and, in conjunction with the bearing modeling, the effects of degraded oil on equipment.

4.1.1.4 Bearing Performance Modeling Efforts

The post-test bearing performance modeling effort will, in conjunction with the oil modeling efforts, produce models of the performance of fluid-filled bearings for incorporation into systems-level codes. Modeling work will be performed to characterize the oil wedge, stability, and drag torque on the rotor in a manner useful for systems codes.

4.1.1.5 Turbine Exhaust Line Purge Testing Modeling Efforts

The modeling of turbine exhaust line purge tests, upon direction by the Turbo-TAG, will be incorporated into the systems-level models discussed in Section 4.1.2. This modeling will allow for the retention of two-phase fluid in the turbine exhaust line as well as its resulting effects on turbine backpressure. As a recently discovered issue, the parameters of the turbine exhaust purge test modeling have yet to be defined by the Turbo-TAG.

4.1.2 Milestone 4 Modeling – Terry Turbopump Basic Science Experiments

The modeling is planned to inform the integral full-scale experiments in Milestones 4-6 and Milestones 5 & 6 modeling with the following:

- Detailed pre-test system level modeling and analysis of all planned Milestone 4 testing discussed in Section 3.1. These modeling efforts may also use detailed computational modeling to better inform the system level model.

- Detailed post-test system level modeling and analysis of all executed Milestone 4 testing to inform Milestone 5 and 6 testing. These modeling efforts may also use detailed computational modeling to better inform the system level model.

- Identify insights to inform the Terry turbopump modeling in Milestone 5 and 6 from results of the testing with iterations to improve the modeling. These modeling efforts may also use detailed computational modeling to better inform the system level model.

- Demonstrate control system theory for a full dynamic response model of a GS-series Terry turbopump based on Z-1 Terry turbopump steam and steam/water turbine inlet conditions for various scenarios: 1F2 unregulated feedback, transition from unregulated feedback to FLEX, and transition from RCIC blackstart to governor control.

4.1.2.1 Z-1 Turbopump Modeling Efforts

Recent modeling efforts[30] have produced a framework which can be used as a foundation for turbine-driven pump models in systems-level codes. In conjunction with the experimental Z-1

[30] SNL, "Terry Turbopump Analytical Modeling Efforts in Fiscal Year 2017 – Progress Report," Sandia Letter

characterization tests, pre-test and post-test system-level models will be created to produce realistic results for Z-1-scale Terry turbopump air and steam test rigs. These post-test models will incorporate the Milestone 3 models and experimental insights (i.e., free jet, turbine exhaust purge line, and bearing performance) as practicable.

4.1.2.2 Full-Scale Technique Confirmation Modeling Efforts

The pre-test and post-test GS-series system-level modeling efforts will be based on the air test experimental test rig. These low-pressure air GS-series models will then enable adequate simulation of full-scale system-level analysis for RCIC and TDAFW low pressure operations.

4.1.2.3 Scoping of Terry Turbine Uncontrolled Feedback Modeling Efforts

The Terry turbopump models developed earlier in the Milestone 4 modeling efforts will be employed in a significant manner to determine test parameters for the uncontrolled feedback testing that would provide the most useful test data, in addition to providing experimentalists predictive insights. The post-test models will provide insights into better refining the accurate prediction of uncontrolled Terry turbopump behavior observed at Fukushima Daiichi Unit 2.

4.2 Organization

The US modeling efforts will be conducted at DOE National Laboratories (SNL and INL) and TAMU. The Japan modeling efforts will be conducted under the guidance of IEA. Both US and Japan modeling efforts will be conducted in collaboration through the Turbo-TAG. Additionally, coordination, prioritization, and direction of the modeling interactions will be provided within the overall project management structure[31] with guidance from the Turbo-TAG.

4.3 Schedule & Deliverables

Table 4.1 provides the schedule and duration for model development for Milestone 3 and Milestone 4. The specific experimental modeling efforts discussed in Section 4.1 are not explicitly called out, but rather the entire suite of pre-test and post-test modeling efforts are tracked.

Report, SNL, September 2017.

31 International TTExOB Initiative Charter – Version 5.3, July 14, 2017.

Table 4.1 Modeling Schedule Specific to Milestones 3 & 4

Schedule	Duration
Milestone 3 – Full-Scale Component Experiment Modeling	
Detailed computational modeling to inform Milestone 3	3 months
Pre-test system level modeling to inform Milestone 3	2 months
Post-test detailed computational modeling	4 months
Post-test system level modeling informed from computational modeling	2 months
Milestone 4 – Terry Turbopump Basic Science Experiment Modeling	
Detailed computational modeling to inform Milestone 4	3 months
MELCOR modeling to inform Milestone 4	2 months
SAMPSON modeling to inform Milestone 4	3 months
Post-test detailed computation modeling	4 months
Post-test MELCOR modeling	2 months
Post-test SAMPSON modeling	2 months
Post-test RELAP-7 modeling	3 months
Integrate MELCOR model into Perry simulator	8 months

Table 4.2 provides the deliverables and duration for Milestone 3 and Milestone 4 modeling efforts.

Table 4.2 Modeling Deliverables Specific to Milestones 3 & 4

Deliverables	Duration
Milestone 3 – Full-Scale Component Experiment Modeling	
Pre-test summary modeling report for Milestone 3	2 months
Post-test summary modeling report for Milestone 3	2 months
Milestone 4 – Terry Turbopump Basic Science Experiment Modeling	
Pre-test summary modeling report for Milestone 4	2 months
Post-test summary modeling report for Milestone 4	2 months

The Milestone 3 & 4 modeling schedule for this effort is summarized as a Gantt chart in Table 4.3. At the conclusion to performance of work for each set of milestones, a ‘hold point’ period of 3-6 weeks will be allocated for the funding organizations to review the program progress and associated funding.

Table 4.3 Modeling of Milestone 3 & 4 Efforts Gantt Chart (1-26 months)

Terry Turbopump Expanded Operating Band Gantt Chart														
		Month												
Modeling Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Milestone 3 – Full-Scale Component Experiment Modeling														
Detailed computational modeling to inform Milestone 3	3 months		■	■										
Pre-test system level modeling to inform Milestone 3	2 months			■										
Post-test detailed computational modeling	4 months						■					■		
Post-test system level modeling informed from computational modeling	2 months												■	
Milestone 4 – Terry Turbopump Basic Science Experiment Modeling														
Detailed computational modeling to inform Milestone 4	3 months							■	■					
MELCOR modeling to inform Milestone 4	2 months		■											
SAMPSON modeling to inform Milestone 4	3 months		■	■										
Post-test detailed computation modeling	4 months										■	■		
Post-test MELCOR modeling	2 months												■	
Post-test SAMPSON modeling	2 months												■	
Post-test RELAP-7 modeling	3 months											■	■	
Integrate MELCOR model into Perry simulator	8 months		■	■	■								■	■
Report Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25-26
Pre-test summary modeling report for Milestone 3	2 months			■										
Post-test summary modeling report for Milestone 3	2 months							■					■	
Pre-test summary modeling report for Milestone 4	2 months			■	■									
Post-test summary modeling report for Milestone 4	2 months												■	■
Industry Staff input on Milestone 3 modeling efforts	4 months		■	■										
Industry Staff input on Milestone 4 modeling efforts	4 months			■	■									
Industry Contributions and Review of Milestone 3 reports	4 months								■	■	■			
Industry Contributions and Review of Milestone 4 reports	4 months												■	■

Appendix A:

Additional Comments and Resolutions

In the course of preparing this document, stakeholders identified several issues that could not be adequately addressed in the main body of the text. Such issues are preserved here.

Regarding the Free Jet (Section 2.1.1) tests:

- There is probably apparatus limitation but we should try the test for the inlet pressure, at least, three conditions. And I suppose in the future we will need much higher pressure condition (around 5-7 MPa, 725-1000 psi) for these component tests. (Tsuzuki, 12/5/2016)
  SNL: Some of this is incorporated into the standards for measuring valve performance. However, the facilities at TAMU are not capable of adequately producing such high pressures (5-7 MPa); such pressures can be considered in the development of the Milestone 5 test plan.

- It may be of interest to determine the wear rate of the nozzle with supersonic water impingement for sustained operability. (Bergman, 1/16/2017)
  SNL: The durations under consideration are not expected to produce significant wear on the nozzles or wheel. However, recalling the worn Terry wheel in the possession of TAMU in which long-term two-phase ingestion in a Terry turbine wore out the buckets, measurement and verification of wear condition for the Terry nozzles and wheel should be done both pre- and post-test as part of the long-term operation procedures in Section 3.1.2.

Regarding Governor and Trip/Throttle Valve (Section 2.1.2) tests:

- While C_v of valves are commonly given for water it is difficult and complex to convert the information to the determine the flow of steam. I would recommend that the C_v for T&T valve be determined (if possible) by using steam. (Bergman, 1/16/2017)
  SNL: The standard for testing, and even the definition itself, revolve around water. The additional parameters (F_L, x_T) are needed to more fully characterize the valve, and should be largely independent of where one is on the steam table. Saturated or near-saturated steam (as produced by the NHTS Lab) is not a compliant material with the standard for testing. Typically, process engineers can get away with using a different effective value for the isentropic coefficient of saturated steam (vs. that of superheated steam) in turbomachinery, but accuracy is then limited. It is a much simpler and cleaner method to test using air tests and water tests (both single phase) to develop the C_v etc. profiles, and then do a limited set of verification tests with what steam is available. The steam verification, which does not comply with the standard for MEASUREMENT of C_v, will demonstrate applicability and ensure confidence that the collected data are useful with correct application of the ISA 75.01.01 flow equations in the saturated steam region.

- The trip/throttle valve is used with fully open or fully closed. What kind of scenario is it considered for the tests with the valve open fractions more than zero and less than unity? Considering the configuration of governor valve, at loss of electric power, it is not likely to occur that the governor valve has a open fraction which is not unity. (Okada, 3/14/2017)

SNL: Normally, the Trip/Throttle valve is used in the fully open position. However, in the US, the Trip/Throttle valve is adjusted directly by operators during RCIC blackstart operations, and will regulate flow during those operations by being between fully closed and fully open; it will be partially open.
As stated in the question, under loss of electric power, the governor valve is expected to be full open if it is open. However, it has been proposed that the governor valve may become stuck in a partially open position, or be extremely slow to move, during the loss of DC power.

In addition, knowledge of the behaviors of both valves across their entire set of positions is important for adequate modeling of the system not only in off-normal conditions but will also improve modeling during normal system operation.

- The Japanese vendors assume that operators adjust manually the "turbine inlet valve" installed in the upstream of the trip/throttle valve, not the trop/throttle valve during blackstart operations.
  I would appreciate if you would inform me of expected procedures in the US for RCIC blackstart. Which one of two procedures listed below is it likely to adopt for the US industry?
  1) Expected procedure 1
     i) Fully open the turbine inlet valve
     ii) Adjust the trip/throttle valve from fully open position
  2) Expected procedure 2
     i) Fully close manually the trip/throttle valve
     ii) Fully open the turbine inlet valve
     iii) Adjust the trip/throttle valve from fully close position (Okada, 4/17/2017)

  SNL: Procedure 2 is approximately how the US Industry performs a RCIC blackstart. Briefly, the RCIC Trip/Throttle valve is closed fully, the steam to turbine valve is opened, certain other valves are aligned for both the turbine and pump, and then the Trip/Throttle valve is slowly opened until the turbine reaches the correct speed. The Trip/Throttle valve is adjusted (slowly opening or closing the valve) until the turbine speed is stable and the flows maintain needed reactor levels.

- As to the governor and trip/throttle valve tests, how is the temperature of fluid for C_v and F_L tests? Is it a room temperature? (Okada, 3/14/2017)
  SNL: Air and water temperatures will be as specified in the testing standards. The standard in the US is the ISA-75.02.01. This standard has been made consistent with IEC 60534. Steam will be at saturation temperature at pressures similar to those of the air tests.

- As to the controller operability test, are results obtained in this test applicable generally to controllers installed at any RCIC systems? In Japan, the controllers installed at the RCIC systems are designed and provided by Japanese vendors. In addition, what kind of scenario is it considered for the tests with ascending and descending voltages applied to the controller? (Okada, 3/14/2017)

SNL: As for the test result applicability, the results will be applicable for any system that behaves as the Woodward EG-type systems do. However, the Toshiba controllers used in Japan, while similar in intended function to the Woodward controllers, may have design differences that result in different behavior in off-normal conditions. If that is the case, it is recommended that Japan supply a Toshiba controller for comparison testing.
The scenario envisions DC battery depletion resulting in lower DC voltages from the battery for the descending voltage tests as well as lower voltage to the equipment in highly loaded or over-loaded DC systems. The ascending voltage tests envision charging power supplied to the batteries as the station recovers from SBO or from decreasing the load on the batteries (load stripping).

Regarding the Oil Testing (Section 2.1.3):

- How to compensate heat loss during the test? I don't know the detailed test apparatus, but I think it will require special apparatus to measure at high temperature. (Tsuzuki, 12/5/2016)
  SNL: This will be addressed in the final laboratory design and construction of the test apparatus, which is beyond the scope of this document

- From 100°C (212°F) water evaporates in atmospheric condition, and in the condition how to mix the oil and water is also important. We should determine the mixing method, and if we can, change the mixing method several times. (Tsuzuki, 12/5/2016)
  SNL: This will be part of the development of detailed, step-by-step laboratory procedures.

- How do we determine 'degraded'? (Tsuzuki, 12/5/2016)
  SNL: For the purposes of the testing discussed here, 'degraded' oil will be the oil that has gone through the treatments/conditioning defined in the oil testing (Section 2.1.3) rather than a set specification of oil characteristics (viscosity, density, color, etc.).

- What kind of scenario is it considered for the tests with raising oil temperature? Coolant water of the lubrication oil is supplied from RCIC outlet. As long as RCIC works, coolant water is supplied to the heat exchanger of oil cooling system. It is not likely to occur that the temperature of oil is raised. It is reported that white metals used in bearings are damaged with the temperature more than 121℃. Are there any reasons why tests are made with oil temperature more than 121℃.? (Okada, 3/14/2017)
  SNL: Regarding the scenario for tests with elevated oil temperature, the cooling water from the Suppression Pool could conceivably exceed 121°C in a long-running event. When the RCIC System is aligned to draw from the Suppression Pool, this water would then be used as the cooling water, which would dictate the temperature of the lube oil.
  As the temperatures of the Babbitt material (Babbitt metal is sometimes termed "white metal") rise, it does get progressively softer. However, it is not clear whether sufficient damage will build up in temperatures near 121 °C to cause system inoperability during the period of system operation. History with Babbitt bearings is that they will continue to perform at some level even with a very soft bearing surface. The typical failure at

slightly elevated temperatures occur on a restart of a machine when the machine was stopped for some reason.

- What kind of scenario is it considered for water mixture tests? Is this phenomena caused by damage of gland seals, or flooding of RCIC room? (Okada, 3/14/2017)
  SNL: Flooding of the RCIC room is not under consideration. Instead, the source of water that contaminates the oil would be condensate from the steam that migrates into the oil. Such contamination of the oil from steam condensate is known to happen.

Regarding the Bearing Testing (Section 2.1.4):

- Judgement of bearing tests, bearing damage. Is the condition of the bearing judged by vibration of the turbine body? (Okada, 3/14/2017)
  SNL: Not only vibration during operation will be considered; bearing temperature measurement during testing and industry-standard physical inspection of the bearings after testing will be performed. In addition, any unexpected behavior beyond changes in sound/vibration will be noted.

Regarding the Exhaust Line Purge Testing (Section 2.1.5):

- If the turbine is running the back pressure is containment pressure, when the turbine trips the exhaust line vacuum breakers prevent water from being siphoned into the exhaust line. (Bergman, 1/16/2016)
  SNL: The backpressure the turbine sees is the exhaust point/containment pressure plus whatever additional flow restrictions, gravity head, etc. exist in the exhaust line downstream of the turbine. Condensation is not the only potential source of moisture in the line; if the turbine is ingesting a two-phase mixture, the liquid from that will end up going into the exhaust line as well.

Regarding the Z-1 turbopump (Section 3.1.1) testing:

- Torque measurement of turbine is important, but I can't understand the meaning of 'turbopump test' without structural information of Terry pump of Z-1 and GS-1/2. Are they very close? (Tsuzuki, 12/5/2016)
  SNL: PIM will provide a GS-series turbopump for tests. As part of the scaled tests with the Z-1 turbopump, consideration will be given to determine what scaling parameters translate the data from the Z-1 Terry turbine with an attached pump to that of the full-scale GS-series turbopump.

- For the dynamic response curves of Section 3.1.1, if available I think using the T&T valve instead of a ball valve would be more realistic. (Bergman, 11/29/2016)
  SNL: This has to do with the ability of a ball valve to be rapidly and suddenly opened to produce a clean step-function of flow, where the valve or operator speed does not play a significant role in the pure dynamics of the wheel-jet system. However, consideration will be given to using the trip/throttle valve as well.

Regarding long-term operations of the Z-1 Terry turbine and GS-1 scaling (Section 3.1.2):

- How to record 'bearing wear and lube oil performance'? Oil temperature will be easily measured (and recorded) but other parameters are difficult to measure, I think. (Tsuzuki, 12/5/2016)
  SNL: Some characteristics can only be fully determined upon post-test disassembly and inspection. Others, such as runout, can be monitored online, and will include effects from the bearing geometry as well as real-time oil performance.

- In this test, the working fluid is only air? How about saturated steam? (Tsuzuki, 12/5/2016)
  SNL: As shown in Table 3.2, the Z-1 long-term tests include both air and steam. However, the GS-series tests require more steam than the NHTS facility can supply; those tests will therefore only be conducted with air at the Turbomachinery Lab.

- How to do if the turbines (Z-1 or GS-1) will be broken or even damaged? Should we stop the test when a little sign of some damage appears, or should we continue the test till the turbine will be broken? This question includes the timing and importance of this long-term test and the next uncontrolled feedback test. (Tsuzuki, 12/5/2016)
  SNL: The GS-series turbines will not be deliberately operated to the point of damage. While turbine will not be operated in such a condition, it is acknowledged that there is some risk in the course of testing, and some damage may be inadvertently produced. It is more likely that the Z-1 turbopump system may sustain a degree of damage; the tests considered most likely to cause damage to the turbopump have been scheduled to be performed at the end of the testing program so as to not interfere with the remainder of the testing.

- Not sure if the money is available, but larger boilers are available skid mounted on semi-truck trailers that can be leased. (Bergman, 1/16/207)
  SNL: Such full-scale steam testing belongs in Milestones 5 and 6.

Regarding Uncontrolled Feedback Testing (Section 3.1.3):

- (Transition to FLEX) The objectives of this test are not clear. When water source is changed from RCIC to a FLEX mode, there are no concerns regarding RCIC turbopump. In a case of loss of load of RCIC turbopump, rotation speed of turbopump increases and turbopump is tripped because of overspeed. There seems to be no concerns during the transition. (Okada, 3/14/2017)
  SNL: Operators in the US need clear guidance via procedures. The guidance includes specific operator actions as well as details on the expected responses from the system resulting from those actions; currently, the details are unknown or unproven. Testing is needed to demonstrate the system response, and is a needed part of the development of the operator guidance. The problem being addressed is that if the temperature of the RPV/Suppression Chamber fluids are changed because of an inrush of cool water then the stable operation of the RCIC turbine may become erratic before the new injection method has stabilized.

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