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Terry Turbopump Expanded Operating Band Full-Scale Integral Long-Term Low-Pressure Experiments – Preliminary Test Plan

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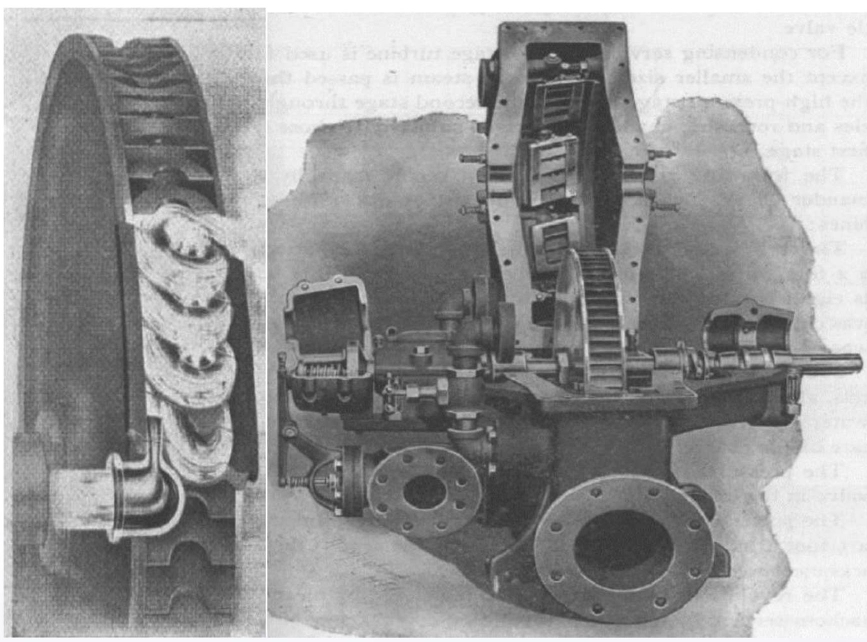

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Abstract

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 5 (full-scale integral long-term low-pressure operations) 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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ACRONYMS

1F2	Fukushima Daiichi Unit 2
BDBE	Beyond Design Basis Event
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owner's Group
CAD	Computer Aided Drafting
CFD	Computational Fluid Dynamics
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
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
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
TTExOB	Terry Turbine Expanded Operating Band
TTUG	Terry Turbine User Group

1. Overall Program Executive Summary

This document details the milestone approach to define the true operating limitations (margins) of the Terry turbopump systems (i.e. RCIC and turbine driven auxiliary feedwater – TDAFW) used in the nuclear industry[1] for Milestone 5 (full-scale integral long-term low-pressure operations) 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 Report, *Terry Turbopump Expanded Operating Band Summary of Program Plan – Revision 1* [1]. The overall joint-sponsored program creates the technical basis to:

- Reduce & defer additional utility costs (e.g., associated with post-Fukushima actions),
- Simplify plant operations (e.g., provide guidance to operators for expanded RCIC 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 control panel
- Provides a potential for regulatory avoidance, 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.

This first-of-a-kind Terry turbopump experimental and modeling approach includes project plan development, first principles analytical modeling, full-scale component testing & modeling, basic scientific Terry turbopump testing & modeling, and full-scale integral system testing & modeling. The project plan includes checks and balances (programmatic year-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 DOE and IAE (Institute of Applied Energy) has been performed. Additionally, scope discussions, value assessments with industry stakeholders (domestic and international), Milestone 3 (full-scale component tests)

[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).

experiments and modeling, and Milestone 4 (Terry turbopump basic science tests) experiments and modeling have been completed to form the basis of this project plan.

An expert technical advisory group of engineers from the Boiling Water Reactor Owner's Group (BWROG), Pressurized Water Reactor Owner's Group (PWROG), Electric Power Research Institute (EPRI), DOE, Japan (IAE), and GE-Hitachi (GEH) 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's use of NEMA SM23 *Steam Turbine for Mechanical Drive Service* guidance. However, the reactor core isolation cooling (RCIC) 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 vessel water level, and that loss of DC power results in RCIC flooding of the steam lines and an assumed subsequent failure of the RCIC turbopump system. This assumption for accident analysis implies that RCIC operation should terminate on battery depletion which can 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 [2][3][4][5].

Use of conservative assumptions regarding equipment functioning as found in PRA applications may limit the anticipated mitigation options considered for normal and emergency operations. Improved understanding of expanded operations of Terry turbopumps can be realized through a combined and iterative process of advanced modeling methods and 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 SRV/SVV setpoint), varied steam quality (100% to 0% - current is 100%), and increased lube oil temperature conditions (215 to 300ºF – current is 160ºF) with limited to no control features active.

Basis for Hypothesis

The events at Fukushima Daiichi, qualitative analysis, and experience in other industries demonstrate the RCIC system (Terry turbopump) has significant additional operating flexibility that is not credited or 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 pressure and suction temperature values. Data indicate the 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 Reference [2] and [3] for additional information.

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 they have a reputation of reliable and rugged performance under a broad range of operating conditions. It is commonly known in industry they can run with water ingestion into the turbine; see Reference [3] for additional information.

Additionally, experience in the nuclear industry reflects the robustness of these systems. The turbine and pump have injected into the RPV/SG for extended times in response to rare events and are tested every cycle 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 [6].

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 (TTExOB Advisory Committee) but from the BWROG and PWROG. 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 TTExOB Advisory Committee will ensure the following tasks/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[3]

- 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. TTExOB Advisory Committee evaluation of expectations and '*adequate confidence*' (as specified above)

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

- These test results will reduce the uncertainty in specific to 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 – Scaled Experiments Replicating Fukushima Daiichi Unit 2 Self-Regulating Feedback

- These test results will reduce the uncertainty in specific to 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 TTExOB Advisory Committee 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 end of each funding organization's fiscal year, 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

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

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 Milestone 4 efforts while the overall program is currently focused on Milestone 2).

1.3 Overview of Milestone 5

For the Milestone 5, Full-Scale Integral Long-Term Low-Pressure Operations, the test series is primarily intended to provide information which will allow for an expanded low-pressure operating band for long-term RCIC and TDAFW operations as well as better design, scale, and model the scaled testing for Milestone 6, if the TTExOB Advisory Committee determines it is necessary to proceed to this subsequent milestone. The goals of Milestone 5 are the following:

- Provide a technical basis to expand the low-pressure operation band,
- Provide a technical basis for improved transition to portable FLEX equipment,
- Determine limits on low-pressure and low-speed operations,
- Evaluate and possibly expand the lube oil temperature band up to 300 ^{o}F
- Extend intervals for preventive maintenance actions,
- Establish the technical basis for guidance on how to transition from BWR Mode 4 operations to RCIC,
- Establish the technical basis for operational changes to the TDAFW/RCIC system to reduce plant risk,
- Provide insights to update operational crew emergency procedure guidance (EPG) to reduce the likelihood that a BDBE will progress to core damage, and
- Provide Terry turbopump performance data for a board range of off-normal operational conditions relevant to long-term transient events.

The Milestone 5 efforts are divided into six areas of experiments: (1) low-pressure long-term steam testing, (2) low-speed long-term steam testing, (3) select Milestone 3 testing, (4) select Milestone 4 testing, (5) low-pressure two-phase steam testing, and (6) low-pressure long-term steam testing with lubrication oil heat-up. All experiments will be conducted at a commercial steam test facility with a GS-series turbopump tests will provide data for modeling efforts discussed in Section 3, provide initial operational/field data on GEH's incipient failure equipment, qualification for reversed engineered components, and provide 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 6 scaled replication of Fukushima Daiichi Unit 2 self-regulating feedback tests.

The modeling efforts for Milestone 5 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 5 experimental efforts.

The subsequent sections provide a more detailed discussion of each experimental and modeling effort. A Gantt chart is provided for each section to allow the reader to better understand the integrated test plan.

1.4 Motivation for Milestone 5

Based on current Milestone 3 and Milestone 4 experiments and modeling, the TTExOB Advisory Committee has recommended to the funding stakeholders that scoping of Milestone 5 testing be conducted. Specifically, the Milestone 3 efforts have reduced uncertainty in specific model parameters in full-scale components, and Milestone 4 has provided insights into Terry turbines based on scaled air and steam tests. Additionally, Milestone 3 and Milestone 4 have provided information that will provide benefit to plant normal operations and maintenance. However, there is a need to conduct full-scale integral testing with low-pressure steam to validate the goals of Milestone 5

2. Full-Scale Integral Long-Term Low-Pressure Experiments

As efforts for Milestone 3 (Full-Scale Component Experiments) and Milestone 4 (Terry Turbopump Basic Science Experiments) near completion in 2019 at Texas A&M University, the TTExOB Advisory Committee in conjunction with Sandia National Laboratories (SNL) and Idaho National Laboratory (INL) have identified a suite of full-scale integral experiments. This milestone is intended to provide information which will allow for long-term operations of TDAFW/RCIC at low system pressures and inform the design, scale, and model the scaled testing to replicated Fukushima Daiichi Unit 2 (i.e., Milestone 6). These experiments are intended to be conducted at pressures and flow rates such that an industrial research facility could conduct them within an achievable timeframe.

The Terry turbopump full-scale integral testing is to be divided into six areas of experiments:

1. Long-term low-pressure tests (Section 2.1.1),
2. Long-term low-speed tests (Section 2.1.2),
3. Select Milestone 3 & 4 tests (Section 2.1.3),
4. Reversed engineered analog controller qualification tests (Section 2.1.4),
5. Low-pressure two-phase tests (Section 2.1.5), and
6. Long-term low-pressure tests with oil heat-up (Section 2.1.6).

The GS-series turbopump tests will provide data for modeling efforts discussed in Section 3, provide initial data on GE-H'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 6 full-scale tests. The objectives for each of these experimental areas will be discussed in detail in the subsequent subsections.

In this effort, the components under investigation will be GS-series Terry turbopump, 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. The dynamic responses to off-normal conditions will be better understood, allowing improved models as well as 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.

2.1 Test Suite

Full-scale component testing is to be divided into six areas of experiments. The objectives for each of these experimental areas will be discussed in detail in the subsequent subsections. Figure 2.1 provides a generic layout of the experimental setup for the test suite.

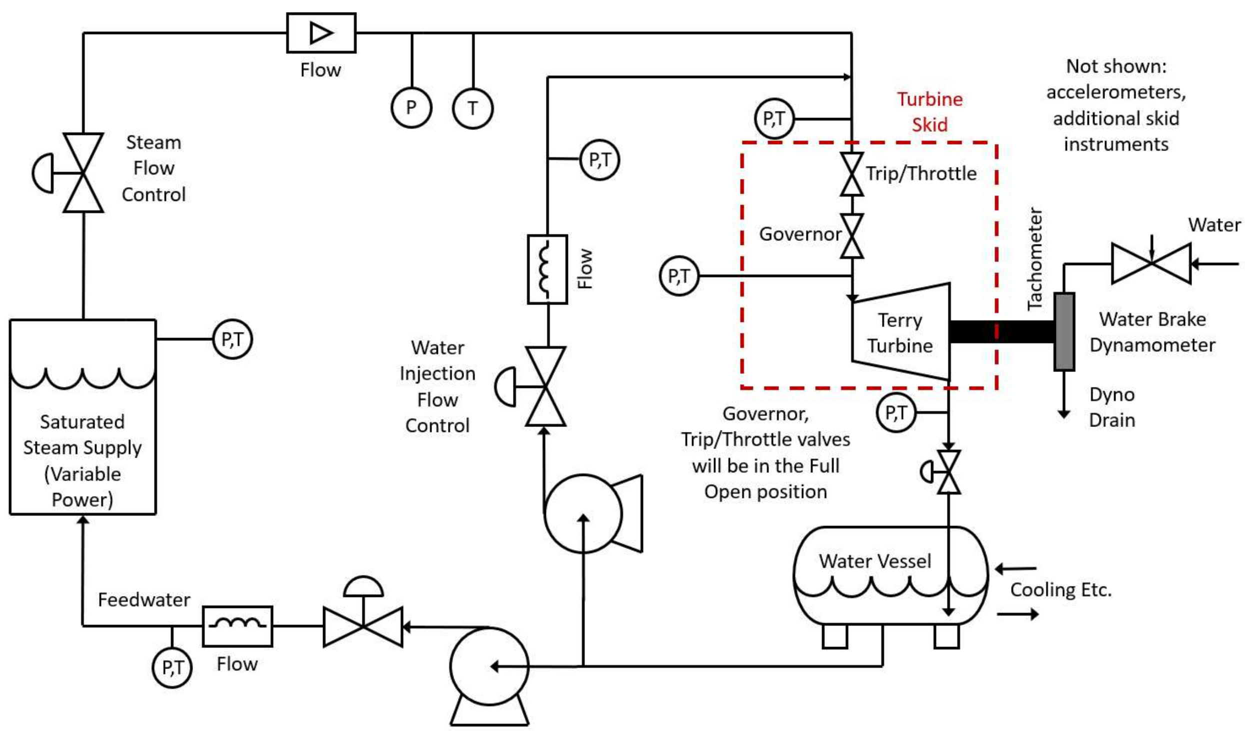

Figure 2.1 Test Suite Generic Piping and Instrument Diagram.

Test Suite Expectations

The expectations for the Milestone 5 efforts are the following:

- Experimental test results will reduce the uncertainty in specific model parameters,
- The tasks will provide full-scaled (steam and steam/water) data which can be directly implemented into fleet-wide RCIC/TDAFW guidance,
- 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 inform the development of a detailed full-scale experimental plan, and further refinements on the cost estimates for the Milestone 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 BDBE conditions

Quality Assurance of Experiments

The quality assurance (QA) requirements for this effort shall abide by established QA levels of rigor at the commercial experimental facility and 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 (e.g., a 2nd or 3rd order NIST standard)

Additional QA requirements through the DOE Office of Nuclear Energy's (DOE-NE) Light Water Reactor Sustainability (LWRS) Program will be applied whenever applicable [7].

2.1.1 Long-Term Low-Pressure Tests

The full-scale testing low-pressure long-term experiments are to be conducted by a commercial testing 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. Corresponding and supporting objectives are as follows:

- Provide an experimental basis for improved system-level modeling efforts discussed in Section 3.2 for Milestone 5 conditions, which in turn will provide information on steam testing from GS-series Terry turbopump performance data under BDBE conditions.

This testing is envisioned to have the following goals:

- Verify incipient failure monitoring with GEH supplied equipment,
    - In-situ monitoring to determine 'failure horizon' for parts or equipment

- Determination of automatic versus manual control to trip, and
    - Action of transitioning from blackstart to governor control

- Development of pump head curves.

Test Parameters

The full-scale confirmatory test measurements need to be integrated with the computational fluid dynamics (CFD) and system-level modeling efforts discussed in Section 3.2. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Evaluation of degradation for a GS-2 Terry turbopump due to long-term operation under various inlet conditions, and

- Establishment of scaling parameters from a GS-2 Terry turbopump (proposed experimental test rig) to other GS-series Terry turbopumps

Test Requirements

The testing planned is envisioned to have the following:

- Establish a high pressure (300-800 psia) steady state to emulate normal operations
- Transition from high pressure to minimum operating pressure over a set period of time
- 100-150 psia minimum operating pressure,
- Turbine back pressure variations of 40-60 psia
- 10 days of continuous operation for each experimental run,
  - Based on ~1.5 times 7 days (maximum operational time)
- Periodic oil testing, and
- Continuous vibrational monitoring.

Initial Test Suite

The proposed initial test suite of experiments shown in Table 2.1 is envisioned to have the following:

- Backpressure: Varied
- Governor valve: Open
- Turbine loading: To maintain speed
- Oil Temperature: Maintained within limits (e.g., oil cooler enabled)
- Added Monitoring: Vibrations/accelerometers
- Inspections and Assays
  - Post-test inspections (internal): Conducted (pre- and-post inspections on bearings and turbine wheel)
  - Pre- and Post-test oil condition assays, and daily oil assays

Table 2.1 Long-Term Low-Pressure Test Matrix

Inlet pressure	40 psi backpressure	60 psi backpressure
800-300 psi, saturated steam	2 hours at 3000 rpm	2 hours at 3000 rpm
300 to 150 psi, saturated steam	1-2 hour transient at 3000 rpm	1-2 hour transient at 3000 rpm
150 psi, saturated steam	10 days at 3000 rpm	10 days at 3000 rpm
100 psi, saturated steam	1 hour at 2000+ rpm	1 hour at 2000+ rpm

2.1.2 Long-Term Low-Speed Tests

The low speed long-term full-scale testing will be conducted by a commercial testing facility. The tests are intended provide knowledge for steady-state Terry GS-size turbopump behavior in the conditions below the standard operating range, in which there are expected to be increases in vibration and in bearing wear. These tests expect to employ a non-NQA Terry turbopump. Corresponding objectives and goals include;

- Development of experimental-based data for realistic system behavior
- Long-term operational stability under extended BDBE conditions
- Determination of the impact of increased vibration and wear on system ability to perform low speed long-term conditions

The testing is envisioned to have the following goals:

- Verify incipient failure monitoring with GEH supplied equipment,
    - In-situ monitoring to determine 'failure horizon' for parts or equipment
- Determine if reduced oil flow through the shaft driven oil pump can cause overheating of the gear pump itself due to insufficient cooling,
- Gain insights into if steam flow in the exhaust line will most likely cause unstable flow creating check valve fluctuations and other undesirable affects in the suppression pool,
    - Including stability of turbine operating speed
- Development of low speed pump head curves.

Test Parameters

The full-scale confirmatory test measurements will to be integrated with the complex computational fluid dynamics (CFD) and system-level modeling efforts discussed in Section 3.2. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Evaluation of degradation/impairment for a GS-2 Terry turbopump due to low speed long-term operation under various inlet conditions, and
- Establishment of scaling parameters from a GS-2 Terry turbopump (experimental test rig) to other GS-series Terry turbopumps

Test Requirements

The testing planned is envisioned to have the following:

- (1500-2200 RPM) minimum operating speed,
    - It is assumed this will be ~75 psia steam pressure
    - RPM range will be informed by Milestone 4 air tests at Texas A&M University
- 5 days of continuous operation for each experimental run,
    - Based on ~1.5 times 3 days (maximum time need to transition to FLEX)
- Post-run bearing inspections,
- Periodic oil testing, and
- Continuous vibrational monitoring.

Initial Test Suite

The proposed initial test suite of experiments shown in Table 2.2 is envisioned to have the following:

- Backpressure: Atmospheric/none
- Governor valve: Open
- Turbine loading: To maintain speed
- Oil Temperature: Maintained within limits (e.g., oil cooler enabled)
- Added Monitoring: Vibrations/accelerometers
- Inspections and Assays

- Post-test inspections (internal): Conducted (pre- and-post inspections on bearings and turbine wheel)
- Pre- and Post-test oil condition assays, and daily oil assays

Table 2.2 Long-Term Low-Speed Test Matrix

Inlet pressure	Duration	Turbine Speed
75 psi, saturated steam	5 days	2200 RPM
75 psi, saturated steam	1 day	1500 RPM

2.1.3 Select Milestone 3 & 4 Tests

Some of the full-scale component and Terry turbopump basic science tests performed in Milestone 3 & 4 could be performed at integral full-scale conditions within this effort based on positive/negative results from the previous testing. These tests serve several purposes;

- Ensure repeatability across diverse test facilities for identical tests (verification),
- Enhance the Milestone 4 scaling efforts for tests performed at different scales than in Milestones 3 & 4,
- Extend the range of validity of Milestone 3 & 4 tests when performed outside/beyond the previous conditions,
- Resolve any anomalous or unexpected behavior identified in Milestones 3 & 4, and
- "Fill in" remaining relevant knowledge gaps identified as results of Milestones 3 & 4

Test Parameters

The scaled and full-scale test measurements need to be integrated with the complex computational fluid dynamics (CFD) and system-level modeling efforts discussed in Section 3.2 as well as the previously collected data in Milestones 3 & 4. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Evaluation of the effects of the facility design for turbopump testing at the same scales
- Enhancement and completion of scaling parameters from a GS-series Terry turbopump (experimental test rig) to other Terry turbopumps
  - Additional full-scale air testing
  - Full-scale steam testing
- Extension of the tested data range to anticipated full-scale operational conditions
- Potential standards-based testing of the GS-1 governor and trip/throttle valves unobtainable for Milestone 3 testing
  - Consideration of valve testing beyond the scope of the standards; i.e., with saturated fluids

Test Requirements

The testing planned is envisioned to have the following:

- Additional Milestone 4 full-scale GS-2 turbine testing
  - Torque vs rpm at various
    - Pressures; turbine inlet of 75-100 psi up to facility or PWR/BWR/turbine limits, backpressure from atmospheric to 60 psig
    - Wetness: Single-phase gas (air or steam)/0% water down to 0% gas/100% water mass fraction (or facility limit)
      - See Section 2.1.5
    - Gas: air or saturated steam
  - Response for turbopump
    - Pump flow conditions for judiciously-selected turbine inlet pressures, wetness
    - Dynamics data: time-response curves for sudden changes in interfacing system conditions

- Extension of Milestone 4 ZS-1 Terry turbine data by collecting at greater pressures
  - Selected data for repeatability
  - Extend Milestone 4 torque curves to turbine pressure limit
    - See Section 2.1.5

- Milestone 3 testing
  - C_v, F_L, x_T curves for untested valves
    - 2.5-inch governor and trip/throttle valves used for GS-1 Terry turbines
  - Consideration of beyond-the-standard tests (i.e., saturated and two-phase steam)

Initial Test Suite

The proposed initial test suite of experiments shown in Table 2.3 (torque table of points to measure torque and flows at steady state) is envisioned to have the following:

- Turbine trip speed should be near normal trip speed (i.e., 4634 rpm) but could be as low as 4400 rpm to protect the turbine under 2-phase conditions
- For turbine inlet steam pressure >60 psi, backpressures shall be;
  - Atmospheric,
  - 15 psig,
  - 30 psig, and
  - 50 psig when turbine inlet steam pressure is >80 psi
- For turbine inlet steam pressures <60 psi, only atmospheric backpressure
- If the turbine is loaded with the pump instead of a dynamometer, the preferred suction pressure is the same as the turbine backpressure with an outlet pressure of 45 psi above the turbine inlet pressure (i.e., if the turbine has a backpressure of 15 psi in a 100 psi test, the pump will preferentially have 15 psig on the inlet and 145 psig on the outlet);
  - The flow pump flow rate will be measured.

Table 2.3 Select Milestone 3 & 4 Test Matrix

Turbine Inlet	1000 rpm	1250 rpm	1500 rpm	2000 rpm	2500 rpm	3000 rpm	3500 rpm	4000 rpm	4250 rpm
150 psi	Saturated	Saturated	Saturated 2-phase*	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
130 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
110 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
100 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
90 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
80 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
70 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
60 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
50 psi	Saturated	Saturated	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated 2-phase	Saturated
40 psi	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated
30 psi**	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated	Saturated

* 2-phase is for steam qualities of 95%, 90%, 85%, and 80% with the possibility of lower qualities of interest. Steam quality is defined as (massflow of steam / (massflow of saturated steam (vapor) + massflow of saturated water (liquid)))

** Low (30 psi) pressures may not be able to turn the turbine; the maximum rotation rate attainable should be noted

2.1.4 Reversed Engineered Analog Controller Qualification Tests

These tests are envisioned to qualify analog controller replacement parts that were reversed engineered (RE). Additionally, the RE parts could be constructed to withstand the extreme environments within the units for a much longer duration though the use of newer materials.

Motivation

This testing series allows utilities and vendors the ability to test and qualify RE parts while full-scale Terry turbopump equipment is at a commercial facility.

Test Parameters

To be determined.

Test Requirements

To be determined.

2.1.5 Low-Pressure Two-Phase Tests

This testing will only use a non-NQA Terry turbopump. It has been deemed this test has too high of a probability for damage to experimental equipment to the NQA Terry turbopump. The testing planned is envisioned to have the following:

- Varied steam conditions through the use of in-line de-superheater valves,
  - Saturated steam at 100% quality to ~90% quality
  - Lower steam quality could be done, if injection system permits
- 1-2 days of continuous operation for each experimental run,
- Periodic oil testing, and
- Continuous vibrational monitoring.

The testing is envisioned to have the following goals:

- Enhance Milestone 4 scaling efforts for tests performed at different scales than in Milestones 3 & 4;

- Extend the range of validity of Milestone 3 & 4 tests when performed outside/beyond the previous conditions;

- Verify incipient failure monitoring with GEH supplied equipment,
  - In-situ monitoring to determine 'failure horizon' for parts or equipment

- Determination of automatic versus manual control to trip,
  - Action of transitioning from blackstart to governor control

- Development of pump head curves, and

- Provide data to inform Milestone 6 efforts.

Test Parameters

This testing is a full-scale continuation of the turbine profiling testing performed in Milestone 4 as well as that described in Section 2.1.3; here, instead of replication/verification of Milestone 3 & 4 results, the emphasis is on the expansion of the developed curves to wetter steam process conditions and more varied pressures. With use of a non-NQA GS-series Terry turbine (rather than inclusion of an NQA-qualified turbine), this work could fall under Section 2.1.3 efforts.

Test Requirements

Informed by Milestone 4 efforts discussed in Section 2.1.3

Initial Test Suite

The proposed initial test suite of experiments shown Table 2.4 in is envisioned to have the following:

- Backpressure: Atmospheric/none
- Governor valve: Open
- Turbine loading: To maintain speed
- Oil Temperature: Maintained within limits (e.g., oil cooler enabled)
- Added Monitoring: Vibrations/accelerometers
- Inspections and Assays
    - Post-test inspections (internal): Conducted (pre- and-post inspections on bearings and turbine wheel)
    - Pre- and Post-test oil condition assays, and daily oil assays

Table 2.4 Low-Pressure Two-Phase Test Matrix

Turbine Inlet*	**2000 rpm**	**3000 rpm**	**4000 rpm**
	Duration		
150 psi, 100%	1 hour	1 hour	1 hour
150 psi, 70%	3 hours	2 hours	2 hours
100 psi, 100%	1 hour	1 hour	1 hour
100 psi, 70%	3 hours	2 hours	2 hours
70 psi, 100%	1 hour	1 hour	1 hour
70 psi, 70%	3 hours	3 hours	3 hours

* Steam qualities of 100% and 70% is defined as (massflow of steam / (massflow of saturated steam (vapor) + massflow of saturated water (liquid)))

2.1.6 Long-Term Low-Pressure Tests with Oil Heat-up

This testing will only use the non-NQA Terry turbopump. It has been deemed this test has too high of a probability for damage to experimental equipment to the NQA Terry turbopump. The testing planned is envisioned to have the following:

- Incremental increases in lube oil temperature from 255 – 300 °F,
    - It can also serve as a surrogate of how the bearings would behave if the oil cooler was isolated from the cooling water or otherwise absent from the system
- 3-7 days of continuous operation for each experimental run,
- Continuous monitoring of turbine shaft position/displacement in the bearings
- Continuous oil testing, and
- Continuous vibrational monitoring

The testing is envisioned to have the following goals:

- Verify incipient failure monitoring with GEH supplied equipment,
    - In-situ monitoring to determine ‘failure horizon’ for parts or equipment
- Development of pump head curves

Test Parameters
Some separate effects testing on the oil and bearings has been performed under Milestone 3 of this testing program; the Milestone 3 findings will inform this effort along with any additional insight gained from the other Milestones. It is intended to be performed as an integrated full-scale set of tests.

The scaled and full-scale test measurements need to be integrated with the complex computational fluid dynamics (CFD) and system-level modeling efforts discussed in Section 3.2. Specifically, the minimum sets of parameters that are needed to meet the objectives are the following:

- Evaluation of the effects of the facility design for turbopump testing at the relevant scales
- Evaluation of the bearing degradation at specified temperatures and shaft speeds and loads
- Evaluation of the oil degradation at specified temperatures
- Evaluation of the combined effects for operational runtime limits

Test Requirements
The testing is envisioned to have the following:

- 3-7 days of continuous operation for each test run
- 75-150 psi inlet pressure
- Oil temperature ramping from below the current operational limit potentially up to 300 °F
    - o Temperatures will be specified specifically for individual tests
    - o Oil condition will be monitored
- Continuous performance data, vibration, shaft runout/position, noise monitoring

Initial Test Suite
The proposed initial test suite of experiments shown Table 2.5 in is envisioned to have the following:

- Backpressure: Atmospheric/none
- Governor valve: Open
- Turbine loading: To maintain speed
- Oil Temperature: Maintained within limits (e.g., oil cooler enabled)
- Added Monitoring: Vibrations/accelerometers and shaft position/runout
- Inspections and Assays
    - o Post-test inspections (internal): Conducted (pre- and-post inspections on bearings and turbine wheel)
    - o Pre- and Post-test oil condition assays, and daily oil assays

Table 2.5 Low-Pressure Two-Phase Test Matrix

Turbine Inlet	190 °F oil	255 °F oil	270 °F oil
150 psi, saturated	3 days at 3500 RPM	3 days at 3500 RPM	3 days at 3500 RPM
100 psi, saturated	3 days at 3000 RPM	3 days at 3000 RPM	3 days at 3000 RPM
70 psi, saturated	3 days at 2500 RPM	3 days at 2500 RPM	3 days at 2500 RPM

2.2 Schedule & Deliverables

The expectation is for Milestone 5 testing to start in FY19, with the start of facility preparations dependent upon the availability of the testing facility. Table 2.6 provides the schedule and duration for Milestone 5.

Table 2.6 Milestone 5 Schedule

Schedule	
Pre-Testing Efforts and Expectations	
Identify and tour (when applicable) potential facilities	2 months
Request-for-Proposal to down-selected test facilities	3 months
Commercial testing facility general preparation	6 months
Expected commercial test facility test execution	14 months
Testing Efforts	
Low pressure long-term tests facility preparation	1 month
Low pressure long-term tests facility test execution	2 months
Low pressure long-term tests post-test modeling analysis (see Section 3.2.1)	4 months
Low pressure long-term tests facility data and analysis report	4 months
Low speed long-term tests facility preparation	2 weeks
Low speed long-term tests facility test execution	1 month
Low speed long-term tests post-test modeling analysis (see Section 3.2.1)	4 months
Low speed long-term tests facility data and analysis report	4 months
Select Milestone 3 & 4 tests facility preparation	1 month
Select Milestone 3 & 4 tests facility test execution	2 months
Select Milestone 3 & 4 tests post-test modeling analysis (see Section 3.2.1)	4 months
Select Milestone 3 & 4 tests facility data and analysis report	4 months
Reversed engineered analog controller qualification tests facility preparation	1 month
Reversed engineered analog controller qualification tests facility test execution	2 months
Reversed engineered analog controller qualification tests post-test modeling analysis (see Section 3.2.1)	4 months
Reversed engineered analog controller qualification tests facility data and analysis report	4 months
Low pressure two-phase tests facility preparation	2 weeks
Low pressure two-phase tests facility test execution	1 month
Low pressure two-phase tests post-test modeling analysis (see Section 3.2.1)	4 months
Low pressure two-phase tests facility data and analysis report	4 months
Low pressure and long-term tests with oil heat-up facility preparation	2 weeks
Low pressure and long-term tests with oil heat-up facility test execution	1 month
Low pressure and long-term tests with oil heat-up post-test modeling analysis (see Section 3.2.1)	4 months
Low pressure and long-term tests with oil heat-up facility data and analysis report	4 months

Table 2.7 provides the deliverables and duration for Milestone 5 efforts.

Table 2.7 Milestone 5 Deliverables

Deliverables	Duration
Test facility data report for each test series	4 months
TTExOB Advisory Committee integrated testing & modeling report for each test series	3 months
Final TTExOB Advisory Committee testing summary report	2 months

The Milestone 5 schedule for this effort is summarized as a Gantt chart in Table 2.8. At the end of each funding organization's fiscal year, a 'hold point' period of 3-6 weeks will be allocated for the funding organizations to review the program progress and associated funding.

Table 2.8 Milestone 5 Gantt Chart (1-28 months)

Terry Turbopump Expanded Operating Band Gantt Chart										
		Month								
Experimental Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18
Milestone 5 – Low Pressure Long-Term Integral Full-Scale Experiments										
Commercial testing facility general preparation	6 months									
Low pressure long-term tests facility preparation	1 month									
Low pressure long-term tests facility test execution	2 months									
Low speed long-term tests facility preparation	2 weeks									
Low speed long-term tests facility test execution	1 month									
Select Milestone 3 & 4 tests facility preparation	1 month									
Select Milestone 3 & 4 tests facility test execution	2 months									
Reversed engineered analog controller qualification tests facility preparation	1 month									
Reversed engineered analog controller qualification tests facility test execution	2 months									
Low pressure two-phase tests facility preparation	2 weeks									
Low pressure two-phase tests facility test execution	1 month									
Low pressure and long-term tests with oil heat-up facility preparation	2 weeks									
Low pressure and long-term tests with oil heat-up facility test execution	1 month									
Report Deliverable	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18
Low pressure long-term tests facility data and analysis report	4 months									
Low speed long-term tests facility data and analysis report	4 months									
Select Milestone 3 & 4 tests facility data and analysis report	4 months									
Reversed engineered analog controller qualification tests facility data and analysis report	4 months									
Low pressure two-phase tests facility data and analysis report	4 months									
Low pressure and long-term tests with oil heat-up facility data and analysis report	4 months									
TTExOB Advisory Committee integrated low pressure long-term testing & modeling report for each test series	3 months									
TTExOB Advisory Committee integrated low speed long-term testing & modeling report for each test series	3 months									
TTExOB Advisory Committee integrated select Milestone 3 & 4 testing & modeling report for each test series	3 months									

	Duration	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18
TTExOB Advisory Committee integrated reversed engineered analog controller qualification testing & modeling report for each test series	3 months									
TTExOB Advisory Committee integrated low pressure two-phase testing & modeling report for each test series	3 months									
TTExOB Advisory Committee integrated low pressure and long-term tests with oil heat-up testing & modeling report for each test series	3 months									
Final TTExOB Advisory Committee testing summary report	2 months									
Industry Contributions and Review of Milestone 5 reports	2 months									

3. Modeling Updates from Milestone 5 Data and Insights

The modeling efforts for Milestone 5 of the program are discussed within this section. This is to ensure that the experimental testing discussed in Section 2 is 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-5, and MELCOR) as well as detailed computations (e.g., CFD), and will be parallel efforts with their associated experimental test suite. 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 5 experimental efforts. Given that this part of the plan is for a two-year effort, the modeling efforts must be closely related to the testing discussed in Section 2. 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.

3.1 Code Description

This effort will involve the use of multiple computation fluid dynamic (CFD) and system-level codes. This section provides a brief overview of each.

3.1.1 SolidWorks

SolidWorks is a commercially available computer aided drafting (CAD) and analysis software package [8]. SolidWorks is a product of Dassault Systems SolidWorks Corp. It is being used to generate 3D CAD models of key RCIC components, such as the Terry turbine wheel, buckets, nozzles, and turbine casing. CAD models are essential for proper conceptualization of system-level models. For example, they provide insights into the configuration of buckets and nozzles (e.g. number of buckets and nozzles, nozzle-bucket angle) that can fit on a turbine wheel of a given size–these quantities are 'model parameters' that are required inputs for the system-level MELCOR and RELAP5-3D models. The CAD models are also integral to the CFD analyses of RCIC using SolidWorks Flow and Fluent.

3.1.2 FLUENT

FLUENT is a commercially available CFD code that is currently developed and distributed by ANSYS, Inc [9]. FLUENT is used to investigate key components of the RCIC system, such as the nozzles of the Terry turbine.

3.1.3 RELAP5-3D

RELAP5-3D is a system-level two-phase thermal hydraulic code used in transient analyses of nuclear power plant systems [10]. RELAP5-3D has been developed by INL for the DOE's Office of Nuclear Energy to simulate BWR and PWR thermal hydraulic responses during nominal and off-nominal operation for the analysis of transients and accidents. The RELAP5–3D code is an outgrowth of the one-dimensional RELAP5/MOD3 code developed at INL. The most prominent attribute that distinguishes RELAP5–3D from its predecessors is the fully integrated, multi-dimensional thermal-hydraulic and kinetic modeling capability.

3.1.4 MELCOR

MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light-water reactor nuclear power plants [11]. MELCOR is being developed at SNL for the U.S. Nuclear Regulatory Commission (USNRC) as a second-generation plant risk assessment tool, and the successor to the Source Term Code package. A broad spectrum of severe accident phenomena in both BWRs and PWRs is treated in MELCOR in a unified framework. These include thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings; core heat-up, degradation, and relocation; core-concrete attack; hydrogen production, transport, and combustion; fission product release and transport behavior. MELCOR applications include estimation of severe accident source terms, and their sensitivities and uncertainties in a variety of applications. Design basis accidents in advanced plant designs (e.g., the Westinghouse AP-1000 design and the GE Hitachi Nuclear Energy ESBWR design) have been analyzed with MELCOR.

3.2 Modeling Efforts

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 5 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* [1].

Modeling Expectations:

The expectations for these Milestone 5 modeling efforts are following:

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

- Apply the integrated advanced Terry turbopump MELCOR system model in an existing nuclear power plant simulator for modeling confirmation and new procedure verification.

- If deemed necessary to go beyond Milestone 5 efforts, the modeling results will reduce the uncertainty in specific full-scale parameters in Milestone 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 6 efforts.

Quality Assurance of Modeling:
The QA requirements for this effort shall abide by established DOE National Lab 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

Additional QA requirements through the DOE-NE LWRS Program will be applied whenever applicable [7].

Modeling Motivation:
In conjunction with the experimental data obtained from the efforts discussed in Section 2.1, 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’)

3.2.1 Milestone 5 Modeling

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

- Detailed pre-test system level modeling and analysis of all planned Milestone 5 testing discussed in Section 2.1. 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 5 testing to inform Milestone 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 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 and steam/water turbine inlet conditions for various scenarios: transition to FLEX from RCIC/TDAFW, BWR Mode 4 operations to RCIC, and operations within an expanded lube oil temperature band.

3.3 Schedule & Deliverables

Table 3.1 provides the schedule and duration for model development for Milestone 5.

Table 3.1 Modeling Schedule Specific to Milestones 5

Schedule	Duration
Detailed computational modeling to inform Milestone 5	3 months
Review of pre-test system level modeling informed from computational modeling	1 month
MELCOR modeling to inform Milestone 5	4 months
SAMPSON modeling to inform Milestone 5	4 months
RELAP-5 modeling to inform Milestone 5	4 months
Post-test detailed computation modeling	2 months
Post-test MELCOR modeling	2 months
Post-test SAMPSON modeling	2 months
Post-test RELAP-5 modeling	3 months
Integrate MELCOR model into BWR simulator	4 months

Table 3.2 provides the deliverables and duration for Milestone 5 modeling efforts.

Table 3.2 Modeling Deliverables Specific to Milestones 5

Deliverables	Duration
Pre-test summary modeling report for Milestone 5	3 months
Post-test modeling report for Milestone 5	2 months
Post-test summary modeling report for Milestone 5	1 month

The Milestone 5 modeling schedule for this effort is summarized as a Gantt chart in Table 3.3. At the end of each funding organization's fiscal year, a 'hold point' period of 3-6 weeks will be allocated for the funding organizations to review the program progress and associated funding.

Table 3.3 Modeling of Milestone 5 Efforts Gantt Chart (1-28 months)

Terry Turbopump Expanded Operating Band Gantt Chart										
		Month								
Modeling Deliverables	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18
Milestone 5 – Low Pressure Long-Term Integral Full-Scale Experiments										
Detailed computational modeling to inform Milestone 5	3 months									
Review of pre-test system level modeling informed from computational modeling	1 month									
MELCOR modeling to inform Milestone 5	4 months									
SAMPSON modeling to inform Milestone 5	4 months									
RELAP-5 modeling to inform Milestone 5	4 months									
Post-test detailed computation modeling	2 months									
Post-test MELCOR modeling	2 months									
Post-test SAMPSON modeling	2 months									
Post-test RELAP-5 modeling	3 months									
Integrate MELCOR model into BWR simulator	4 months									
Report Deliverables	**Duration**	1-2	3-4	5-6	7-8	9-10	11-12	13-14	15-16	17-18
Pre-test summary modeling reports for Milestone 5	3 months									
Post-test modeling report for Milestone 5	2 months									
Post-test summary modeling report for Milestone 5	1 month									
Industry Staff input on Milestone 5 modeling efforts	4 months									
Industry Contributions and Review of Milestone 5 reports	4 months									

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