# Terry Turbopump Expanded Operating Band Research

**Douglas Osborn and Matthew Solom**
Reactor Safety Technologies Pathway

**Abhay Patil, Duy Thien Nguyen, & Karen Kirkland**
Texas A&M University

**Masao Chaki, Nobuyoshi Tsuzuki**
Institute of Applied Energy (Japan)

**Randy Bunt**
Southern Corp

**Chan Patel**
Exelon Corp

In conjunction with the United States (U.S.) nuclear industry and the Government of Japan, the U.S. Department of Energy (DOE) supports efforts to enhance understanding of operational characteristics and limitations of Terry turbopumps and the systems that employ them: a reactor core isolation cooling (RCIC) system for boiling water reactors (BWRs), and a turbine driven auxiliary feedwater (TDAFW) system for pressurized water reactors (PWRs). The solid-wheel Terry turbine design is known to be robust and can ingest wet steam without damage [1]. However, the resulting degradation in performance under two-phase conditions is poorly understood. In addition, the current mechanistic understanding in single-phase conditions is insufficient for adequate modeling in systems-level codes such as MELCOR and the Reactor Excursion Leak Analysis Program (RELAP).

The typical nuclear application of Terry turbines attaches them to pumps, such as the TDAFW system and the RCIC system for nuclear power applications; oil, gas, and process facilities also employ Terry turbines for various steam applications. Notably, the RCIC systems employed at Fukushima Daiichi (Units 2 and 3) operated for far longer than existing analyses suggested they would. Instead of failing within a 4 to 12 hour timeframe as assumed by past analyses, the RCIC system of Unit 2, for example, provided cooling water to the reactor for nearly three days following the earthquake and tsunami of March 11, 2011, and did so in the absence of electrical power to its controller [2]. The exact cause of its ultimate failure remains unknown.

To remedy the current lack of off-normal information, the Terry Turbine Expanded Operating Band (TTEXOB) Project is investigating the operation of Terry turbines from the component level to the system level both computationally and experimentally. Work completed through the TTEXOB Project is via a phased approach [3]. During 2015, studies into the principles and phenomenology of Terry turbines were completed, which provided valuable input for full-scale component testing and basic science experiments. Experimental testing is currently underway at Texas A&M University. Future plans consisting of integral full-scale experiments for long-term low-pressure operations and replicating Fukushima Daiichi Unit 2 self-regulating feedback will be informed by data generated by the Texas A&M University experiments and subsequent modeling.

Also, individual components of a Terry turbine will be subjected to experimental testing at Texas A&M University. Single- and two-phase flow through Terry steam nozzles will be explored, while first-of-a-kind experimental visualization of two-phase supersonic jets is planned for future experiments. A full understanding of the behavior of these jets is crucial as they have a first-order effect on turbine performance. In addition, both the lubrication oil and turbine's bearings will be examined under extreme conditions and the governor and trip/throttle valves will undergo standardized testing and profiling for flow and pressure changes versus position. To date, no such flow profiling is known to have been performed for these specific valves.

Future testing at Texas A&M University will explore the performance of Terry turbines and produce torque curves under various conditions for both single- and two-phase ingestion. A smaller-scale Terry ZS-1 turbine (~10% the size of a full-scale TDAFW or RCIC Terry turbine), shown in Figure 1, will see both steam/steam-water and air/air-water conditions. In addition, scaling parameters will be established by subjecting a full-scale Terry GS-2 turbine

(GS turbine types are used in TDAFW and RCIC systems) to the same air and air-water conditions as used for the ZS 1 starting in October 2018 and ending in February 2019. Air and air-water testing of the ZS 1 has already begun. The final part of this testing will be to subject the ZS 1 with a pump attached to wet-steam feedback at low pressure conditions to explore the potential for self-regulating feedback, as seen at Fukushima Daiichi in the RCIC and TDAFW systems.

This self-regulating mode is thought to have occurred in Unit 2 at Fukushima Daiichi and would be responsible for the RCIC system's continued operation after the loss of electrical power to the controller. Upon the loss of electrical power, the hydraulic components of the turbine's governor are designed to move the governor valve to a full-open position (or fails 'as-is' for the newer governor controllers), allowing manual control from the Trip/Throttle valve. However, if no operator action is taken to regulate from the Trip/Throttle valve (as was the case at Fukushima), increased steam flow to the turbine would be expected to result in a mechanical overspeed trip. As seen at Fukushima Daiichi Unit 2 in the proposed self-regulating mode for a RCIC system, flow from the RCIC pump to the reactor exceeds the boil-off rate from decay heat and overfills the vessel. The overfilled vessel 'spills over' to the Main Steam line, sending a two-phase steam-water flow to the RCIC turbine. As the increasing wetness of the steam both removes inventory from the reactor as well as degrades turbine performance, a negative feedback loop can be created where increased turbine speed increases flow, resulting in wetter steam that degrades the turbine's performance and slows feedwater flow to the reactor. This may produce oscillatory behavior, or the system may reach a stable operating point.

*Figure 1. Experimental Setup for Air and Air-Water Tests of Terry ZS-1 Turbine.*

Characterizing the true operational limits, including any self-regulating mode criteria, go beyond explaining some of the curious phenomena observed during the Fukushima events. Understanding Terry turbine pump performance will improve the predictive nature of system-level codes and allow plant operators the ability to use emergency procedures derived from known, quantified parameters; this in turn allows for the distribution of scarce plant resources to where they are most urgently needed. The overall TTEXOB project creates the technical basis to:

- Reduce and defer additional utility costs:
  - Associated with post-Fukushima actions
  - Prevent the need of non-reactor grade water sources required during FLEX events
  - Extend the interval between preventive maintenance actions.
- Simplify plant operations:
  - Provide guidance to operators for expanded RCIC or TDAFW operations.
- Provide a better understanding of the true margin, which could reduce overall risk of operations.

The expectation is to have all efforts at Texas A&M University completed by summer 2019 and the overall TTEXOB project (to include full-scale, low-pressure, long-term testing and scaled replication of Fukushima Unit 2) completed by summer 2022.

### *References*

1. J. Kelso et al., "Terry Turbine Maintenance Guide, RCIC Application," EPRI Technical Report 1007460, Electric Power Research Institute, Palo Alto, CA (2012).
2. K. Ross et al., "Modeling of the Reactor Core Isolation Cooling Response to Beyond Design Basis Operations – Phase 1," SAND2015-10662, Sandia National Laboratories, Albuquerque, NM (2015).
3. Sandia National Laboratories, "Terry Turbopump Expanded Operating Band Full-Scale Component and Basic Science Detailed Test Plan – Final," SAND2017-1725, Sandia National Laboratories, Albuquerque, NM, December 2016.