EVALUATION OF IMPULSE TURBINE PERFORMANCE UNDER WET STEAM CONDITIONS

A Thesis

by

NICHOLAS GERARD LUTHMAN JR

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Karen Kirkland
Committee Members,	Yassin Hassan
	Gerald Morrison
Head of Department,	Yassin Hassan

May 2017

Major Subject: Nuclear Engineering

ABSTRACT

After the Great East Tohoku Earthquake of 2011, operations at three critical reactors at the Fukushima Daiichi site were disrupted. All three reactor plants had automatic shutdowns. After a reactor is shutdown from power, decay heat must continue to be removed for several hours. The earthquake caused electrical equipment disruption which interrupted power supply from off-site. In Unit 2, emergency diesel generators and battery power were also affected. This interruption of on-site and off-site power affected operability of decay heat removal systems.

In Unit 2, the Reactor Core Isolation Cooling System (RCIC) was an installed means of removing decay heat. The RCIC System uses a tangential flow impulse turbine called a Terry turbine to power a pump, which directs cooling water into the Reactor Pressure Vessel (RPV). Though DC and AC power were unavailable, the RCIC System was able to operate for 70 hours. One reason for this may be lowered efficiency due to moisture carryover in the steam line.

The events of the plants which were operating at Fukushima Daiichi have been modelled using several computational codes. Instrument data is limited due to the loss of electrical power, so assumptions were necessary. To more fully understand the events of Fukushima Daiichi Unit 2, it was desired to investigate the performance of a tangential flow impulse turbine under two-phase flow conditions. Estimation techniques have been made of the effect of two-phase injection on turbine performance, but these were also tested for this unique turbine design.

A Terry turbine similar to those used in the RCIC Systems was installed in an experimental facility. The facility was equipped to inject compressed air or steam, along with a water component, into the inlet of the turbine. The turbine shaft work was measured by a water brake dynamometer. Dry and wet mixes from 60 g/s to 0 g/s were injected into the turbine down to the lower limit of operability. Torque, shaft work, and isentropic efficiency were obtained for 1500, 2000, 2500, and 3000 shaft revolutions per minute (RPM).

The steam tests produced higher shaft work and torque than the air tests due to the higher enthalpy content of steam. Air, however, achieved similar isentropic efficiency to the steam tests. The 1912 approximations of Baumann for low-quality steam had good agreement with the results from tests using the wet mixes.

DEDICATION

For my family. Thank you.

ACKNOWLEDGMENTS

I owe many thanks to those who have helped me in this effort. Dr. Kirkland, for her guidance and encouragement. My wife, Tina, for her support. Richard Livingston, Samuel King, Ben Lear, Andrew Marvel, Josh Hanophy, Bruce Washington, Tyler Hughes, and Kohei Tsutsumi for their help in operating equipment in the lab. Matthew Solom, Nick Wynne and Matt Garza for helping me when I had questions. Lendell Keene and Tom Revak for their help and advice in refurbishing and operating the turbine. Kyle Ross, Doug Osborne, Brad Beeny, and the rest of the staff at Sandia National Laboratories who provided feedback and encouragement as construction and testing progressed. Chan Patel, Mark Bergman, Rebecca Retherford, and the rest of the members of the BWR Owner's Group who provided industry perspective on the work. Thank you all.

CONTRIBUTORS AND FUNDING SOURCES

Funding for this study was provided by the Department of Energy Nuclear Engineering University Program. Additionally, equipment was donated by Mr. Lendell Keene of Keene Turbomachinery Services, and technical assistance by the staff of TW Revak.

NOMENCLATURE

ACRONYMS

AC	Alternating Current
AFW	Auxiliary Feed Water
ASTEC	Accident Source Term Evaluation Code
BWR	Boiling Water Reactor
CST	Condensate Storage Tank
DAQ	Data Acquisition
DC	Direct Current
IAEA	International Atomic Energy Agency
INPO	Institute of Nuclear Power Operations
MAAP	Modular Accident Analysis Program
PWR	Pressurized Water Reactor
RCIC	Reactor Core- Isolation Cooling
RELAP	Reactor Excursion and Leak Analysis Program
RHR	Residual Heat Removal
RPM	revolutions per minute
RPV	Reactor Pressure Vessel
SAMPSON	Severe Accident Analysis code with Mechanistic Parallelized Simulations Oriented towards Nuclear Field
SBO	Station Blackout

SCXI	Signal Conditioning eXtensions for Instrumentation
TEPCO	Tokyo Electric Power Company
TTV	Trip and Throttle Valve
UPS	Uninterruptible power supply
URV	Upper Range Value
VI	Virtual Instrument
UNITS	
ft-lbf	foot-pounds
g/s	grams per second
GPM	Gallons per minute
HP	Horsepower
inH2O	Inches of water
mA	milliamps
psia	pounds per square inch absolute
psig	pounds per square inch gage
s	seconds

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Page

1 INTRODUCTION

On March 11, 2011, a very large earthquake occurred under the ocean in the vicinity of Japan. The seismic activity resulted in a tsunami which impacted operations of nuclear power plants at the Fukushima Daiichi site.

Off-site power to all six plants of the Fukushima Daiichi site was lost due to seismic activity. Tsunami waves disrupted the DC power installations of units 1, 2, and 4.

Three of the reactors at Fukushima Daiichi were operating that day. All operating plants experienced automatic reactor shutdown scrams due to earthquake. Units 2 and 3 utilized the General Electric BWR 4 design with a Mark I containment. These plants also utilize a system known as the Reactor Core Isolation Cooling (RCIC) system. The RCIC system provides a path for decay heat removal from the Reactor Pressure Vessel (RPV). Under Station Blackout (SBO) conditions, the RCIC system relies on DC electrical power from backup batteries. The batteries at Unit 2 and Unit 3 were originally designed to operate for four to eight hours.[3, 4]

Fukushima Daiichi Units 2 and 3 were both able to use RCIC to supply cooling for time spans well beyond eight hours. In Unit 2 especially, the system performance was remarkable. In Unit 2, both AC power and battery-supplied DC power were disrupted by flooding from the tsunami. By design, loss of all electrical power to the RCIC system results in the turbine governor valve failing in the fully open position. With full steam flow admitted, the turbine should speed up rapidly, and trip on overspeed shortly thereafter.[4, 5]

Instead, the RCIC system of Unit 2 continued injecting cooling water at approximately design capacity for nearly 70 hours.[6] The present research is an investigation of the RCIC turbine operation under long-term SBO conditions. A thorough understanding of the mechanism that allowed such operation would be useful in understanding the events of Fukushima Daiichi, and it may be useful in future operations involving RCIC and other similar systems.

2 BACKGROUND

Each of the operating nuclear power units of Fukushima Daiichi in the days following the Great East Japan Earthquake of March, 2011 was subject to a unique set of conditions. Units 2 and 3 employed BWR/3 designs with the Mark I containment and RCIC. In the event of an SBO condition, the batteries for these plants were designed to allow operations for eight hours.[7] Both Unit 2 and Unit 3 exceeded this design operating duration. The Unit 3 RCIC had battery power available, and operated for approximately 20 hours before the turbine tripped for an unknown reason. Unit 2 had battery power interrupted, yet the RCIC system injected water for about 70 hours. For this reason, the Unit 2 RCIC system is the point of interest for this study.

There are several factors that challenged extended RCIC operation in Unit 2. Moisture carryover into the turbine, pump cavitation, and erratic governor control all could have caused the system to fail prior to 70 hours, but remarkably, they did not.

The RCIC system operates by using steam from the Reactor Pressure Vessel (RPV) to spin a turbine. The turbine is directly coupled to a pump. Turbine speed regulation depends on a DC power supply. The RCIC pump takes suction from either of two sources: the Condensate Storage Tank (CST) or the suppression chamber. Discharge may be directed to the CST and/or the RPV. In this case, discharge was directed to the RPV. A representative diagram is given in Figure 1.

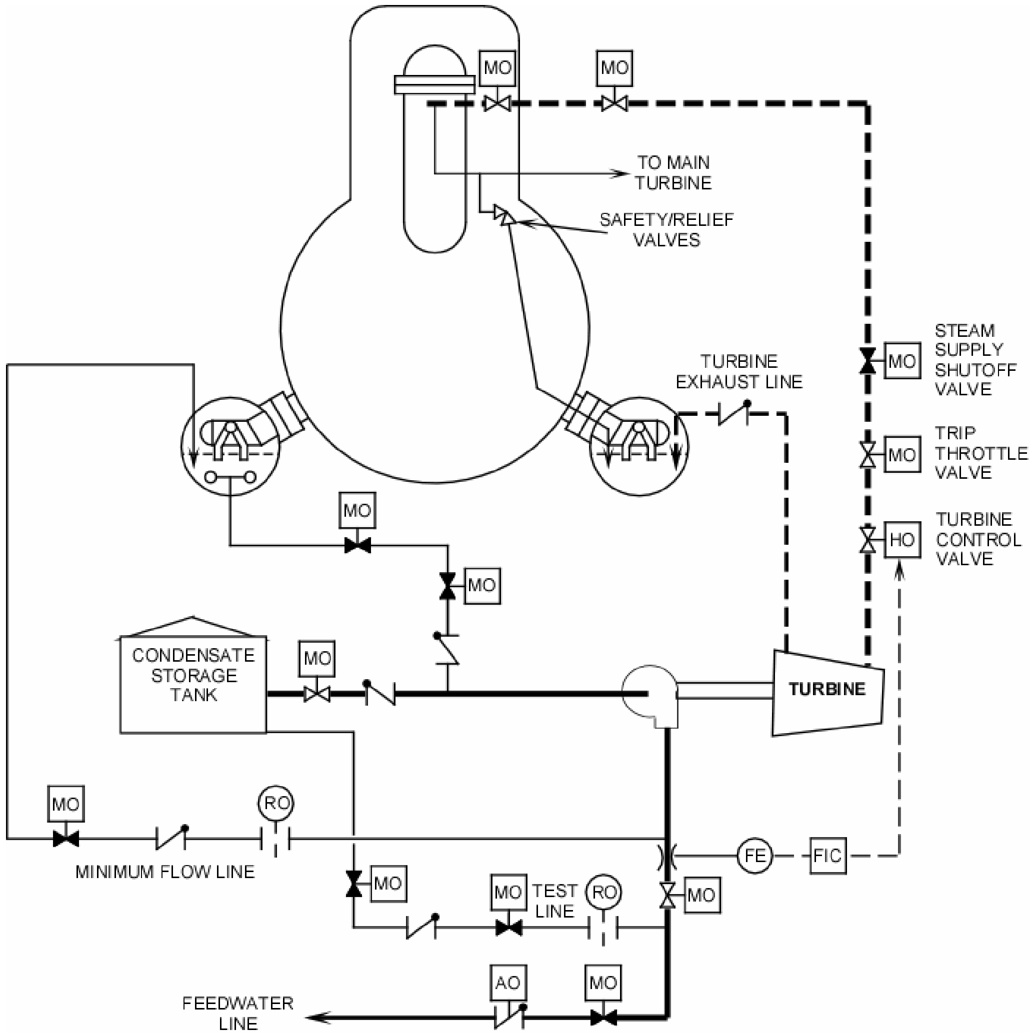


Figure 1: Diagram of RCIC system for BWR/3 with Mark 1 containment.[1]

Injection rates can be estimated to be approximately rated flow until March 12 at 04:30. This is based on the change in CST level over the period when RCIC pump suction was aligned to the CST. In later stages, current Modular Accident Analysis Program (MAAP) models assume an injection rate of approximately 1/3 rated capacity.[6] This was assumed to account for lower turbine efficiency in two-phase flow conditions.

Loss of power to reactor pressure vessel instruments could allow overfilling of the RPV, and introduction of liquid into the main steam line. Moisture carryover into the turbine would result in a reduced turbine efficiency, and lower speed. The feedback mechanism has the potential to allow RCIC operation without battery power.

2.1 RCIC System Speed Control

Steam enters the turbine through the Trip Throttle Valve (TTV). This valve shuts in the event of an overspeed condition. After the TTV, steam passes into converging/diverging steam inlet nozzles. These nozzles are designed to cause the steam to accelerate to supersonic velocities. The nozzles direct the fast-moving steam at the turbine rotor. The rotor is a solid metal wheel with buckets milled into the outer surface. The steam delivers impulse to the buckets, and is then reversed in direction. Reversing chambers are used to redirect the steam back into the buckets to deliver additional impulse to the wheel. The expended steam is then directed to the exhaust portion of the casing, and then into the exhaust piping.

The RCIC system operates in response to inputs from multiple sources. Steam from the reactor, DC electrical power, and the overspeed trip mechanism affect operation of the RCIC system directly. A governor system automatically adjusts turbine speed to maintain desired feed flow. A flow controller compares actual feed injection flowrate to target flowrate, and passes a corresponding electrical signal to the turbine governor actuator. The actuator adjusts control oil pressure. Control oil pressure controls the motion of the throttle linkages, which adjust the steam supply to raise or lower turbine speed. Because the pump is coupled directly to the turbine shaft, pump response is immediate. The injection flowrate signal is dependent upon DC power supply; loss of this power supply will result in the governor valve moving to the fully open position. The last major input to the RCIC system is the overspeed trip. The overspeed trip is initiated by a mechanism affixed to the turbine rotor. Upon reaching a predetermined speed, the overspeed trip mechanism initiates the shutting of the Trip and Throttle Valve (TTV).

2.2 Terry Turbine Water Ingestion

Past work has been done investigating Terry solid wheel turbines' structural integrity upon ingestion of water slugs. The RCIC system employs an impulse turbine. The turbine wheel has a very rugged and durable design. The vendor performed water injection testing. For these tests, water volumes of up to 600 gallons were injected both during initial startup, and during operation at rated speed. For the at-speed tests, loading was representative of typical auxiliary pump. Inspections yielded no detectable damage to the turbine. This illustrates that the RCIC turbine can withstand excessive moisture carryover. However, the performance characteristics of this turbine type under conditions of continuous two-phase injection was not studied.[8]

2.3 Event Timeline

The preceding design features and operational notes are useful background for evaluating the events timeline of Fukushima Daiichi Unit-2. Subsequent to the reactor SCRAM due to earthquake, the Unit 2 RCIC system was manually started three times. After the first two startups, the RPV high water level trip (L8) caused RCIC shutdown. The tsunami caused loss of battery power almost immediately after the third startup.

This loss of power precluded a third L8 trip. Loss of DC power also caused a loss of turbine speed governor functionality. As previously discussed, the governor was designed to fail in the fully open position. The intent of this design was for the turbine to shut down on an overspeed trip in the case of governor failure. The two possibilities for this case are that the turbine did not reach the overspeed trip setpoint, or the overspeed trip mechanism failed. Neither can be eliminated with certainty. In any event, the RCIC system appears to have continued injecting water until March 14.[6]

2.4 Identification of Current Knowledge Gaps

In the years since the Fukushima earthquake and tsunami, new data has become available. The power station was in station blackout (SBO) conditions. This resulted in limited instrument data, deranged electrical equipment, indication that RCIC was operating for some time, and indication that moisture carryover may have been occurring into the RCIC turbine.

2.4.1 Aspects with High Level of Knowledge

- Instrument data up to tsunami
- Estimates of damage
- Indication that Unit 2 RCIC System was operating without DC power
- Approximations of turbine efficiency losses due to wet steam

2.4.2 Desired Data

- Efficiency of Terry turbines in general
- Extent of electrical derangement
- Losses due to moisture in Terry turbine

    - Reversing chambers are a unique feature
- Validation of assumption
    - Computational models have obtained good agreement with logged data points and by using Baumann's efficiency loss guideline for wet steam
- Verification of damage
    - Unit 2 machinery spaces are still inaccessible

2.5 Terry Turbine Characteristics

The Terry solid-wheel turbine line features a single solid wheel with buckets milled in. It operates using a single pressure stage and a compound velocity stage. The velocity compounding uses a set of reversing buckets which direct exhaust steam back into the buckets of the wheel. An example is given in Figure 2.

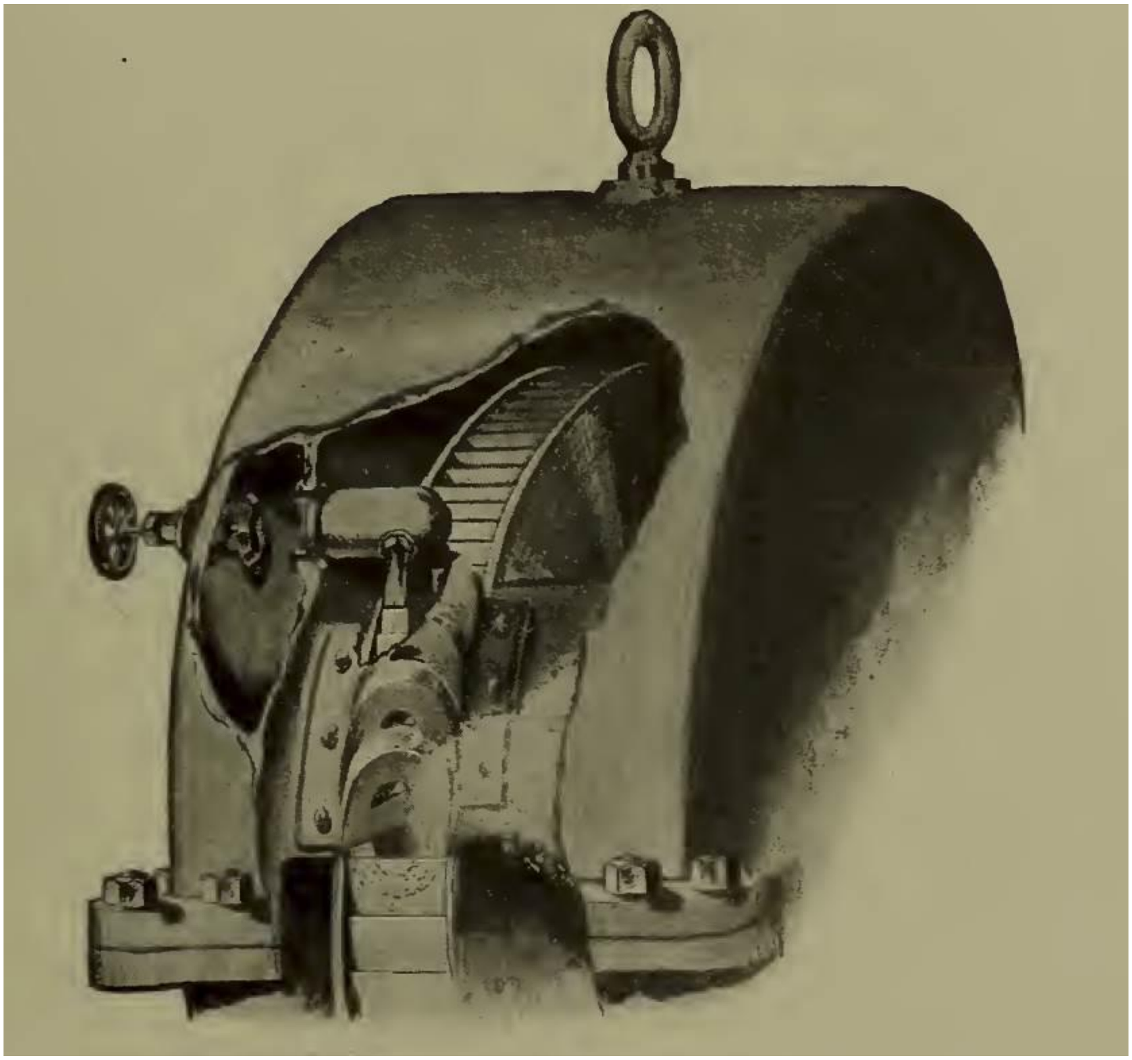


Figure 2: Terry turbine, with steam injection nozzle and reversing chambers.[2]

The turbine used in the RCIC system requires DC power to operate the speed governor system. The only other power requirement is steam from the reactor.

In normal operations, the governor throttles steam flow to maintain the turbine speed properly. Upon loss of control power, the governor valve fails in the open position. This results in the turbine speeding up. The design intent was for the turbine to trip on overspeed for the case of loss of control power.

The unique construction of the solid-wheel turbines does not result in very high efficiency, but it allows for some operational advantages. The turbines require no warmup, and are resilient against damage from water slugs. These features are well-adapted to the RCIC system.

The design of the RCIC system was to provide cooling when the reactor is isolated from the turbine. It was assumed that in the event of a core isolation event, on-site power is available, or off-site power or emergency diesel-supplied power would become available.

This is not strictly an accident scenario. Any case in which the core is isolated may be a useful situation for the RCIC system. If the reactor is shut down, the main steam cutout valve would be shut. Steam is no longer directed to the main turbine, so the RCIC can be used to remove decay heat.

2.6 The RCIC System in Fukushima Daiichi Unit 2

Unit 2 experienced severe conditions after the earthquake. It was really two casualties: first an earthquake, then a tsunami. The earthquake resulted in an automatic reactor shutdown by SCRAM. The second casualty was flooding due to the tsunami.

The end result is that the RCIC system of Unit 2 operated for 70 hours in absence of normal electrical power supplies. The mechanism that allowed this extended operation is not known conclusively, but it can be considered a benefit. Investigation into the phenomena that allowed this extended operation seems worthwhile.

2.7 Project Motivation and Objective

Why did the Unit 2 RCIC operate for 70 hours without battery power? The answer to this question is not definitively known. One possible explanation is that the liquid carryover in the steam line resulted in a decreased turbine efficiency. With this lower efficiency, an overspeed trip may have been avoided upon loss of governor control power.[4]

The current experiment is designed to investigate this possibility. Injection of low-quality steam into a Terry solid-wheel turbine is investigated. Motivation stems from the Fukushima plants.

There is reason to believe, after the performance of the Unit 2 RCIC system, that RCIC turbopumps are capable of long-term operation, even upon loss of normal control functions. The current experiment is designed to investigate possible mechanism for how this system could be controlled. Specifically, the experiment is meant to measure performance during injection of two-phase flow.

2.8 Problem Statement

The turbine is known to be rugged enough to withstand water slug injection. Published data with more specific details of turbine performance is needed to characterize its behavior under two-phase flow conditions. The data collected in this test series is intended to pursue such a characterization and to validate computational models.

It is known that a turbine will have lower efficiency if water is injected along with steam.[9] The end goal is to quantify the relationship of water content to turbine efficiency for a tangential impulse type turbine.

2.9 Importance of the Research

This research topic is important because, to the author's knowledge, there have been no attempts in the literature to quantify the effect of moisture carryover on the power output of a single pressure stage, compound velocity stage, single-wheel tangential flow turbine. This is a specific turbine design that is used in a limited number of applications. Furthermore, when this turbine style is used, it would rarely be subjected to two-phase fluid injection. A thorough knowledge of these topics would be valuable additions to the current knowledge of reactor safety systems and operational procedures in beyond-design-basis events such as those of the Fukushima Daiichi nuclear power plants.

The International Atomic Energy Agency (IAEA) Fukushima Daiichi Accident Technical Report Volume 2 further substantiates the importance of this research, as noted in the following excerpt, which is used with permission from the IAEA. The IAEA retains the copyright.

> "It is worth noting that the Unit 2 RCIC system remained operable far longer (nearly three days) than would have been expected, given the loss of DC power and the resulting uncontrolled operation. It is believed that in this uncontrolled operation mode, the RPV water level rose to the level of the steam lines, causing liquid water carryover into the RCIC system turbine, which in turn led to a reduced water injection rate and an effective self-regulating level control at the elevation of the

steam lines. In addition, it is also believed that seawater flooding of the Unit 2 torus room led to significant heat rejection from the suppression chamber, which prevented overheating of the water in the suppression pool and likely played a role in extending the operation time of the RCIC system. These effects need to be clarified in order to develop a better understanding of the operating behaviour of the RCIC system and its ability to prevent onset of core damage."[4]

The data from this test will be included in a database for use in validating Fukushima RCIC turbine models. The models will be assessed against this experiment data and available data from the Fukushima plants. Specifically, this data will be pertinent to two-phase injection into the RCIC turbine, and the resulting change in power production.

3 LITERATURE SURVEY

Unit 2 operated far longer than the design operating criteria of eight hours. It is believed that this was due to overfilling of the Reactor Pressure Vessel (RPV), resulting in a self-regulation that limited the water input to the RPV. Seawater flooding of the torus room also may have provided some cooling to the suppression chamber, providing further benefit. These effects need to be studied further to clarify the ability of RCIC to provide core cooling.[4]

Alone, or in concert with computer codes, this characterization of moisture losses for this turbine design will provide a more complete understanding of the events of Fukushima Daiichi Unit 2. This may enable the previously unidentified capabilities of the RCIC system to be employed in operating procedures.

It is also desired to determine the failure mechanism of the turbine. This failure mechanism is currently unknown.[4] Though this is not the main focus of the research, it may provide a contribution to the answer to this question.

For this thesis, the turbine models should be reviewed, or RCIC system systems level models where focus is on the turbine. There have been several investigations into the events of Fukushima Daiichi using computational codes. Codes include MAAP, MELCOR, ASTEC, SAMPSON, and RELAP/ScdapSIM.[6, 10-13] An analytical approach was also taken by Lopez et al., which applied the Rankine cycle to the RCIC system, with the RPV supplying the heat in and the suppression chamber acting as the heat sink.[13]

Approximations were used in all of the following models to more closely obtain results to those of the Fukushima log data.

The analytical approach of Lopez et al assumed that the water level of the reactor pressure vessel (RPV) remained constant over 70 hours. The description of the turbine given in the introduction is applicable to an axial-flow turbine, but does not accurately describe tangential-flow turbine, such as that employed in the RCIC system.[13]

The TEPCO model of Yamanaka et al, which used the MAAP software, assumed an injection rate of approximately 1/3 rated capacity to account for degraded turbine performance with two-phase flow. This is a rough estimation, and a good starting point. This approximation leaves room for empirical studies of two-phase flow through this turbine type.[6]

The ASTEC model applied PWR assumptions to BWR events, and the transient flows of water injection rates were assumed by necessity. These water injection flows are a major factor, and so validation of this assumption is desired.[11]

The SAMPSON code, published by Suzuki et al., obtained results that relied on assumption of partial load operation of the RCIC system. Furthermore, the partial loading was estimated such that the mass of steam extracted was exactly equal to the mass of water injected to the RPV. This adjustment led to better correlation with logged data.[12] Such an un-designed, yet functional control system would be fortunate indeed! This mode of operation could perhaps dispense with some requirements of the normal operating mode, such as dependence upon RPV level trips and DC power.

The MELCOR code used a RCIC pump injection controller to fix the RCIC boundary conditions based on plant data. The pump injection controller is used instead of a thermodynamic model. This approach is functional in obtaining simulation results that align with the Fukushima logs, but experimental data would allow improvement of the predictive power of the MELCOR models.

3.1 Moisture Carryover Loss Estimations

Baumann provided a system of estimation that is simple to apply: a 1% increase in wetness yields a 1% drop in efficiency.[9] This estimation is simple to apply, and provides an accessible hypothesis for the performance of the ZS-1 turbine.

There was an empirical test of efficiency of a Pelton turbine under air-water two-phase flow done by Akagawa and Asano.[14] The efficiency tracked linearly with the gas fraction. There are notable differences between the Pelton turbine and the Terry turbine in this study. The Pelton wheel uses a converging steam inlet nozzle whereas the Terry turbine employs a converging-diverging steam inlet nozzle. Also, the Terry turbine uses a set of reversing buckets, which the Pelton turbine lacks. Maximum air flowrate achieved in the Akagawa test was 17 g/s.

3.2 Technical Approach

Performance testing of the ZS-1 turbine will be conducted using either steam or air for the gas phase with a liquid water fraction. Air tests are simpler in that air will not go through a phase change in transit. Saturated steam, however, may condense when in contact with the colder turbine surfaces and water that is below the saturation temperature.

The ZS-1 turbine will be coupled to a water brake dynamometer. Metered air or steam will be injected into the inlet of the turbine. The turbine will be brought up to speed. The turbine will be brought up to speed and loaded. After the turbine is loaded, water will be injected. This water will be metered. The dynamometer will be adjusted so that steady speed and inlet pressure are obtained.

Data will be collected in 500-RPM increments up to a maximum of 3000 RPM. This is to allow comparison between full speed testing and test runs with steam/air content that is much lower.

It is intended to produce power curves for input mass flowrates with speed as an independent variable. These can be compared to the raw data will be available for reference, but speed /quality curves will be the readily-understood data sets.

3.3 Other Technical Considerations

Pressure and temperature will be taken at the inlet and exhaust of the turbine. Temperature readings will be taken down the steam line. The temperature can be analyzed at points along the steam line. For a mixture of steam and water, the mixture may enter the saturation dome. At this point, heat can be transferred from the fluid to the surroundings without a change in temperature. These latent heat of condensation losses will be characterized using heat losses of superheated steam.

For steam tests, the water in the Feedwater Storage Tank will be heated up to 90°C. This will allow less interplay between the phases. For air tests, the water will not be preheated. There is no anticipated evaporation of the water for air tests. The air is much colder than the steam, due to its expansion and it goes through the refrigerator-dryer prior to entering the main steam piping.

Other data points of interest are coastdown times. For very low-quality steam, the turbine is unable to sustain any loading, and will simply coast down. Coastdown time will be compared from gas/water wet injection and from air/steam injection only. For instance, a run of 45 g/s water and 15 g/s of steam will be compared to coastdown from a run of 15 g/s of steam only. Repeatability studies will be performed of selected tests. The heater capacity can also be compared to the steam production, since no feed is applied during these tests.

3.4 Contribution to the Literature

Baumann provided a guideline of 1% lowering of efficiency for each 1% mass fraction of water.[9] The Terry Solid Wheel turbine has a unique design, and it is uncertain how its performance will react to moisture carryover. This type of efficiency data has not been published before, so it seems worthwhile to make public empirical results from this turbine type.

Computer models may do a good job of matching Fukushima logs retrospectively, but they depend upon assumptions. Thus far the only empirical estimates are those obtained from the Fukushima plants. It is much more difficult to make a predictive model, particularly when they involve so much complexity. Experimental data is essential in building an accurate simulation. Ultimately, all systems level codes are either based on empirical data or on a priori assumptions such as equations. Empirical data is very valuable in this sense, and can provide a useful service. Items such as the turbine performance in abnormal conditions will not be available from anywhere but a specialized experimental facility. Commercial reactor managers will certainly not be eager to subject their equipment to unnecessarily stressful operating conditions.

To summarize, moisture carryover presence at the inlet of a Terry turbine can affect turbine performance. This change in performance can have an effect on reactor safety. This experiment is an investigation into this aspect of turbine performance. It is intended to provide independent support for modeling efforts.

4 EXPERIMENTAL FACILITY DESIGN AND CONSTRUCTION

4.1 Experimental Facility Layout

The major equipment of the facility are the steam generator, the water injection pump, the turbine, the turbine, exhaust volume, and connecting piping. A simplified diagram is provided in Figure 3. Gas is directed from the steam generator to an injection point where water may be added, and then the mix is directed to the turbine inlet. The gas may be steam or air. Both the gas and water are metered.

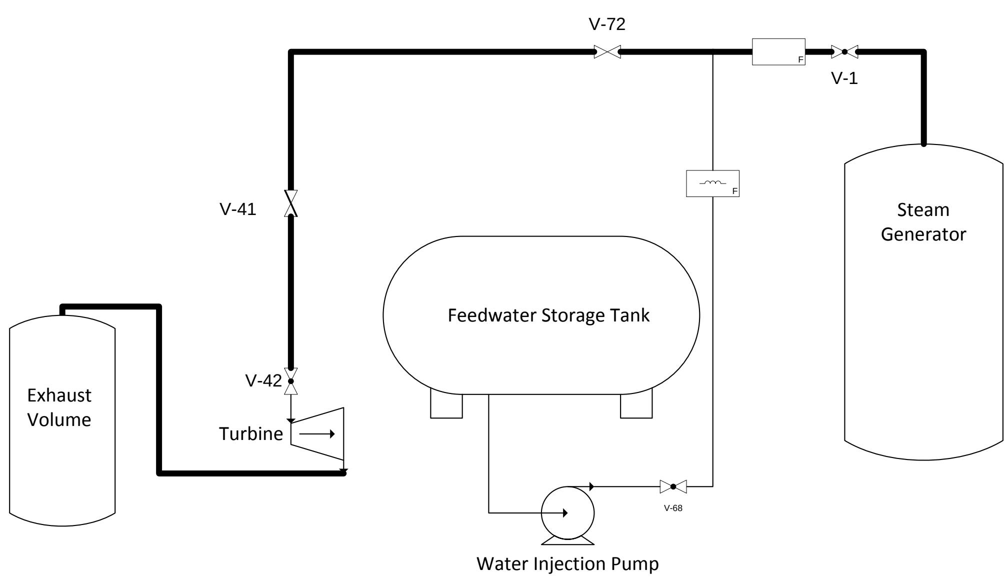


Figure 3: Simplified experimental facility diagram.

4.2 Experimental Equipment

4.2.1 Turbine

A suitable turbine for this test series was identified in a storage area of a Houston area turbomachinery service provider, Keene Turbomachinery Services A portion of the storage area can be seen in Figure 4. Mr. Keene graciously agreed to loan the turbine to Texas A&M University for testing.

Figure 4: Surplus turbines at Keene Turbomachinery Services.

Before testing, a refurbishment was necessary. The turbine was transported to TW Revak, for a thorough refurbishment (Figure 5).

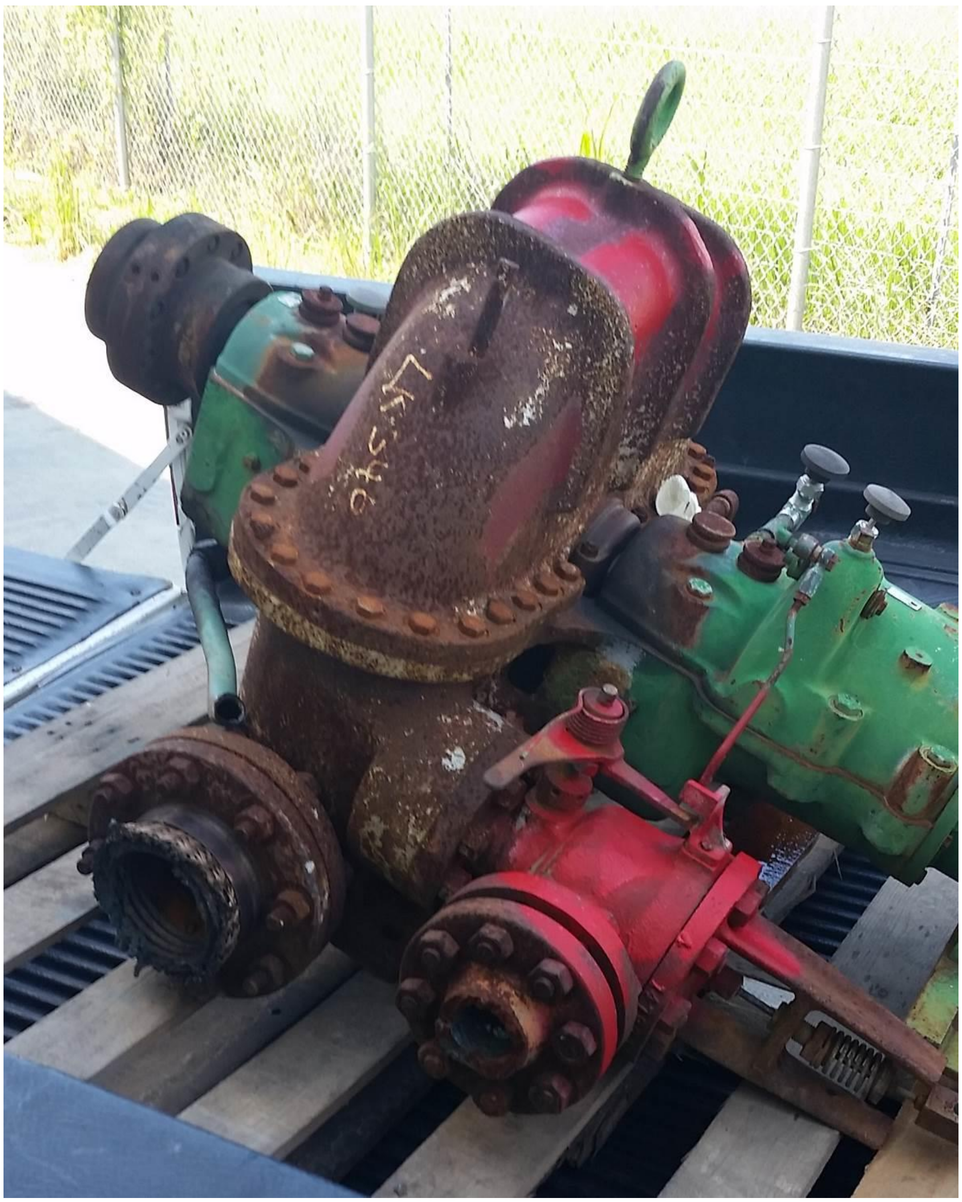


Figure 5: Turbine en route to be refurbished.

The turbine was disassembled. The upper casing and bearing covers were removed, and the rotor and shaft were lifted out. A photo with component labels just before shaft removal is given in Figure 6.

Figure 6: Turbine disassembly.

The Trip Throttle Valve (TTV), shown in Figure 7, was found to be seized in the open position. The TTV is a butterfly valve which is designed to shut in the event of an overspeed condition. The old valve stem was hammered out and replaced, and the valve was returned to service.

Figure 7: Trip Throttle Valve, with seized valve stem.

The turbine came equipped with three steam nozzles, pictured in Figure 8. Two of these nozzles were removed, and their installation ports plugged to adapt the turbine to the flowrates expected during testing. The throat of each pre-existing nozzle was 0.380 inches in diameter.

Figure 8: Lower casing, with original nozzles and reversing chambers.

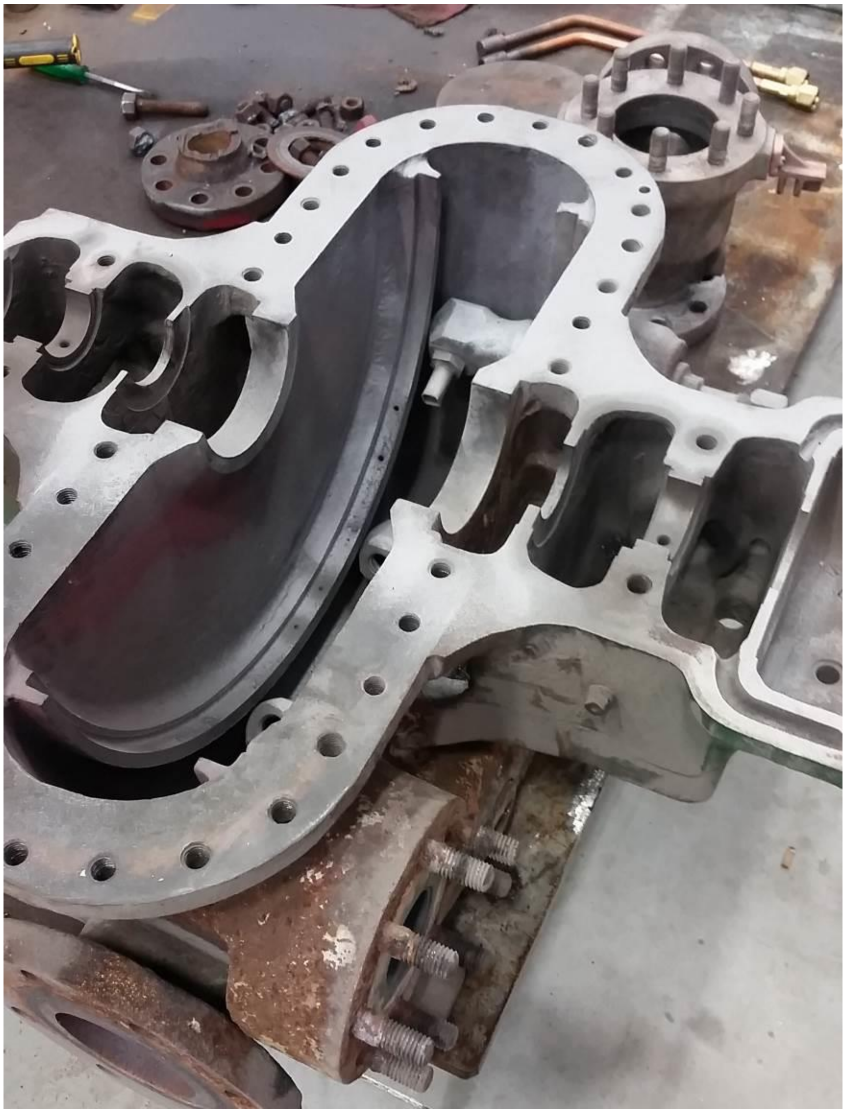


Figure 9: Lower casing, after sandblasting, with two nozzles removed.

The turbine was then sandblasted, reassembled, painted, and returned to service as "The Duchess," an experimental test turbine (Figure 10). The lower half of the casing is shown after sandblasting in Figure 9.

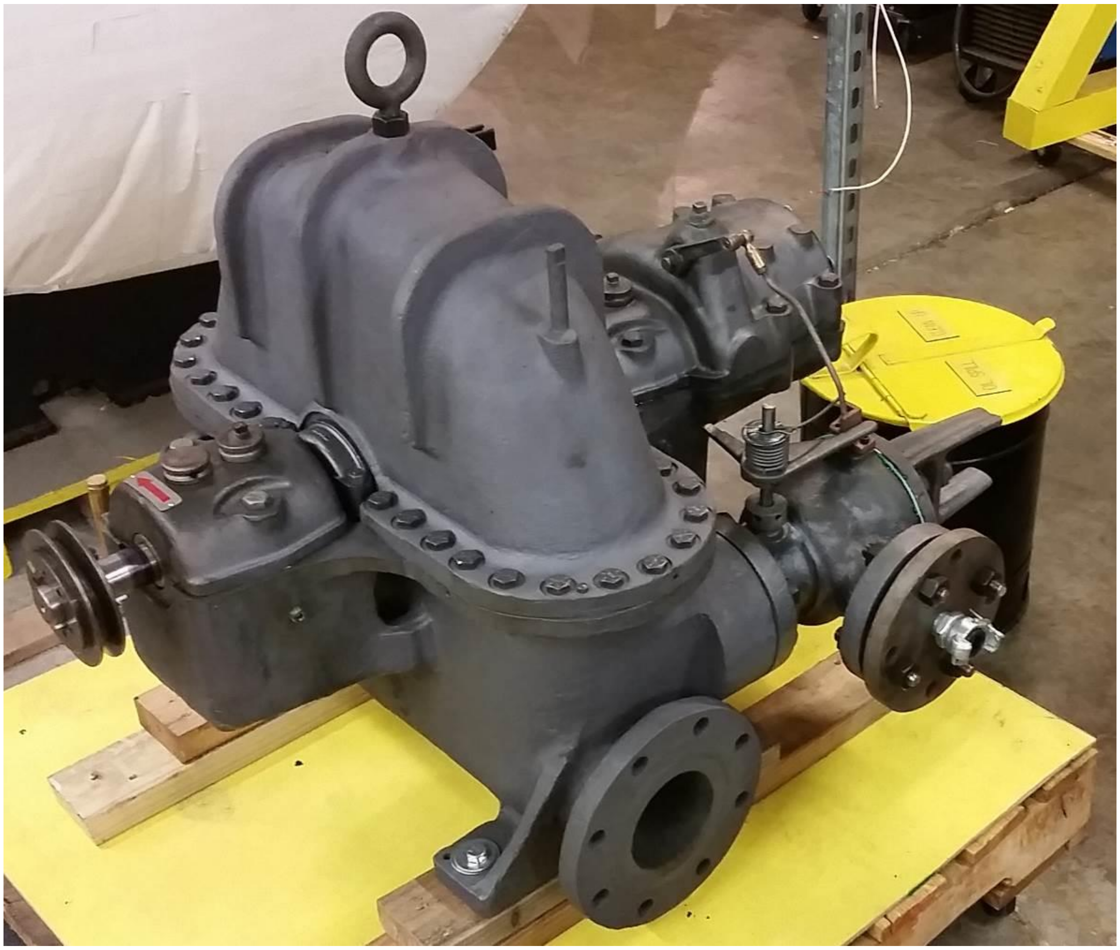


Figure 10: “The Duchess.”

The Duchess is a Terry Solid-Wheel ZS-1 model. The Z indicates the wheel diameter (pitch) is 18 inches. The S stands for steel. The 1 indicates that there are nozzles in only the lower half of the casing. The shaft is 1 3/8-inch in diameter, with a keyway in the drive end for coupling fitup. The bearings are beryllium bronze.

The casing allows for installation of four nozzles, but only one nozzle was used for this experiment. Each nozzle port is equipped with a set of reversing chambers to redirect steam into the turbine wheel. The shaft seals consist of three carbon rings on each side of the wheel. Leakoff piping is supplied between the second and third rings on each side of the shaft.

The casing is equipped to accommodate a Woodward TG-13 governor valve. This governor valve was removed for this test series. Speed was controlled by hand-operated valves. Also included is a mechanical overspeed trip. A spring-loaded mechanism is attached to the rotor. Upon reaching the overspeed setpoint, the spring pressure is overcome, and the mechanism contacts a linkage which shuts the Trip Throttle Valve (TTV). The TTV is a butterfly valve just upstream of the inlet plenum. The steam inlet nozzle has a nominal 0.380-inch throat diameter. This inlet nozzle has a converging-diverging flow path which is designed to enable the gas flow to reach supersonic speed, and directs this flow into the turbine buckets.

The turbines in use at Fukushima Daiichi Unit 2 and Unit 3 were model GS-1 or GS-2. These share many characteristics with the ZS-1 used in this experiment. They employ a tangential flow path, and have a solid milled turbine rotor with reversing chambers. Their wheel pitch is 24 inches. This is a larger size than the ZS-1 wheel pitch of 18 inches, but for the purpose of investigating the effects of water ingestion, the ZS-1 was determined to be an acceptable choice.

The turbine is supported by a test platform. The test platform, shown in Figure 11, consists of a large stainless steel base and supports made from mild carbon steel angle iron and C-beams. The test platform was fabricated locally. The test platform is not bolted to the floor. Instead, it is placed on rubber sheeting to absorb vibrations. This is a requirement of the dynamometer. Figure 12 shows the turbine installed on the test platform with instrumentation installed.

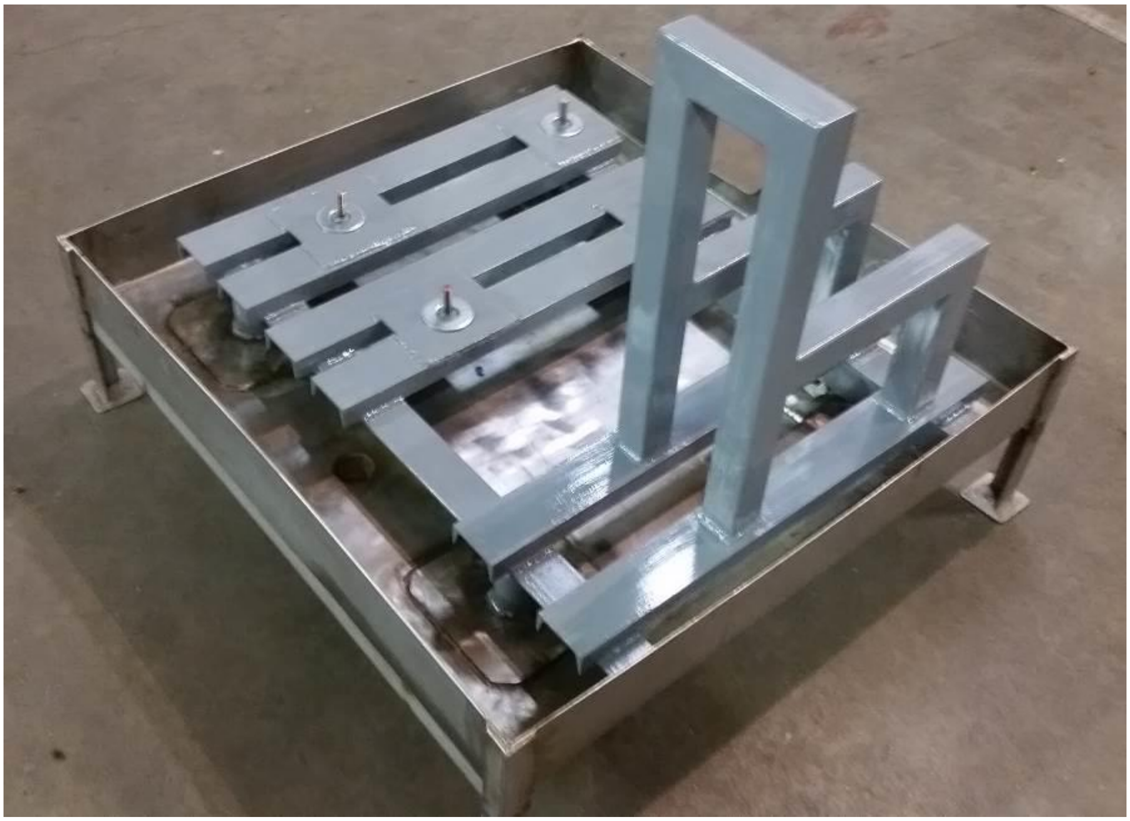


Figure 11: Test platform, fabricated and painted.

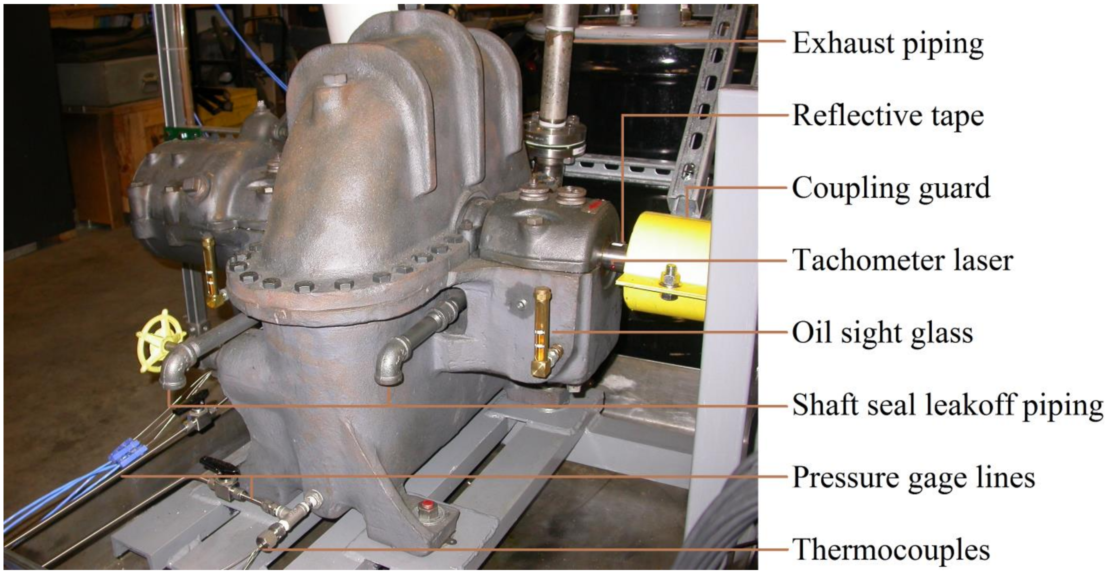


Figure 12: The Duchess, on platform, with instrumentation installed.

The turbine drives a Lovejoy L110 rubber spider coupling (Figure 13), which is coupled to the dynamometer shaft. A coupling guard is installed during operations.

Figure 13: Shaft coupling.

The inlet piping is 1.5-inch NPS piping that branches from the Main Steam line and includes a 9-inch stainless steel braided corrugated segment to minimize stresses to piping due to operational stresses, as well as to simplify alignment during installation. The piping includes two thermal sensing ports with thermocouples. These were included to characterize the heat losses of the piping upstream of the turbine.

Exhaust piping is directed to a 55-gallon drum. Like the inlet piping, the exhaust piping includes a steel corrugated hose segment to minimize piping stresses (Figure 14). The exhaust pipe protrudes 18 inches into the drum. For steam testing, water level is maintained greater than 20 inches from the bottom so that the quench volume of water within the drum can condense the steam. For air tests, the drum is drained.

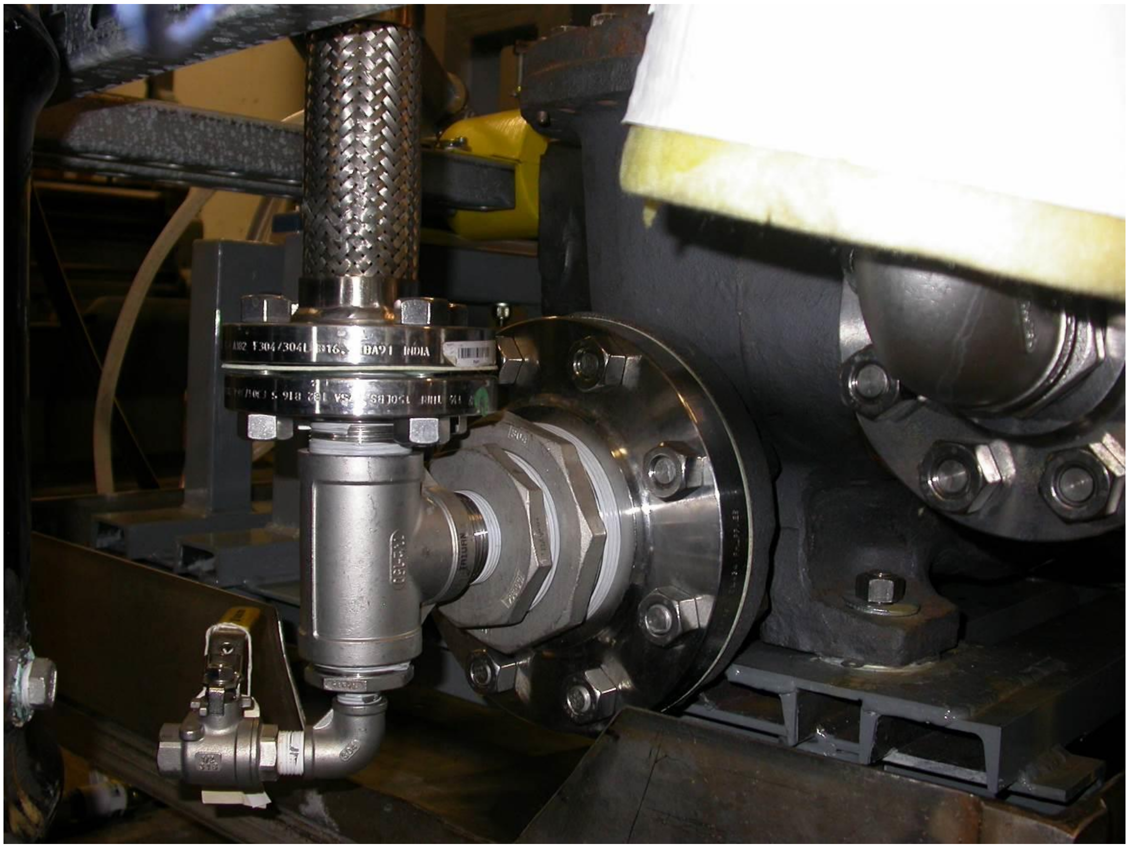


Figure 14: Turbine exhaust flange.

4.2.2 Water Deionization System

To minimize fouling and scaling, deionized water was used for all tests that required water. The water was passed through a Culligan mixed bed system, shown in Figure 15. In this system, the water passes through several components in series: an activated charcoal filter, a cartridge filter, two mixed bed resin tanks, and another cartridge filter.

An automatic monitoring device indicates when the resin must be regenerated. Regeneration is required after approximately 350 gallons are purified because relatively high levels of total dissolved solids are in the water supply. This system was installed in the facility prior to the start of the ZS-1 experiment.[15]

Figure 15: Cartridge filter and resin tanks for deionization system.

4.2.3 Pump

A five-stage centrifugal pump is used to feed the Steam Generator and inject liquid flow into the Main Steam line is. The model is Dayton 5UXF5, and it was installed prior to the ZS-1 research. It is driven by a 0.75 HP, 115VAC electric motor. Maximum boost pressure is 93 psi. The inlet and outlet are 0.75-inch NPT connections. The nominal speed is 3450 RPM. This speed is not user controlled, so flow adjustments are performed by throttling system valves.[15]

4.2.4 Steam Generator

For this experiment, a steam generator manufactured by Kennedy Tank and Manufacturing Co. was used. The steam generator was a part of the facility prior to the ZS-1 experiment. Its capacity of 130-135 gallons. The tank was hydrostatically tested to 180 psig. During operations, pressure was limited to 135 psig, and maximum temperature is 350°F. It is of a vertically-mounted cylinderical shape; diameter is 24 inches, and height is 60 inches. Total height is approximately 72 inches if the curved heads are accounted for. It is supported by four legs at the base, and additional piping, relief valves and moisture separaters are built above the unit. It is fabricated from schedule 10 stainless steel 304 pipe. The assembly is enclosed in two-inch thick rigid fiberglass insulation. A photo of the steam generator pressure vessel and associated equipment is shown in Figure 16.[15]

Figure 16: Steam generator and blowdown drum.

The steam generator uses six electric immersion heaters. The heaters operate using 3-phase 480 VAC. Total nominal heat capacity is 157 kW. The heaters are submerged below the water surface. The sizes of the heaters differ: two are two kW capacity screw-in heaters, one is a three kW screw-in type, and the remainder are fifty-kW heaters of 8-inch flange type. Two of the fifty-kW heaters can be powered in 25-kW intervals. The third has 6.25 kW intervals. The total nominal heat input can be divided to supply a total of 2, 3, 4, 5, 6.25, 7, 8.25, 9.25, 10.25, 11.25, 12.5, 13.25, and so on up to a maximum of 157 kW. The heaters and control system were produced by Watlow Process Systems.[15]

A small moisture separator is attached to the Main Steam Line, between the Steam Generator and the Steam Line Isolation Valves. The moisture separator was manufactured by Clark Reliance. Both the Steam Generator and the moisture separator are ASME-code rated. A saturated steam/water mix from the steam generator enters the moisture separator through a 1.5-inch line. Moisture is separated out and directed back to the Steam Generator, while dry saturated steam can flow down the Main Steam Line.[15]

The steam generator includes instrumentation. Bulk temperature is measured by four thermocouples at different vertical placements penetrating the vessel. These thermocouples supply temperature information to the DAQ for different elevations within the Steam Generator. There are also two pressure transducers in the Steam Generator. There are a differential pressure transmitter which provides level indication based on reference leg and variable leg water column heights, and an absolute pressure detector to indicate Steam Generator pressure.[15]

There are locally-readable indications of Steam Generator pressure and level as well. The level indicator uses a magnetic float to provide level indication. Pressure indication is a bourdon tube pressure gage on top of the pressure vessel. The level indicator includes a reed switch, which provides heater interlock functionality. When a thermal overload is detected at the heaters or when the level float lowers below a certain level, power to the heaters is interrupted.[15]

The steam generator is connected to the main steam line, the feed line, two Kunkle pressure relief valves, a vent line, a vacuum breaker line, a drain line, an air connection which includes a quick-disconnect fitting.[15]

The relief valves are ASME-code rated. Both are set to lift at 115 psig. The discharges are directed to a blowdown drum which is partly filled with water to provide condensing action. The vent line is directed outside the laboratory space.[15]

The vacuum breaker is included to prevent drawing a vacuum inside the steam generator as the water cools and steam condenses. It comprises a ball valve, a check valve, and an air filter. The ball valve is shut while the system is in operation, to preclude leakage through the check valve. When the system is in a shutdown condition, the vacuum breaker ball valve should be open. The air filter prevents dust from entering the system and causing contamination.[15]

4.2.5 Feedwater Storage Tank

The Feedwater Storage Tank, shown in Figure 17, provides makeup water for the Steam Generator, and it also is the source of water injection into the steam line. It was installed in the facility prior to the start of the ZS-1 research. It is a horizontal cylinder with approximately 1,400 gallon volume. It was originally produced in 1952 by Wyatt Metal & Boiler Works. It is constructed of 304 Stainless Steel. The stamped ASME-API pressure rating is 88 psig; maximum temperature rating is 400°F. The inner diameter is 59 inches, and total length from end to end is approximately 122 inches. The vessel legs support the vessel approximately 18 inches above the surface beneath. The face with the ASME-API stamped plate will be referred to as the front face; the side to the right when facing toward the front head from the rear head will be referred to as the right side. Vessel penetrations include a 6-inch NPS flange beneath the front end where the pump takes suction, a 20-inch manhole at the top for personnel access, and a 4-inch NPS flange near the back end of the top.[15]

Figure 17: Feedwater storage tank and turbine.

4.2.6 Vessel Connections

The 1.5-inch flange atop the front end of the vessel provides connections for pressure relief, vacuum breaker, vent, and generic main steam line functions. A 1.5-inch pipe splits into separate lines for these features. The top line is connected to the main steam line. This can be used to pressurize the vapor space or to drain water from the main steam line. Relief valves branch from the tee as well. The two pressure reliefs are 0.5-inch Kunkle valves set to 88 psig. They are ASME-rated. They discharge to an atmospheric blowdown drum. This drum, like the Steam Generator blowdown drum, is partially filled with water to condense steam. A manual vent is also piped to the drum. A third relief valve is also directed to the drum. This is the pump discharge relief, set to 150 psig. The vacuum breaker for the Feedwater Storage Tank is larger than that of the Steam Generator, and it does not have an isolation valve. It is equipped with an air filter as well. The vacuum breaker is designed to prevent the Feedwater Storage Tank from drawing a vacuum. In the event that the pump discharge was directed to the vapor space while steam is present, steam bubble collapse could conceivably draw a rapid vacuum, resulting in damage to the pressure vessel. For this reason, the vacuum breaker should in no case be isolated, and so no isolation valve is provided.[15]

4.2.7 Air Compressor

For air tests, compressed air is supplied by a QT-15 reciprocating air compressor from Quincy compressor. A photo of the compressor is given in Figure 18. The compressor was installed before the start of the ZS-1 experiment. The compressor operates in two stages. It is air cooled, and splash lubricated. The compressor is driven by a belt coupled to the electrical motor. Air is sucked into the intake valve into the first stage cylinder where it is compressed to about 125 psig. The low pressure air then exits through the discharge valve and is routed to the second compression stage. The heat that is generated in the first compression cycle is dissipated through an intercooler of finned copper tubing. The flywheel includes fan blades to direct airflow toward the intercooler and compressor cylinders to remove heat. The low pressure air enters the second compression stage, where it is compressed to 175 psig. The high pressure air is then directed to an air cooled aftercooler. The aftercooler allows the water vapor contained in the air to condense to liquid phase. This condensate is removed by a moisture separator.

The air is directed to a 120-gallon receiver tank. One revolution of the crankshaft facilitates one complete compression cycle. A dipper connected to the connecting rod splash lubricates the internals with oil. The V configuration of the compressor head is designed to operate as a balanced unit with a total of four cylinders. Rated output is 51 CFM at 175 psig.[16]

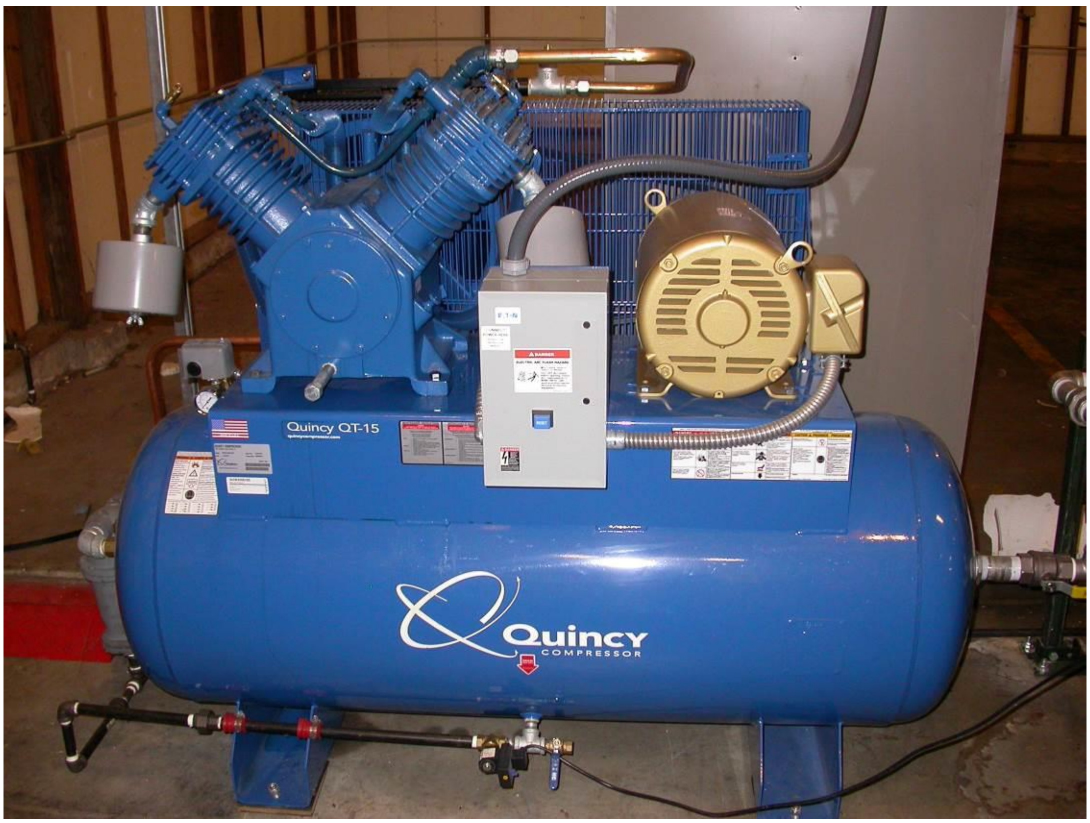


Figure 18: Facility air compressor.

The compressor is belt driven by a 15 HP Baldor electric motor. The motor is driven by a 3-phase 460 VAC power supply. The magnetic starter containing the EATON contactor and an overload relay is situated on the front of the unit. Power is supplied through a 30-A three-pole breaker. A pressure switch causes the compressor to start when the receiver pressure is less than 125 psig and to stop when the pressure reaches 175 psig. After the compressor stops, an unloader valve vents air from the pistons. This allows for easier subsequent startups.[16]

The compressor unit is secured to the floor with 0.5-inch diameter wedge anchors. The nylock nuts were installed loosely to prevent stresses to the compressor and concrete floor due to the vibrations occurring in normal operation. Rubber and cork insulation pads were installed under the compressor feet to dampen vibrational stresses to the piping and building foundation.[16]

During operation, large amounts of moisture condense inside the receiver tank. A solenoid operated drain valve was installed to automatically drain this condensate at 45-minute intervals. The outlet of the valve is 0.5-inch black iron piping. It directs the condensate outside the building.[16]

The compressor intake is equipped with two 10-micron inlet air filters and silencers to remove large particulates. A 5-micron particulate filter and a 0.01 micron coalescing oil filter are installed downstream of the receiver tank. The filter housings are both aluminum, with 1.5-inch NPT threaded connections. The filters feature automatic condensate drain valve and indicators to display when filter changeout is needed. This filter combination provides a clean and relatively oil-free air supply for the experimental facility.[16]

Following the filters, the air travels through a refrigerated air dryer. The Quincy QPNC-100 dryer lowers the temperature of the compressed air to 39°F, resulting in condensation of entrained moisture. This moisture is piped to outside of the laboratory space. Operation of the dryer is completely automatic; it maintains a dew point of 39°F which results in an estimated relative humidity of 20%. The dryer inlet and outlet are 1.5-inch NPT connections. Electrical power is 115VAC with a 20-A plug.[16]

Downstream of the air dryer, air pressure is regulated by a 1.5-inch Speedaire relieving type pressure regulator. After the regulator, the air supply line branches into hose connections and the main line, which connects to the steam generator. For air tests, the regulated air pressure is directed to the steam generator. For these tests, the Steam Generator was drained of all water to maximize the air volume available for testing.[16]

4.2.8 Data Acquisition System

The Data Acquisition System comprises both the hardware and software that interpret and record data that is produced in an experiment. This includes thermocouple, pressure transmitter, flowmeter, load cell, and turbine speed data. The Data Acquisition System was installed before the ZS-1 experiment began. However, the PC was upgraded at the start of this testing, and the software was modified to accommodate newly installed instruments.[15]

4.2.8.1 Hardware

Instrument signals are received by a National Instruments SCXI system connected to a PC. The SCXI, PC, and converter equipment are shown in Figure 19. The SCXI consists of an SCXI-1000 chassis with four installed modules: two SCXI-1102 module, one SCXI-1102B module, and one SCXI-1102C module. These models are differentiated by their respective lowpass filters. The 1102 bandwidth is 2 Hz, the 1102B bandwidth is 200 Hz, and the 1102C bandwidth is 10 kHz. Each of these modules has 32 voltage/thermocouple inputs, and a cold junction sensor input from the terminal block. Each channel has an independent amplifier and filter. Each module connects to its instruments using an SCXI-1303 terminal block and the necessary wiring.[15]

Figure 19: Data acquisition control station.

The PC connects to the SCXI-1000 chassis through a shielded cable. The cable connects from the back of one of the SCXI-1102 modules to an NI PCIe-6341 card in the PC. The analog input signals are multiplexed into a single channel between the chassis and the PC. Most of the multiplexing is handled using the LabVIEW software with DAQmx drivers, and is transparent to the user. However, configuration can be optimized to prevent unexpected phenomena such as extra settling time due to channel-to-channel gain transitions. Best practice is to group like signals together (e.g. avoid putting a small signal on channel 0, a large signal on channel 1, a small signal on channel 2, etc.).[15]

The current hardware permits thermocouple wire to be connected directly to the terminal blocks. However, current loops cannot. Instruments that use 4-20 mA analog outputs require intermediate treatment. This is performed by placing a 249-Ohm resistor in the current loop. Normally, a 250-Ohm resistor would be used to produce a 1-5V signal. A 249-Ohm resistor was used here instead to allow more margin for offscale high signals. Additionally, a 249-Ohm resistor would be used internally in the 1102 module to make it a 4-20 mA channel. The current from each instrument is passed through its connected resistor; the voltage drop is measured by the SCXI system by connecting both ends of the resistor to the input terminals for that specific channel.[15]

4.2.8.2 Software

The Data Acquisition system runs LabVIEW 2015 32-bit under 64-bit Microsoft Windows 7 Professional with SP1. The DAQmx drivers are version 15. The LabVIEW Virtual Instrument (VI) was designed to be frugal with CPU resources while retaining the required functionality. Figure 20 shows the graphical user interface for the data acquisition system.[15]

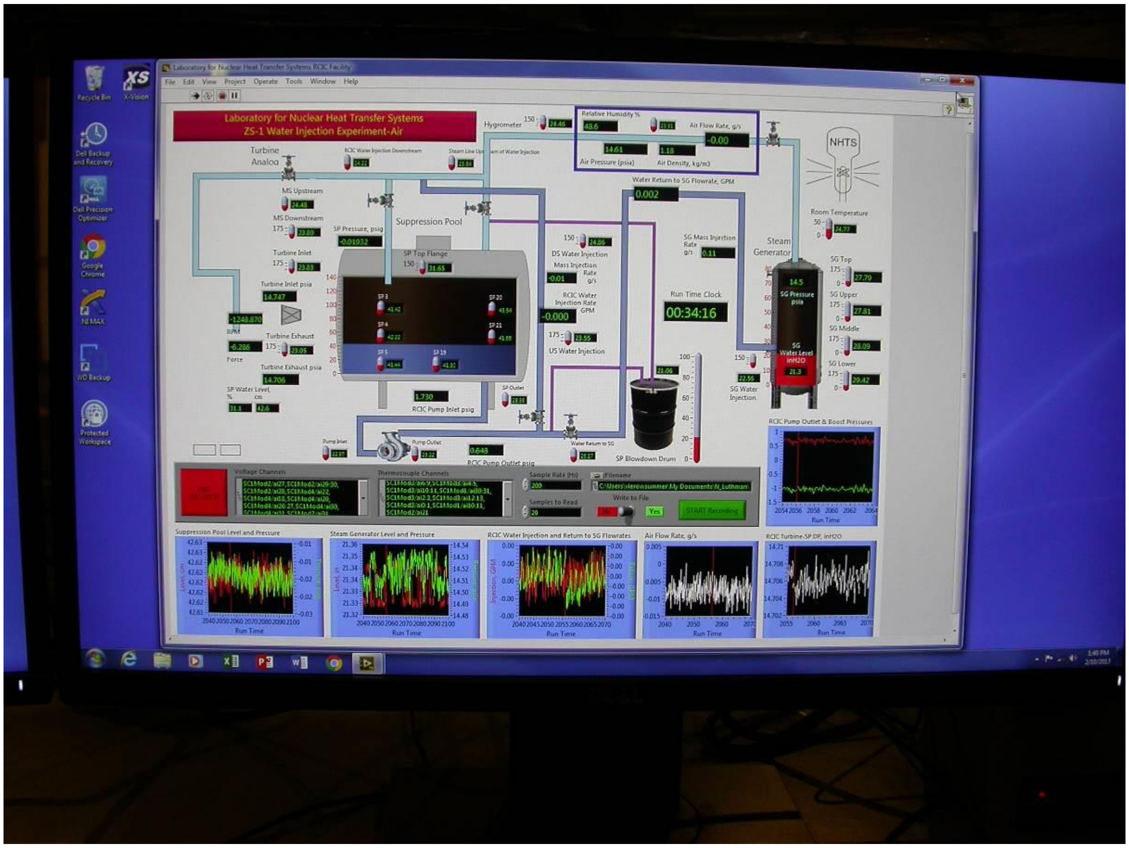


Figure 20: LabVIEW graphical user interface.

The LabVIEW VI for this experiment was based on those used for previous experiments performed in the Laboratory for Nuclear Heat Transfer Systems, primarily the RCIC Suppression Chamber Stratification experiments. Similar conventions are used in the interface and data logging. It also incorporates data averaging for each channel, along with standard deviation of each sample set. This assists in determining uncertainty as well as characterizing the amount of rapid fluctuations occurring in a channel on very short time spans.[15]

For each channel, a collection of samples is obtained and averaged. Over a span of one second, 200 samples are collected and averaged over 20 groups. This yields 10 records per second. The averaging function reports both the mean and the standard deviation. These will be in units of temperature for thermocouples, and units of voltage for all other instruments. The mean and standard deviation are recorded, and then the mean value is passed to a code block containing the calibration profile for that particular channel. The raw voltage is converted to a fraction from 0 to 1 of the full scale for the instrument. A signal of 4 mA corresponds to 0, and a signal of 20 mA corresponds to 1. Then, the obtained value is passed to a code block transforming it with the set range of the instrument. This reports the value in units appropriate to the instrument, i.e. 20 psia, 1.0 gpm, etc. Thermocouples do not require this processing, because DAQmx implements all processing internally. Additional processing may be needed for some instruments. One example would be a transformation of differential pressure readings into vessel water levels. Additionally, some unit conversions may be necessary, especially if the value of one instrument depend upon a reading from another instrument. In all cases, the final computed value before motivation each instrument is recorded.[15]

Steam flow values from vortex flowmeter are an example of a data point which is dependent upon other values. The instrument incorporates pressure and temperature compensations, and steam density is computed using a dll from the X Steam Tables. For this instrument, some intermediate values are recorded as well.[15]

Aside from logging data, the LabVIEW VI displays a large amount of operational data to the user in the form of numerical indicators and charts. These indicators are superimposed on a graphic of the ZS-1 Turbine Experiment. This allows the user view the live data, and also provides information that can assist in determining valve positions and other manual controls. The VI can be seen at remote operating stations. The two remote operating stations are the water injection control station, Figure 21, and the air/steam injection control station, Figure 22.[15]

Figure 21: Water injection control station.

Figure 22: Air/steam injection control station.

4.3 Instrumentation

4.3.1 General

Instruments near the steam generator are given in Figure 23. The instruments in vicinity of the Feedwater storage tank are featured in Figure 24. Instrumentation on or near the turbine are in Figure 25. A list of instruments is given in Table 1.

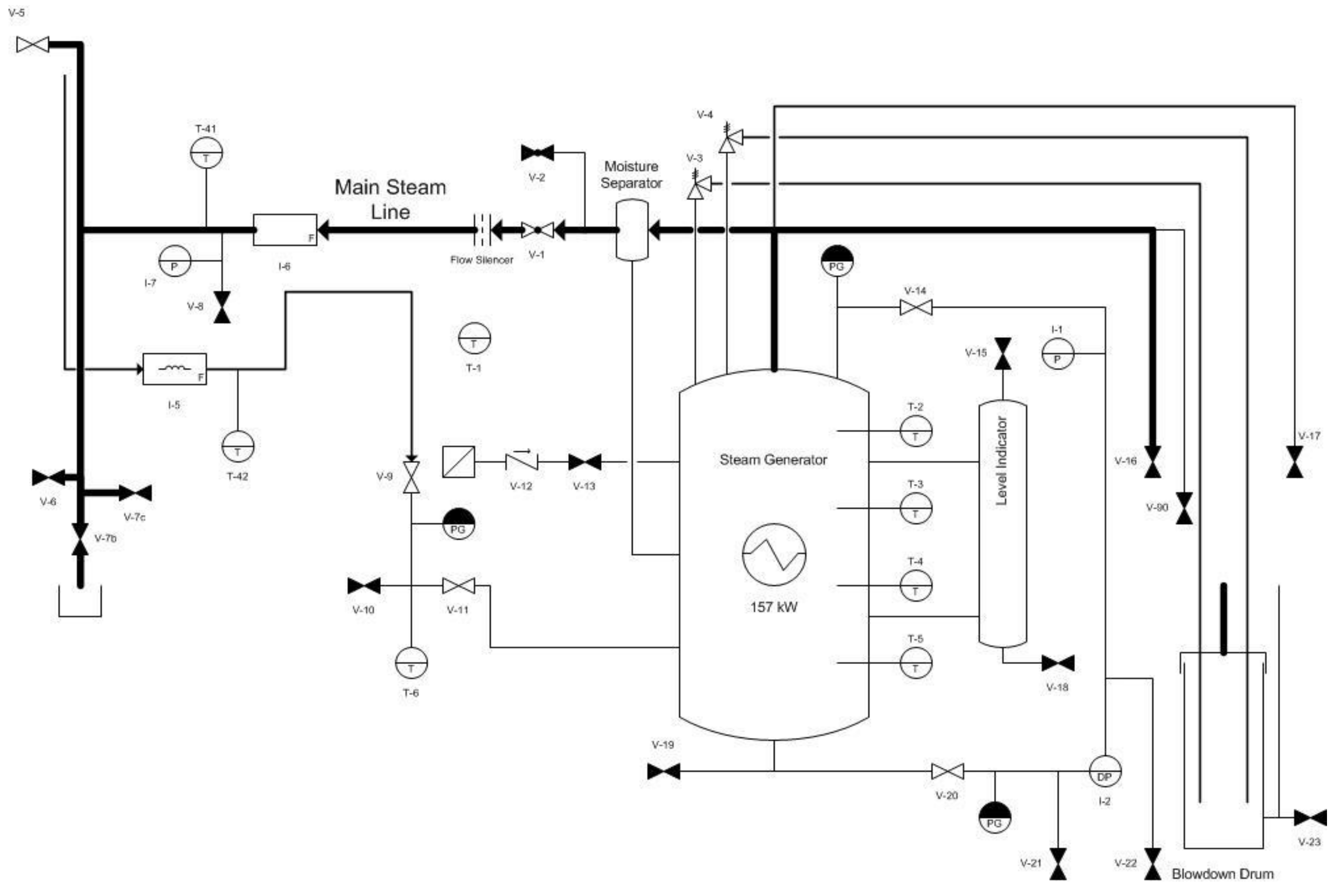


Figure 23: Steam generator with associated piping and components.

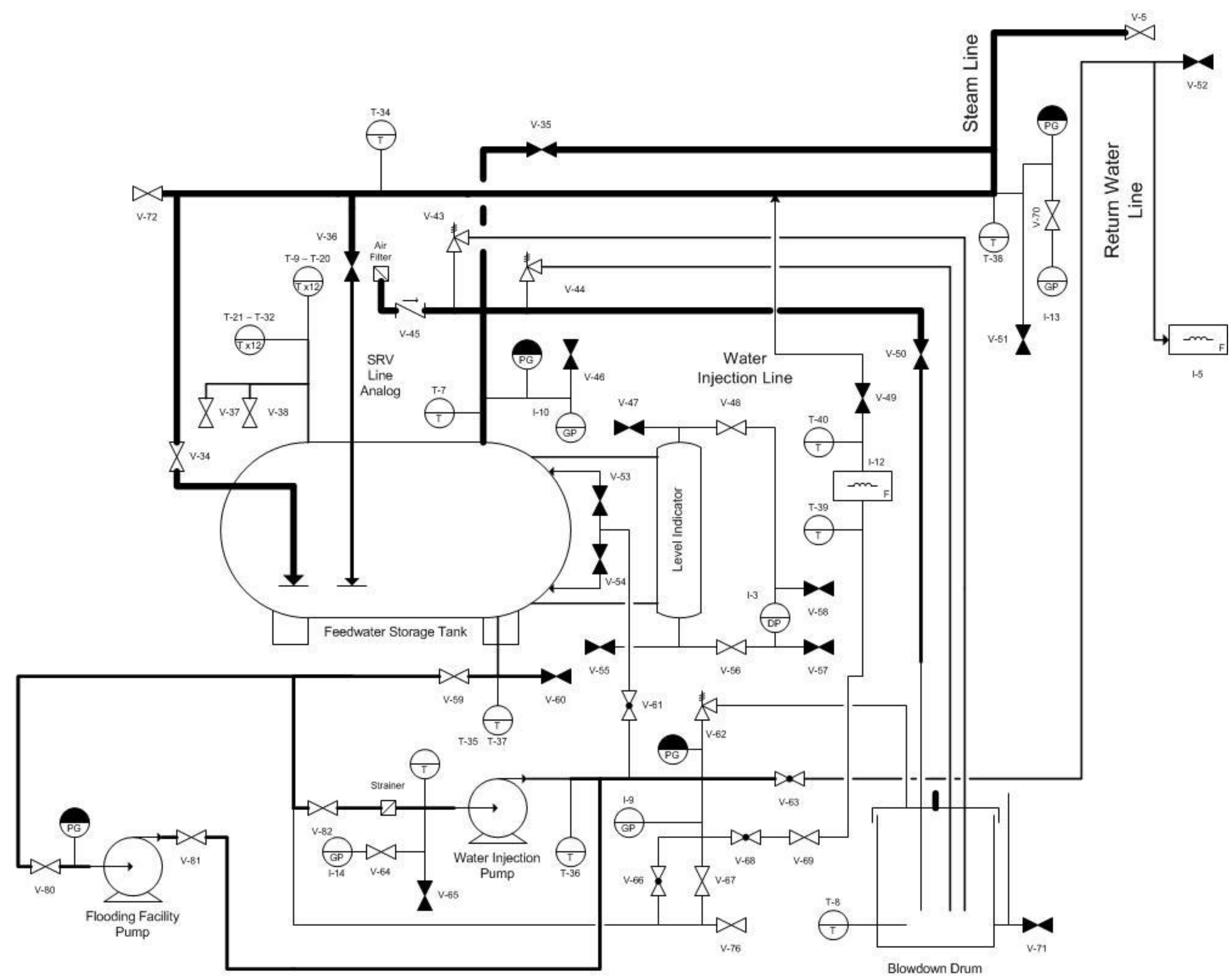


Figure 24: Feedwater storage tank with associated piping and components.

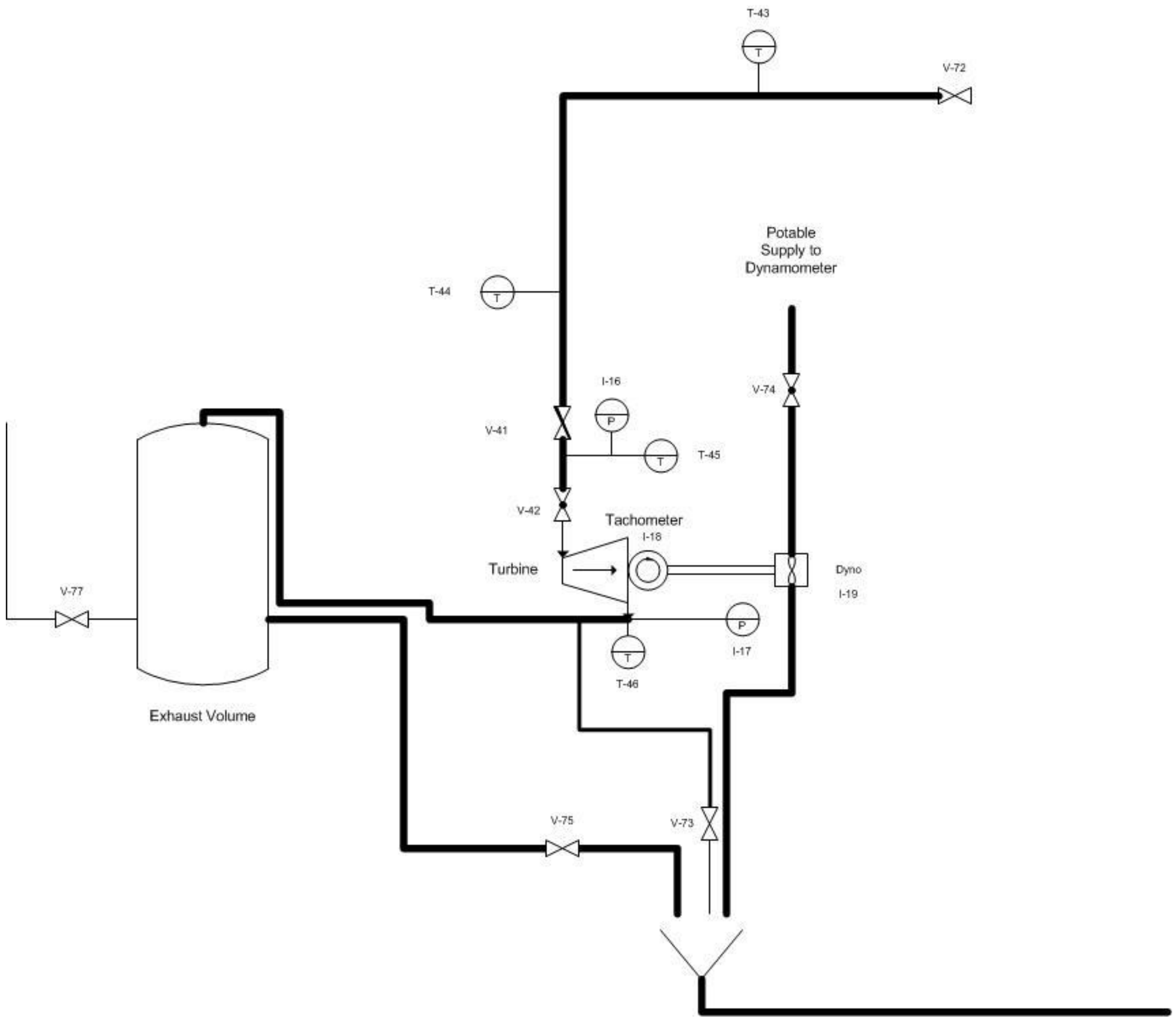


Figure 25: Turbine with associated piping and components.

Table 1: List of instruments.

Instrument	Manufacturer	Model	Range	Instrument Error
T-1 to T-46	Omega	Type T; SLE	0-350°C	±0.5°C or 0.4% of reading
I-1	Honeywell	ST3000 STA940	0-150 psia	±0.10% of upper range value (URV)
I-2	Honeywell	ST3000 STD924	0-110 inH2O	±0.075% of URV
I-3	Honeywell	ST3000 STD924	0-80inH2O	±0.075% of URV
I-5	Yamatake	MagneW 3000 PLUS	0-5 GPM	±0.5% of rate
I-6	Foxboro	83W	0-2400 Hz	±1% of reading for flow rates in accurate range
I-7	Honeywell	STA3000 STA940	0-130 psia	±0.10% of URV
I-9	Dwyer	682-3	0-250 psig	±0.13% of URV
I-10	Dwyer	673-7	0-100 psig	± 0.25% URV
I-12	Badger	M2000	0-1 GPM	± 0.25% of rate
I-14	Dwyer	673-7	0-100 psig	± 0.25% of URV
I-16	Rosemount	3051CA	0-75 psia	± 0.04% of URV
I-17	Rosemount	3051CA	0-75 psia	± 0.04% of URV
I-18	Monarch	ACT-3X	5-5,000 RPM	± 0.001% of reading
I-19	Omega	LC-101	0-25 lbf	± 0.04% of URV

4.3.2 Flowmeters

Fluid flow was monitored by three flowmeters in this experiment. A Foxboro 83 vortex flowmeter was used in the steam/air line, and a Badger M2000 magnetic flowmeter was used on the water injection line. A Yamatake MagneW3000 PLUS magnetic flowmeter was used to monitor water flowrates when feeding the steam generator.[15]

4.3.3 Vortex Flowmeter

A Foxboro 83W water-style vortex flowmeter is installed in the 1.5-inch steam line. It is located approximately 100 inches downstream of the Main Steam Cutout Valve. This length was to allow at least 30 pipe diameter lengths, which are needed to achieve developed flow and an accurate measurement. The flowmeter transmits a standard analog 4-20 mA signal to the DAQ. The maximum steam flow that can be registered is approximately 96 g/s. The flowmeter can measure both steam and air flow. Pressure and temperature measurements are required to calculate the flow value from the signal of the meter. These are located 6 and 8.25 inches, respectively, downstream of the flowmeter.[15]

Vortices are generated within the flowmeter when the fluid encounters the installed baffle. The baffle causes vortex shedding, and the shedding frequency is measured by the instrument using a piezoelectric differential pressure sensor. The shedding frequency is directly related to flow rate. The vortices shed alternately on either side of the obstruction. This results in differential pressures across the sensor that vary with time at the frequency of the shedding. [17] The properties of the fluid, measured immediately downstream of the meter, are used to determine density and the correction factors of the meter so that the flow conditions can be characterized. A temperature correction factor corrects for thermal expansion in the meter material.

4.3.4 Water Injection Flowmeter

Magnetic flowmeters operate by sending a conductive liquid through a magnetic field. Magnetic induction results, generating a voltage perpendicular to both the magnetic field and the flow of the liquid. This magnetic field is picked up by electrodes placed within the detector. The spacing of the electrodes and the magnetic field are known, and so the voltage will be directly proportional to the flow velocity.[15, 18]

Two magnetic flowmeters were used. The first is a Badger M2000, which was used to measure lower flowrates injected into the steam flow. It employs a 15-mm flange connection, and can detect flowrates from 0.02 to 5 GPM. Accuracy for this meter can exceed ± 0.25%. It can also accept process fluid temperatures up to 150°C. The detector requires a minimum fluid conductivity of 5 micromhos/cm.[18] Temperature measurements are taken 6 inches upstream and 2 inches downstream of the detector.[15]

The second magnetic flowmeter is a Yamatake MagneW 3000 PLUS detector with a 0.5-inch NPS wafer-style detector. The system comprises an MGG18 detector and a MGG14C converter. The detector can measure flowrates up to 28.01 GPM with an error of ±0.2% to ±0.5%. The minimum liquid conductivity for the detector is 3 micromhos/cm.[19] The range is set to 0-5 GPM for the 4-20 mA analog output signal. Liquid temperature is measured 4 inches downstream of the meter to more fully characterize the mass flow.[15]

4.3.5 Pressure Transmitters

The turbine facility uses five different models of pressure transmitter. These models are Dwyer 682-3, Dwyer 673-7, Honeywell ST3000 STA940 absolute pressure transmitter, Honeywell ST3000 STD924 differential pressure transmitter, and two Rosemount 3051C absolute pressure transmitters. In addition to the pressure transmitters, there are several analog pressure gages used throughout the facility. The bourdon tube gages are not used for data collection. Rather, they are used as operational aids.[15]

The Dwyer 673-7 pressure transmitters come with a fixed range of 0 to 100 psig, and the 682-3 registers 0 to 250 psig. Both transmit an analog 4-20 mA signal. Three of these Dwyer gage pressure transmitters are installed in the facility. One is at the Water Injection Pump discharge, one is at the Water Injection Pump suction, and a third is in the Feedwater Storage Tank vapor space. No adjustments are available for these instruments, so their transmitted data was used only to monitor pressure during operation, not to collect precision measurements.[15]

The Honeywell pressure transmitters can interface with the Honeywell Smart Field Communicator. There are multiple benefits to this tool, such as quick connections to the transmitter, rapid output range adjustment, and simple calibration procedures. Adjustment of ranges is done with a few button presses, and no potentiometers adjustments are necessary. Transmitter output can be set to Manual Loop to hold specific values, which aids in calibrating the 4-20 mA current loop.[15]

The STD924 model can measure differential presures from -20 to +400 inH20. The detectors can withstand high common-mode case pressure, and so these transmitters are very useful for measuring liquid levels in pressure vessels. One STD924 monitors Steam Generator water level and the other monitors Feedwater Storage Tank level. [15]

The STA940 model reads absolute pressure from 0 to 500 psia. Turndown adjustments are used to read lower pressures. One measures steam generator pressure, a second measures pressure in the vapor space of the Feedwater Storage tank, and another measures Main Steam Line pressure downstream of the vortex flowmeter. The Steam Generator pressure transmitter transmits from 0 to 150 psia, the Feedwater Storage Tank transmits from 0 to 100 psia, and the Main Steam line transmits from 0 to 130 psia.[15]

The Rosemount 3051C transmitters can transmit from 0 to 150 psia. The 3051C pressure transmitters installed in the system are calibrated from 0 to 75 psia. The instrument overpressure limits are 1500 psia. They can be adjusted and calibrated using the Emerson 475 Field Communicator, which provides benefits similar to the Honeywell Smart Field Communicator. One transmitter is installed in the Turbine inlet plenum near the nozzle inlet, and the second is installed in the turbine exhaust space near the nozzle exhaust.[15]

4.3.6 Thermocouples

For this experiment, thermocouples are used to measure temperatures at several locations. There are six thermocouple sensing points along the steam line between the vortex flowmeter and the turbine steam inlet nozzle, and another is installed the turbine exhaust region. The nozzle inlet sensor port is directly next to the nozzle inlet valve. The exhaust sensor is in the bottom of the exhaust portion of the casing, also near the nozzle exhaust. Five thermocouples monitor water temperature along the line from the Feedwater Storage Tank, through the Feedwater Injection Pump, and into the main steam line. Four thermocouples monitor Steam Generator internal temperatures. One monitors the feed temperature just before injection to the Steam Generator, another is just downstream of the Yamatake flowmeter, and one monitors laboratory ambient temperature.[15]

All of these thermocouples are Omega type T thermocouples with special limits of error. The error limit of these thermocouples is the greater of ±0.5°C, or ±0.4% of the total reading. This thermocouple type operates using copper-constantan wire. All are ungrounded, and have stainless steel sheathing. Lengths vary from 12 to 120 inches. Diameters range from 0.032 inches to 0.062 inches. The thermocouples used here are ungrounded. In this case, it is recommended that they be ground referenced on the negative terminal. This has been enabled for all thermocouples in the facility.[15, 20]

4.3.7 Vessel Instrumentation

Several instruments are installed to provide indication of conditions within the Feedwater Storage Tank. These include 23 thermocouples for temperature indication. Thermocouples and internal piping are supported by a support structure within the vessel. This support structure is fabricated from stainless steel strut channel and stainless steel threaded fasteners. The feed of the support structure are stainless steel blocks padded with silicone rubber pads. To ensure adherence to the ASME-API certification stamp, there are no mechanical attachments coupling the support structure to the vessel.[15]

An Orion magnetic level indicator is located at the front head to provide visual water level indication. A Honeywell differential pressure transmitter is used to take a more precise measurement of water level; this level is transmitted to the data acquisition system. The high pressure side is connected to a reference column which is connected to the top of the pressure vessel vapor space. The low pressure side is connected to the liquid section of the vessel. Vessel level is obtained by measuring the difference in head between the reference leg and the variable leg. A Dwyer 673-7 gauge pressure transmitter is installed in the 1.5-inch flange that monitors vessel pressure. [15]

4.3.8 Tachometer

Turbine rotational speed is detected by a Monarch ROLS-W laser sensor. In Figure 26, the sensor is visible at the bottom of the photograph, and the red laser dot is visible on turbine shaft. The sensor signal is transformed into a 4-20 mA signal and transmitted to the DAQ by a Monarch ACT-3X tachometer/transmitter, shown in Figure 27.

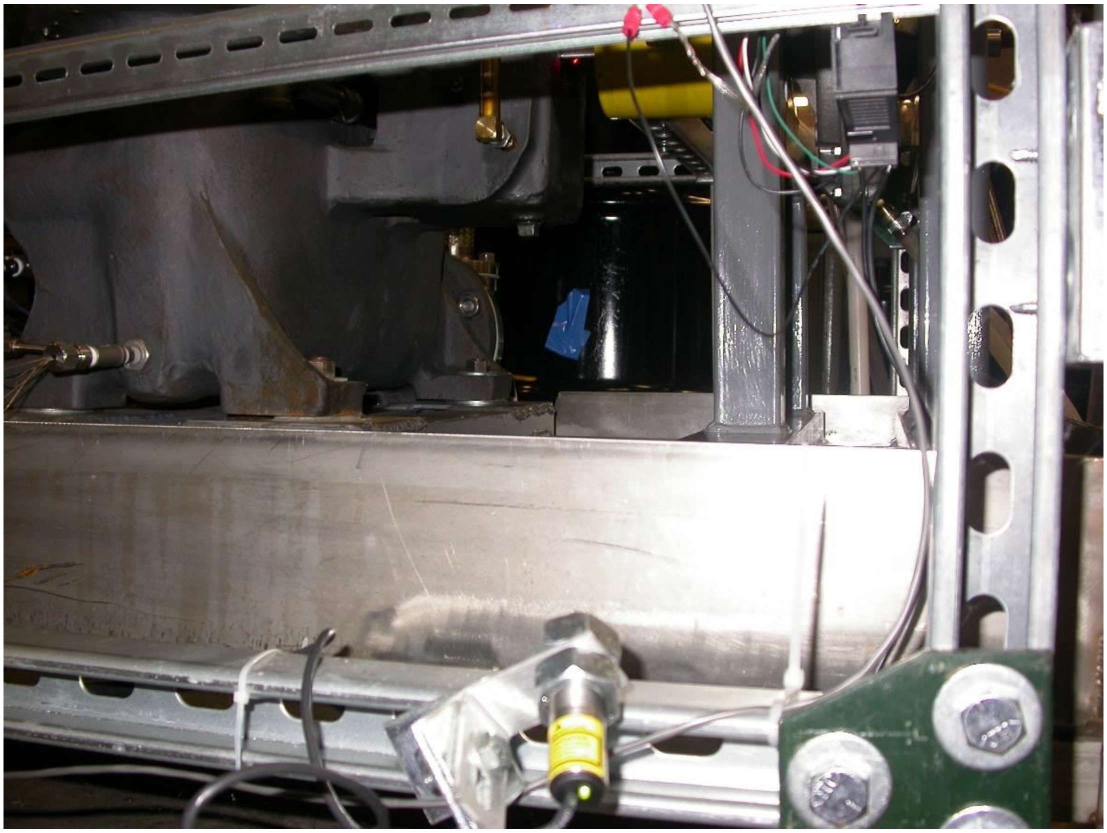


Figure 26: Monarch ROLS-W Tachometer sensor.

Figure 27: Tachometer display.

4.3.9 Dynamometer

The turbine is loaded using a water brake dynamometer. The Stuska XS-19 model was used for this experiment. The dynamometer, like the turbine, is supported by the test platform. The instrument functions by using the viscous shear of water.

The dynamometer shaft spins at the same speed as the turbine shaft. This causes the water brake, which can be likened to a flywheel, to turn within the dynamometer casing. The dynamometer is loaded by directing water flow to the casing. The water brake imparts a shear tensor to the water, and the water transmits shear to the outer casing. An Omega LC101-25 load cell is attached to a point on the outer casing. The dynamometer is shown in Figure 28, and the load cell is shown in Figure 29.

The load cell measures the tensile force between the dynamometer outer casing and the test frame. Together with the distance from the center of the shaft, this force can yield a moment. This moment can combine with the shaft RPM to produce the power generated by the turbine. Equations for these calculations are given in Eq. (2) and Eq. (3) on page 86.

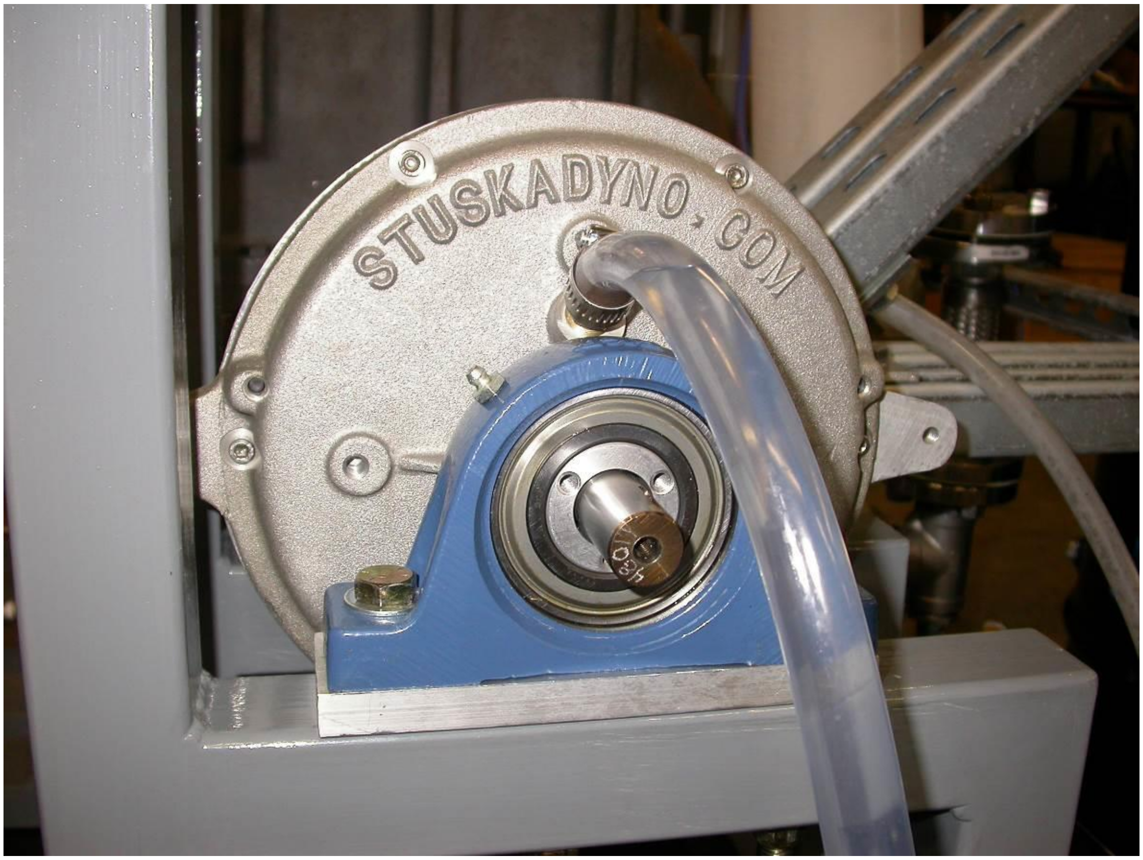


Figure 28: Dynamometer, with water supply tubing attached.

Figure 29: Load cell attachment to dynamometer.

The turbine, on test platform, with inlet and exhaust piping and instrumentation installed, is shown in Figure 30.

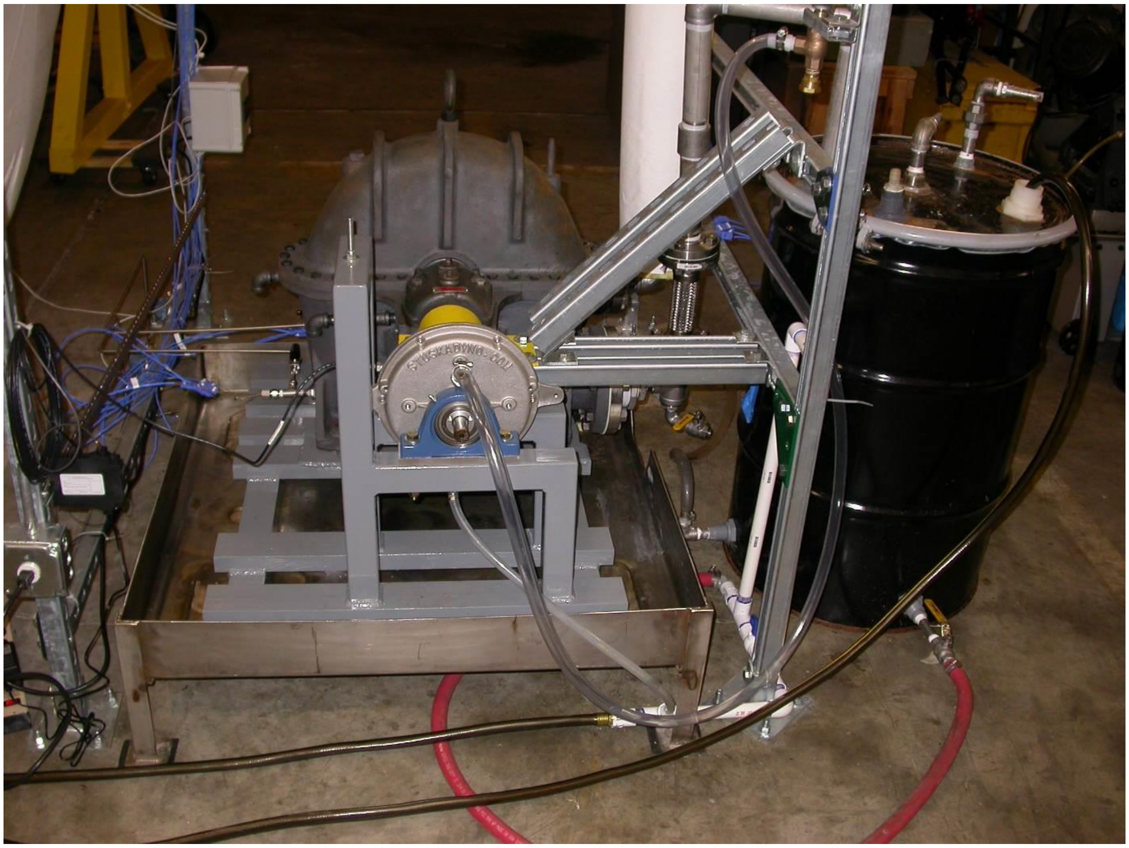


Figure 30: Turbine, with dynamometer attached.

4.4 Calibration

To provide confidence in the data set, the instruments must have some sort of calibration. To that end, calibrations have been carried out where applicable.[15]

The Honeywell ST3000 Series 900 transmitters used for steam line pressure, steam generator pressure, steam generator level, and feedwater storage tank level were calibrated in two phases: first sending them to calibrate their pressure readings; and secondly, performing a signal calibration on their 4-20 mA outputs to implement in the data acquisition software. Once the pressure measurements were calibrated, signal calibration profiles were developed. Signal calibration was done using the same methods for pressure transmitters and magnetic flowmeters. A small LabVIEW VI was developed for this task. It uses a two-point calibration. The Honeywell Smart Field Communicator was used to set the transmitters to transmit 100% of their full-scale 20 mA signals. These signals were recorded by the software and time-averaged for a span of greater than 100 seconds. Then, the instruments were set to output their lowest signal; this is 0%, or 4 mA. The signal was again recorded and time-averaged for greater than 100 seconds. Full linearity straight through from the measurement to the analog output to the analog to digital conversion in the DAQ, this two-point calibration is sufficient to fully derive the curve.[15]

Two-point calibrations can be described using an equation of a line, given in Eq. (1).

$$y = a \times (x - b) \tag{1}$$

Calibration data for instruments used in the experiment are given in Table 2.

Table 2: Calibration profiles for instruments used in the experiment.

Instrument	Instrument Name	a	b
I-1	SG Absolute Pressure Transmitter	0.2510	0.9965
I-2	SG Level Transmitter	0.2510	0.9968
I-3	Feedwater Storage Tank level	0.2510	0.9967
I-5	SG Return Flowmeter	0.2509	0.9958
I-6	Main Steam Line Flowmeter	0.251	0.991
I-7	Main Steam Line Pressure Transmitter	0.25102	0.99650
I-12	Water Injection Flowmeter	0.25112	0.99662
I-16	Turbine Inlet Pressure Transmitter	0.2510	0.9958
I-17	Turbine Exhaust Pressure Transmitter	0.2508	0.9962
I-18	Tachometer	0.251023	0.994734
I-19	Load Cell	0.2513	1.001

The load cell has a range of 0-25 lbf. Calibration data was collected for 0% and 100% loading. For the zero setpoint, the load cell was suspended from a hanger with both eyebolts installed, and no weight suspended. For 100% loading, a set of interlocking test weights was suspended from the bottom eyebolt. The test weights, plus the weight of the hanger, provide a total of 25 lb of mass. This two-point calibration was implemented into the LabVIEW VI. The weights and tolerances are given in Table 3.

Table 3: Load cell test weights.

Mass	Quantity	Tolerance
2 lb	2	±0.0002 lbs.
10 lb	2	±0.001 lbs.
1 lb	1	±0.01 lbs.

The Foxboro vortex flowmeter calibration procedure involves calculation of an expected upper range frequency, temporary setting of DIP switches, and removal of electronics from the flowmeter body. The sensor unit is disconnected, and a function generator is installed in its place. The function generator is operated at the calculated upper range frequency, and then at zero while making adjustments to potentiometers. At this point, the temporary connections must be removed, the electronics returned to the housing, and the DIP switches set. For the steam setup, an upper range frequency of 2400 Hz was used. This was determined to be an upper range frequency that would allow the entire band of desired flowrates to be detected. Additionally, the function generator available does not isolate its signal as required by the transmitter. Instead, its signals are ground-referenced. In order to allow the signals to float, the function generator was plugged into an uninterruptible power supply (UPS). The UPS was then unplugged from the wall to remove the ground reference during operation. During the procedure, frequency was read by an oscilloscope to verify that the reported frequency on the function generator was within tolerance.[15]

The LabVIEW packages are equipped to read thermocouples. It is assumed that the thermocouples maintained their Special Limit of Error tolerances with minimal drift or degradation. With regard to thermocouples, the necessary tasks are to ensure the electrical connections are made properly and that the DAQ hardware reads the signals properly. The current DAQ card is an NI PCIe-6341 X Series data acquisition card. This card falls under a two-year calibration compliant with ANSI/NCSL Z540-1-1994. This is the NI "Compliant Calibration" service level.[15]

Example calibration certificates are given in the following figures: Figure 31 and Figure 32 are the certificates from the turbine inlet and outlet pressure transmitters, Figure 33 is the tachometer calibration certificate, and Figure 34 is the load cell calibration certificate.

EMERSON
Process Management

23 June, 2016

Emerson Process Management
Rosemount Inc.
8200 Market Blvd
Chanhassen, MN U.S. 55317-9786

Calibration Data Sheet Consistent with ISO 10474 3.1 or EN 10204 3.1

Customer Information	Manufacturer Information
Name: TEXAS A AND M UNIVERSITY **PO:** Ref 503123	**Sales Order:** 4610121 **Line:** 2

Device Information	Calibration Information
Device Type: Pressure Transmitter **PDTag:** **Serial No:** 2831256 **Model No:** 3051CA2A22A1AB4Q4 **Module Serial No:** 6557803 **Output:** Linear **Device ID:** 6557803	**Factory:** CHANHASSEN, MN, USA **Station Name:** CHAN_PRESSURE_CALIBRATION_15 **Operator ID:** 34934 **Calibration Date:** 6/23/2016 6:05:26AM Internal Ref # 12182729

Equipment Used

EqNumber:	EqName:	CalDueDate:
E3-56134	Multimeter	7/20/2016 8:50:00AM
E3-58598	Load Box	4/20/2017 1:45:00PM
P3-54296	Pressure Controller	8/2/2016 11:24:00AM

Calibration Data

Range: 0.000 TO 75.000 PSI

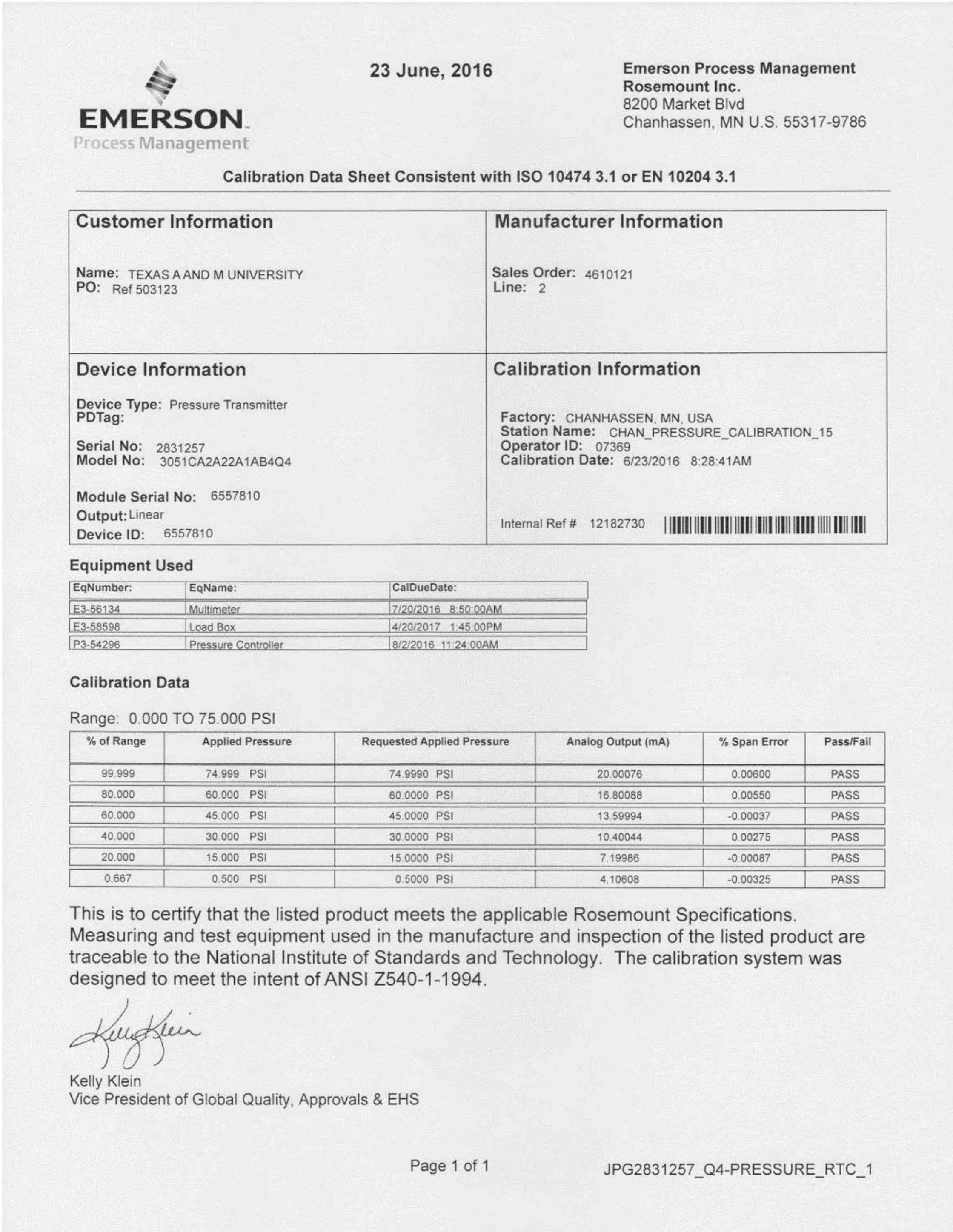
% of Range	Applied Pressure	Requested Applied Pressure	Analog Output (mA)	% Span Error	Pass/Fail
99.999	74.999 PSI	74.9990 PSI	20.00002	0.00138	PASS
80.000	60.000 PSI	60.0000 PSI	16.80066	0.00413	PASS
60.000	45.000 PSI	45.0000 PSI	13.60026	0.00163	PASS
40.000	30.000 PSI	30.0000 PSI	10.40054	0.00338	PASS
20.000	15.000 PSI	15.0000 PSI	7.20040	0.00250	PASS
0.667	0.500 PSI	0.5000 PSI	4.10682	0.00138	PASS

This is to certify that the listed product meets the applicable Rosemount Specifications. Measuring and test equipment used in the manufacture and inspection of the listed product are traceable to the National Institute of Standards and Technology. The calibration system was designed to meet the intent of ANSI Z540-1-1994.

Kelly Klein
Vice President of Global Quality, Approvals & EHS

Page 1 of 1 JPG2831256_Q4-PRESSURE_RTC_1

Figure 31: Turbine inlet pressure transmitter calibration certificate.



EMERSON.
Process Management

23 June, 2016

Emerson Process Management
Rosemount Inc.
8200 Market Blvd
Chanhassen, MN U.S. 55317-9786

Calibration Data Sheet Consistent with ISO 10474 3.1 or EN 10204 3.1

Customer Information	Manufacturer Information
Name: TEXAS A AND M UNIVERSITY PO: Ref 503123	Sales Order: 4610121 Line: 2
Device Information	**Calibration Information**
Device Type: Pressure Transmitter PDTag: Serial No: 2831257 Model No: 3051CA2A22A1AB4Q4 Module Serial No: 6557810 Output: Linear Device ID: 6557810	Factory: CHANHASSEN, MN, USA Station Name: CHAN_PRESSURE_CALIBRATION_15 Operator ID: 07369 Calibration Date: 6/23/2016 8:28:41AM Internal Ref # 12182730

Equipment Used

EqNumber:	EqName:	CalDueDate:
E3-56134	Multimeter	7/20/2016 8:50:00AM
E3-58598	Load Box	4/20/2017 1:45:00PM
P3-54296	Pressure Controller	8/2/2016 11:24:00AM

Calibration Data

Range: 0.000 TO 75.000 PSI

% of Range	Applied Pressure	Requested Applied Pressure	Analog Output (mA)	% Span Error	Pass/Fail
99.999	74.999 PSI	74.9990 PSI	20.00076	0.00600	PASS
80.000	60.000 PSI	60.0000 PSI	16.80088	0.00550	PASS
60.000	45.000 PSI	45.0000 PSI	13.59994	-0.00037	PASS
40.000	30.000 PSI	30.0000 PSI	10.40044	0.00275	PASS
20.000	15.000 PSI	15.0000 PSI	7.19986	-0.00087	PASS
0.667	0.500 PSI	0.5000 PSI	4.10608	-0.00325	PASS

This is to certify that the listed product meets the applicable Rosemount Specifications. Measuring and test equipment used in the manufacture and inspection of the listed product are traceable to the National Institute of Standards and Technology. The calibration system was designed to meet the intent of ANSI Z540-1-1994.

Kelly Klein
Vice President of Global Quality, Approvals & EHS

Page 1 of 1

JPG2831257_Q4-PRESSURE_RTC_1

Figure 32: Turbine exhaust pressure transmitter calibration certificate.

Certificate of Calibration

Model:	ACT3X-1-1-4-2-0-0	Serial Number:	1483312
Date Calibrated:	05/23/2016	Calibration Expires:	11/23/2017
Temperature:	22 (Celsius)		
Scale:	1	Pulses Per Revolution:	1

NIST Reference: Frequency WWVB

This instrument has been calibrated using standards and instruments which are traceable to the National Institute of Standards and Technology and meet the requirements of MIL-STD-45662A. This certificate may only be duplicated in full unless approved by us in writing. This certificate is only valid for the instrument mentioned above and the modes listed below. The instrument was found to be within specification.
Equipment used in calibration:

MANUFACTURER	MODEL #	SERIAL #	CALIBRATION DATE	EXP DATE
Tektronix	AFG3021	C020836	12/29/2015	12/29/2016

Tachometer Calibration (The generated signal is measured by the Instrument)

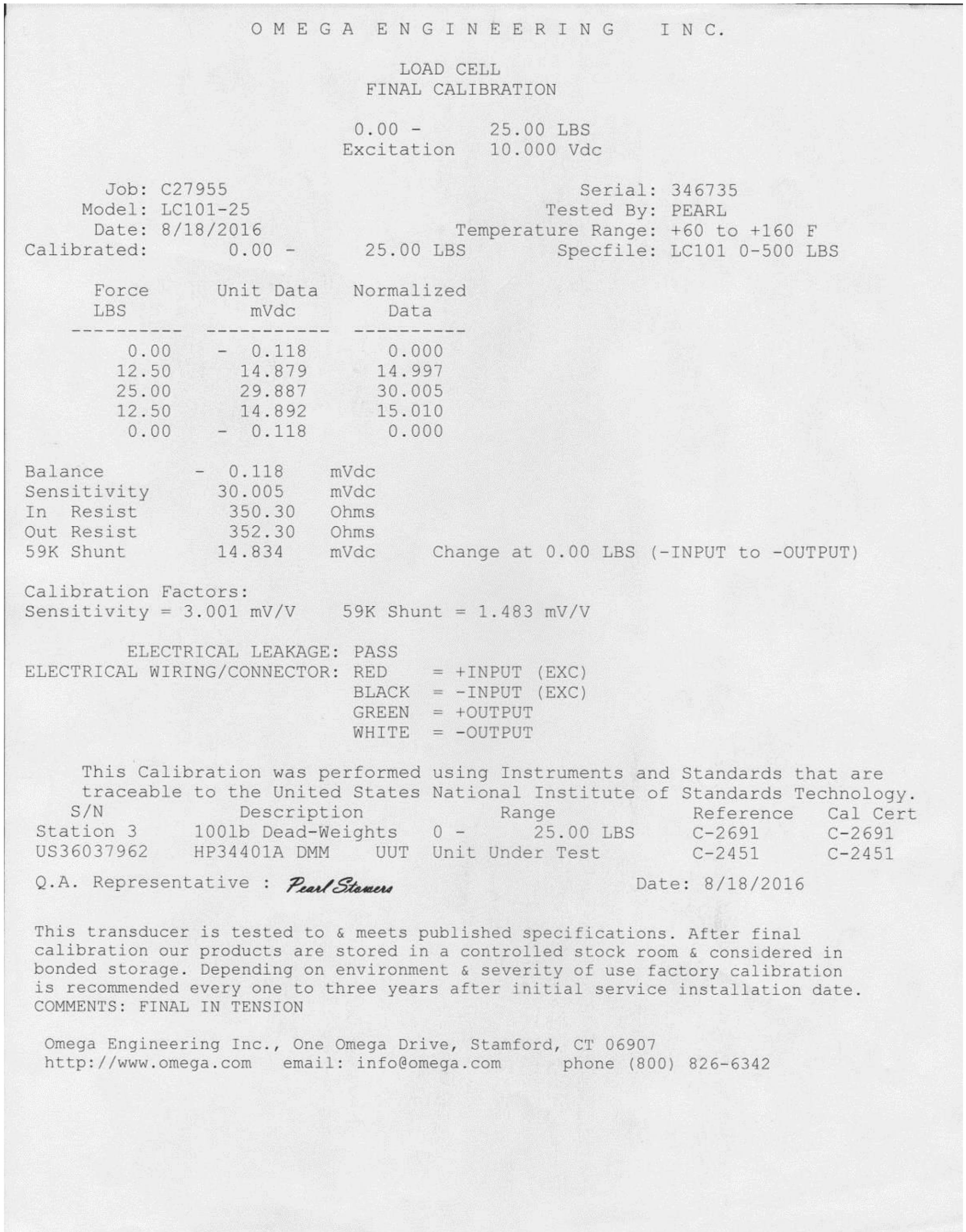
RPM Set	UUT RPM	Acceptable RPM Range	Result
5	5.000	4.99995 to 5.00005	PASS
50	50.000	49.9995 to 50.0005	PASS
500	500.000	499.995 to 500.005	PASS
5000	5000.004	4999.95 to 5000.05	PASS
50000	50000.030	49999.5 to 50000.5	PASS
100000	100000.100	99999 to 100001	PASS
500000	500000.300	499995 to 500005	PASS

Calibrated by: Monarch Calibration Lab. 15 Columbia Drive. Amherst, NH 03031

Technician: SK S K Date: 5-23-16

Document #: CAL-500-002 Rev 3.2 Page 1 of 1 Certificate Serial #: 1483312

Figure 33: Tachometer calibration certificate.



O M E G A E N G I N E E R I N G I N C.

LOAD CELL
FINAL CALIBRATION

0.00 - 25.00 LBS
Excitation 10.000 Vdc

Job: C27955
Model: LC101-25
Date: 8/18/2016
Calibrated: 0.00 - 25.00 LBS

Serial: 346735
Tested By: PEARL
Temperature Range: +60 to +160 F
Specfile: LC101 0-500 LBS

Force LBS	Unit Data mVdc	Normalized Data
0.00	- 0.118	0.000
12.50	14.879	14.997
25.00	29.887	30.005
12.50	14.892	15.010
0.00	- 0.118	0.000

Balance	- 0.118	mVdc	
Sensitivity	30.005	mVdc	
In Resist	350.30	Ohms	
Out Resist	352.30	Ohms	
59K Shunt	14.834	mVdc	Change at 0.00 LBS (-INPUT to -OUTPUT)

Calibration Factors:
Sensitivity = 3.001 mV/V 59K Shunt = 1.483 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR: RED = +INPUT (EXC)
BLACK = -INPUT (EXC)
GREEN = +OUTPUT
WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N	Description	Range	Reference	Cal Cert
Station 3	100lb Dead-Weights	0 - 25.00 LBS	C-2691	C-2691
US36037962	HP34401A DMM UUT	Unit Under Test	C-2451	C-2451

Q.A. Representative : Pearl Stamers Date: 8/18/2016

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.
COMMENTS: FINAL IN TENSION

Omega Engineering Inc., One Omega Drive, Stamford, CT 06907
http://www.omega.com email: info@omega.com phone (800) 826-6342

Figure 34: Load cell calibration certificate.

5 SHAKEDOWN TESTING AND FACILITY IMPROVEMENTS

5.1 Shakedown Testing

The major equipment installed in the facility for this experiment was the turbine, including with its inlet and exhaust piping, as well as the dynamometer and load cell. Structural support was also required for the turbine, dynamometer, and piping.

5.1.1 Turbine

The turbine was first installed to the test platform without any coupling connected to the shaft. The turbine was brought up to speed using compressed air via a 3/4-inch hose. Speed was monitored using a handheld laser tachometer.

After the inlet piping was installed and the permanent tachometer were installed, the turbine was retested again. The dynamometer was aligned with shim plates and installed, and then the turbine was spun up again. Lastly, the exhaust piping was installed.

5.1.2 Inlet Piping

The inlet piping was installed up until the connection to the turbine. The piping was pressure-tested up to the turbine connection by installing a valve at the turbine connection point. The inlet piping was then pressurized to 120 psia using the air compressor, and inspected for leaks. All noted leaks were repaired. The turbine was then positioned in place, and connected to the inlet piping. The inlet of the turbine up until the nozzle inlet valve was then brought to pressure. Leakage was noted at two points on the casing of the turbine. These were the stem of the Trip Throttle Valve (TTV) and the stem of the nozzle throttle valve. Both of the packing nuts were tightened. The leak at the nozzle inlet valve was able to be sealed, but the TTV was limited in its adjustment because the tightness of the stuffing box began to interfere with the automatic operation of the TTV.

The inlet piping was tested using air, steam, and mixtures of air/water and steam/water. Water hammer was anticipated during the steam/water mixtures were expected to stress the inlet piping. The first tests were air and air/water mix: 60 g/s air, then 55 g/s air with 5 g/s water were admitted to the turbine. After this, 45/15 and 30/30, and 15/45 and finally 60 g/s water were admitted to the turbine. No repairs were necessary, and no significant water hammer was noted. Instrument readings were steady.

5.1.3 Exhaust Piping

Because it lacks an isolation valve, and is subject to only low pressures, the exhaust portion of the turbine was subjected to only an operational joint tightness test. The exhaust pipe was installed into a water tank, and the turbine was operated using steam. Steam flow was throttled up in increments of 10 g/s to a final flowrate of 60 g/s. Minor leakage of less than two drops per second were noted at the shaft seal drains. No other leaks were noted in the exhaust piping or casing.

Exhaust consisted of a piping leg connected via threaded joints, directed to a 55-gallon drum. The piping employs a 9-inch corrugated stainless steel braided hose to allow for vibrations and misalignments. The exhaust was monitored for vibrations and signs of trouble.

In most steam/water tests, there is no issue with the piping being cleared of liquid, even though there is a significant rise in the piping. This is similar to the RCIC design in reactor plants; the turbopump is located below the suppression chamber to allow a significant NPSH to be applied to the suction of the pump. In consequence, steam is directed downward and then upward again. Condensate can collect in low points. In the plants, barometric condensers are employed to clear the condensate. In the experimental facility, a manual drain is installed at the exhaust low point.

5.1.4 Dynamometer

The dynamometer was connected and aligned to the turbine shaft. The turbine was brought up to speed using compressed air. Noises were noted while bringing the turbine up to speed. The dynamometer was realigned to the turbine shaft by shimming the pedestal bearings. Again the turbine was brought to speed. The improved alignment alleviated the noise.

The structure and coupling guard were installed to protect the coupling and prevent pieces from becoming missile hazards.

The load cell attaches to the dynamometer and the structural frame using eyebolts that minimize strain in the load cell body. Care was taken in designing the test platform to provide fastening points between the frame and dynamometer that are orthogonal to the axis of the shaft and to the axis of the torque arm. This ensures that the measured torque value is truly the torque delivered by the turbine.

5.1.5 Instruments

Pressure instruments were connected electronically with 4-20 mA cable to the converter box. Gage line was connected and the instrument bodies were vented. Offset was applied for the height of the instrument piping leg. The gage lines were uninsulated so that steam tests would still have a water leg of consistent height. Instruments were aligned using the Emerson 475 Field Communicator. Calibration was taken at zero 4 and 20 mA points. Offset was then applied through LabVIEW. Ambient readings were taken, and compared to other instruments such as the main steam line absolute pressure transmitter.

5.2 Modifications

During steam testing, certain thermocouple temperature indications along the steam line were noted to be consistently lower than others. These differences were within the documented uncertainty of the thermocouples. The old thermocouple sensors were replaced with new sensors of identical model for two reasons. First, the old thermocouples were several years old. Second, replacement ensured that all thermocouples along the steam line were from the same batch. The newly installed thermocouples, yielded more consistent temperature values along the steam line.

5.3 Post-Shakedown Repairs

No repairs were necessary after the shakedown testing period.

5.4 System Modifications and Enhancements

After shakedown testing, a non-horizontal branch of piping that had been used in previous tests was removed. This was to remove a confounding element: there was a possibility of losing water from steam/water and air/water mixes down the non-horizontal piping branch. The piping branch was replaced with a plug. This is to prevent loss of water, which could accumulate by falling out into the lower portion of the piping.

6 TESTING

6.1 Differences Between Air and Steam Tests

6.1.1 Temperature

Air in these tests travels through the turbine at much lower temperatures than the steam. After traveling through the compressor, the air passes through a refrigerated air dryer before entering the steam generator. Additionally, expansion as the air passes through the piping and into the steam generator causes further cooling. Typical air pressures, for air-only tests, are 45 psia.

6.1.2 Pressure

Typical air pressures at the turbine inlet, for air-only tests, are 45 psia. A steam test inlet pressure. Steam inlet pressure is approximately 70 psia. Despite having the same mass flowrate, the gases behave much differently in the piping.

6.1.3 Length of Trial

To constitute qualified data, each trial is required be maintained over a certain period with parameters within a given band. The bands are RPM within 50 RPM of the target, gas flow within 2 g/s of the target flowrate, and the water flow within 1 g/s of the target flowrate. These conditions must be maintained for at least thirty seconds to obtain a qualified dataset.

6.2 Test Planning

There are several test formats possible for this facility. Air testing, steam testing are the two basic modes. Additionally, water injection is possible for either tests type. Water injection is via the five-stage water injection pump. For steam testing, injected water can be preheated. This allows for less mass transfer between phases (i.e. less steam turns into water from contact).

Loading of the turbine is variable. Assuming mass flowrate is controlled and held constant, loading of the turbine can be adjusted to obtain a desired speed. Loading is planned to be adjusted to power outputs for speeds between 1500 and 3000 RPM, in 500 RPM increments.

The overall testing plan involves testing and comparison of water/steam and water/air ratios. Low-quality tests limit the speed to lower RPM ranges. Below 50% quality, the tests are limited to coast down tests. These can be compared without water injection. Water injection is expected to add drag, essentially causing lower power to be produced by the turbine. Power will be even less than that required to maintain any steady rotation rate.

Test matrix is given in Table 4 and Table 5.

Table 4: Target control variables

Variable	**Value**
Steam flow rate	Up to 60 g/s
Air flow rate	Up to 60 g/s
Water temperature-air tests	75-306 °F
Water temperature-steam tests	285-306 °F
Inlet Pressure-steam tests	55-75 psia
Inlet Pressure-air tests	35-45 psia
Inlet Quality	0.00-1.00
Steam Inlet Temperature	285-310 °F

The steam and air flowrates were selected to give a comparison between the gas types. 60 g/s was found to be sufficient to enable loading of the turbine for a sufficient duration to collect a steady state data set.

Table 5: Test flowrates

Gas Flow (g/s)	Water Flow (g/s)
60	0
55	5
45	15
30	30
15	45
0	60
0	30
0	15
0	0

Table 6: Air tests performed.

Gas Type	Turbine Speed (RPM)	Gas Injection (g/s)	Water Injection (g/s)
Air	3000	60	0
		55	5
		55	0
	2500	60	0
		55	5
		55	0
		45	15
		45	0
	2000	60	0
		55	5
		55	0
		45	15
		45	0
		30	30
	1500	60	0
		55	5
		55	0
		45	15
		45	0
		30	30
		30	0

Table 7: Steam tests performed.

Gas Type	Turbine Speed (RPM)	Gas Injection (g/s)	Water Injection (g/s)
Steam	3000	60	0
		55	5
		55	0
		45	15
		45	0
		30	30
		30	0
	2500	60	0
		55	5
		55	0
		45	15
		45	0
		30	30
		30	0
	2000	60	0
		55	5
		55	0
		45	15
		45	0
		30	30
		30	0
	1500	60	0
		55	5
		55	0
		45	15
		45	0
		30	30
		30	0
		15	45
		15	0

Water temperature was intended to be maintained near saturation during the steam tests to minimize the amount of steam that condensed when the water and steam started to mix. Lower water temperatures were allowed in the air tests because no phase change was expected from the air in the line.

Inlet pressures were chosen to facilitate choked flow. Choked flow occurs in nozzles when the critical pressure ratio is reached.

The entire band of inlet quality from 0.00 to 1.00 was selected to allow a full characterization of turbine performance.

Steam inlet temperature was based on saturation conditions for the pressure bands.

6.3 Example Tests

A representative test is given in Figure 35. This test is with 60 g/s air injection and no water injection. Notable features are the initiation of air flow, followed by a drop in pressure as flow is admitted to the turbine. The turbine is loaded as speed approaches 3000 RPM. Loading results in an increase in load cell force, torque, and power. Test data is collected in the span between approximately 2900 and 2940 seconds. During this period, gas flow and turbine loading are adjusted to maintain turbine in the band between 2949 and 3051 RPM, and gas flow between 58 and 62 g/s.

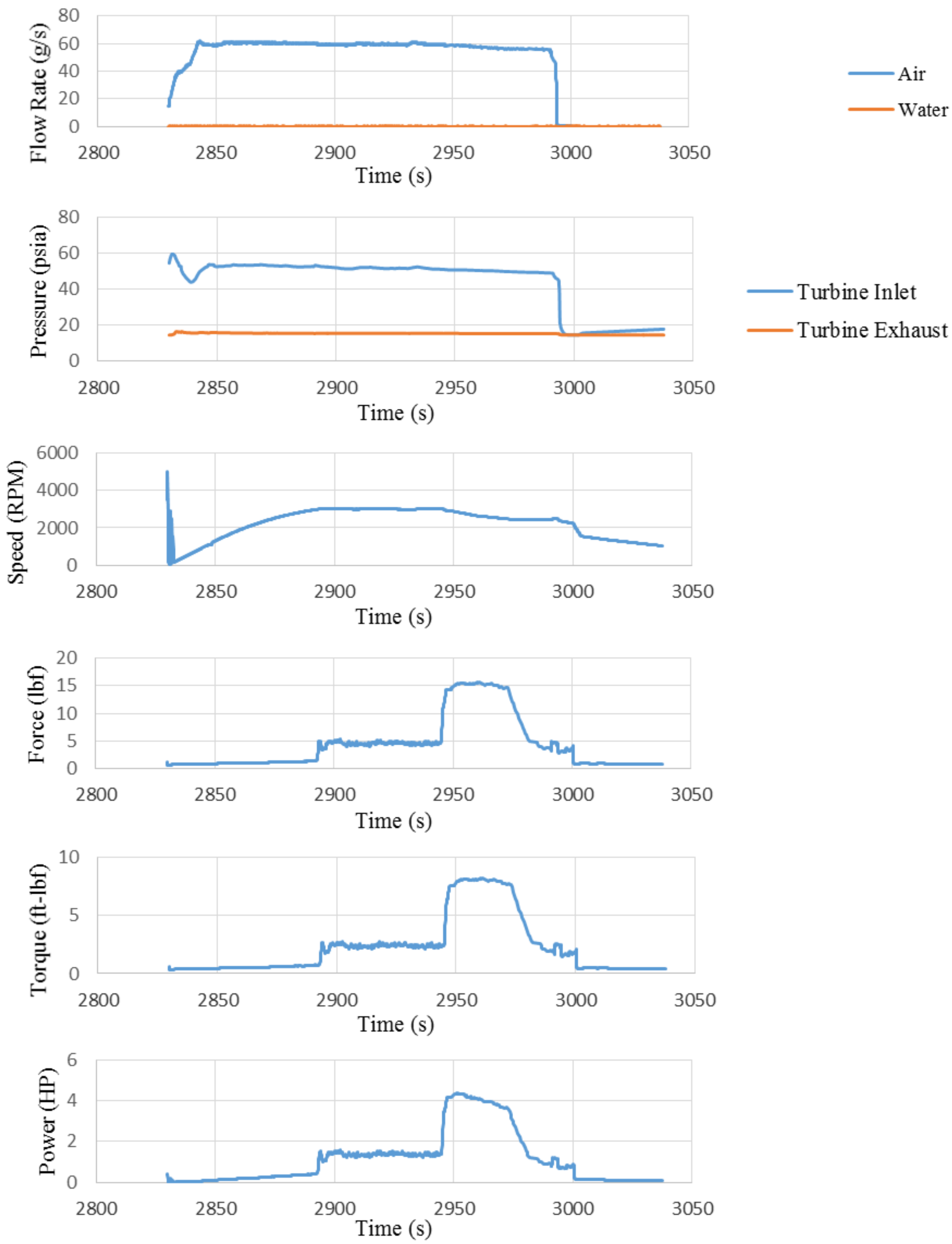


Figure 35: Representative air test data.

The combined data from this test can be summarized by plotting power and torque over the test span. A test summary data point for torque is given in Figure 36, and a test summary data point for power is given in Figure 37. Torque and power were calculated using Eq. (2) and Eq. (3), respectively.

$$\mathbf{T} = Fr \qquad (2)^{21}$$

$$\dot{W}_{sh} = 2\pi \dot{n} \mathbf{T} \qquad (3)^{21}$$

$\mathbf{T}$: torque (ft-lbf)

F : applied force

r : moment arm length

$\dot{W}_{sh}$: rate of shaft work

$\dot{n}$: shaft revolutions per unit time

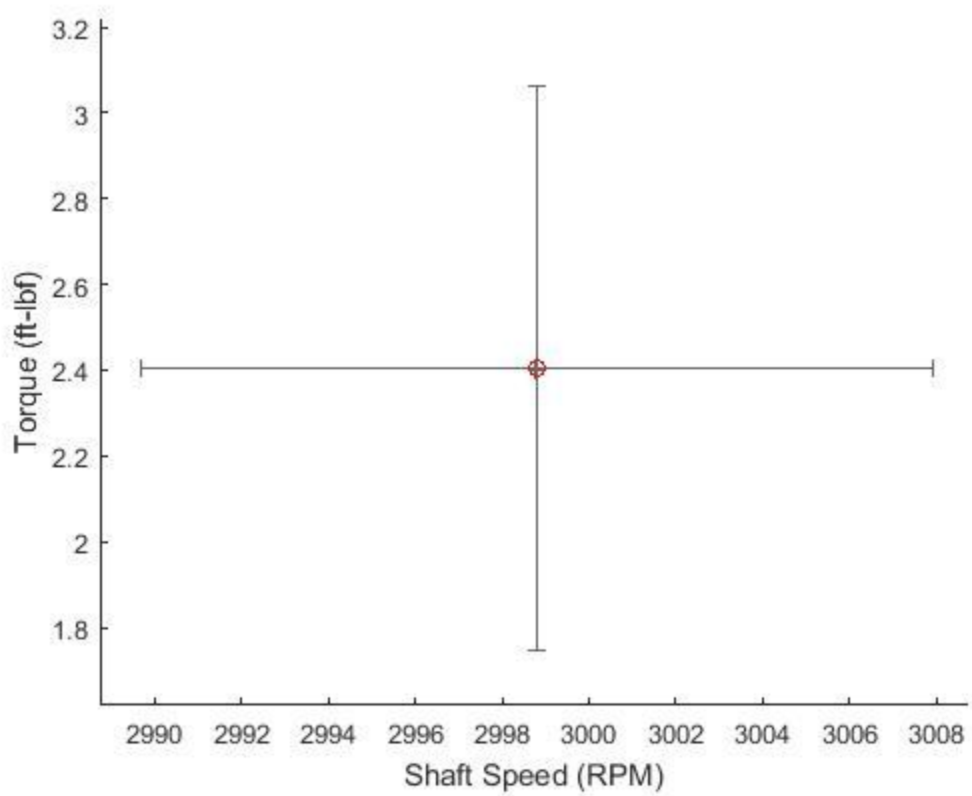


Figure 36: Summary torque data point for 60 g/s dry air test.

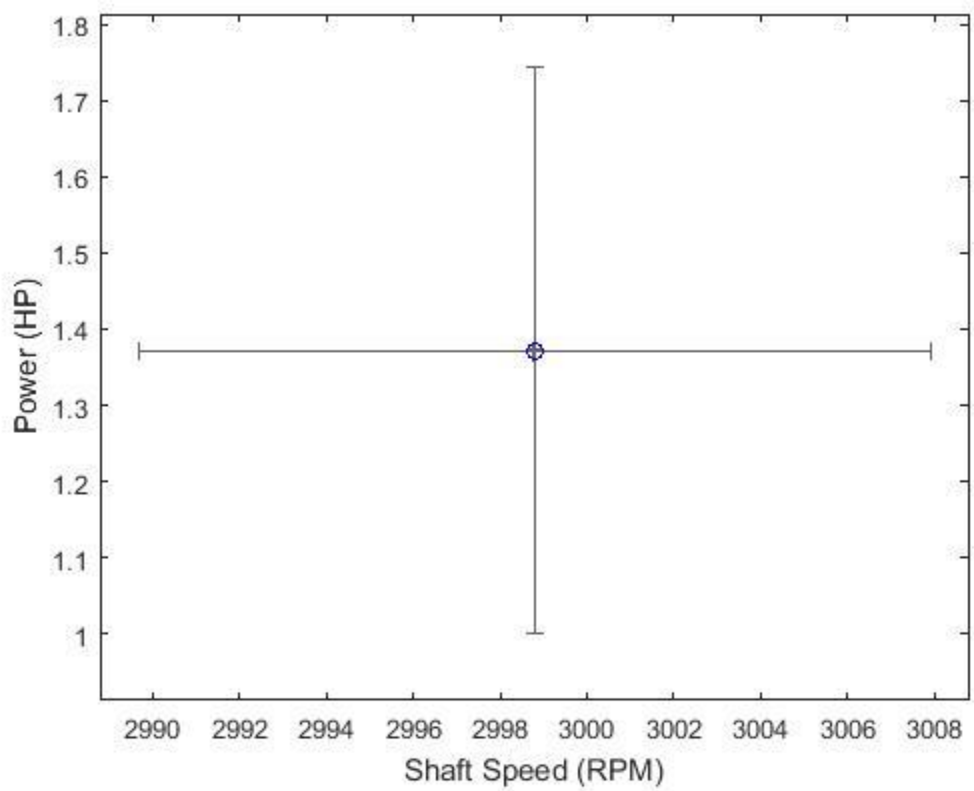


Figure 37: Summary power data point for 60 g/s dry air test.

Error bars include sample standard deviation and mean instrument uncertainty over the course of the test. The sample standard deviation is calculated using Eq. (4)(5) and Eq. (5).(5)

$$\bar{x} \equiv \frac{1}{N}\sum x_i \qquad (4)^{22}$$

$$s^2 \equiv \frac{1}{N-1}\sum\left(x_i - \bar{x}\right)^2 \qquad (5)^{22}$$

$\bar{x}$: mean of all measurements

x_i : individual measurement value

N : number of measurements

s : sample standard deviation

Torque and power are derived measurements, so instrument uncertainty was propagated to obtain a derived uncertainty for each of these measurements. Where measurements with associated uncertainties are summed, Eq. (6) was used to propagate uncertainty. When measurements are multiplied or divided, Eq. (7) was used. Uncertainty limits for the instruments are given in Table 1.

$$\sigma_u = \sqrt{\sigma_x^2 + \sigma_y^2} \qquad (6)^{23}$$

$$\left(\frac{\sigma_u}{u}\right)^2 = \left(\frac{\sigma_x}{x}\right)^2 + \left(\frac{\sigma_y}{y}\right)^2 \qquad (7)^{23}$$

x, y: direct measurements

u: derived measurement

σ : uncertainty in measurement

7 RESULTS AND ANALYSIS

7.1 Uncertainty Analysis

Uncertainty of measurements stems from multiple origins: accuracy limitations of the instruments, fluctuations due to random error, operator adjustment, and error due to conversion from analog to digital signals. The conversion from analog to digital is treated as negligible; it is very small. The accuracy limitations of the instruments are given in Table 1. Random errors and operator adjustments during data collection are included using standard deviation over the test duration. All plots include two sets of error bars. The wider error bars mark the sum of instrument uncertainty and the standard deviation of the measured quantity over the duration of the test. The more narrow error bars show the range of instrument uncertainty only. In many plots, the instrument uncertainty error bars are so small that they are not discernable on the scale of the plot.

7.2 Steam Tests

For an equal mass injection rate, steam produced more power and more toque than air in all comparable tests in the series. A summary of the torque and power values obtained in steam tests are given in Figure 38 and Figure 39. The wet steam is a dry steam component, plus an injected portion of water which brings the total mass flowrate to 60 g/s. For instance, 45 g/s wet steam contains 45 g/s of steam, plus 15 g/s of injected water.

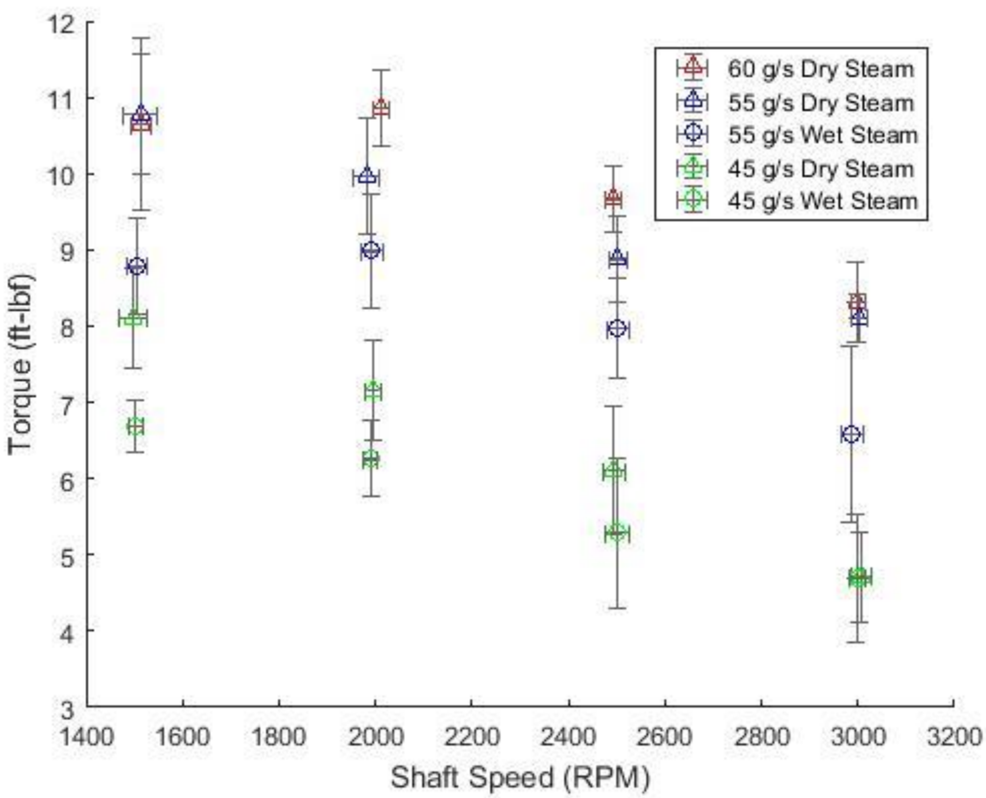


Figure 38: High-flow steam torque summary data.

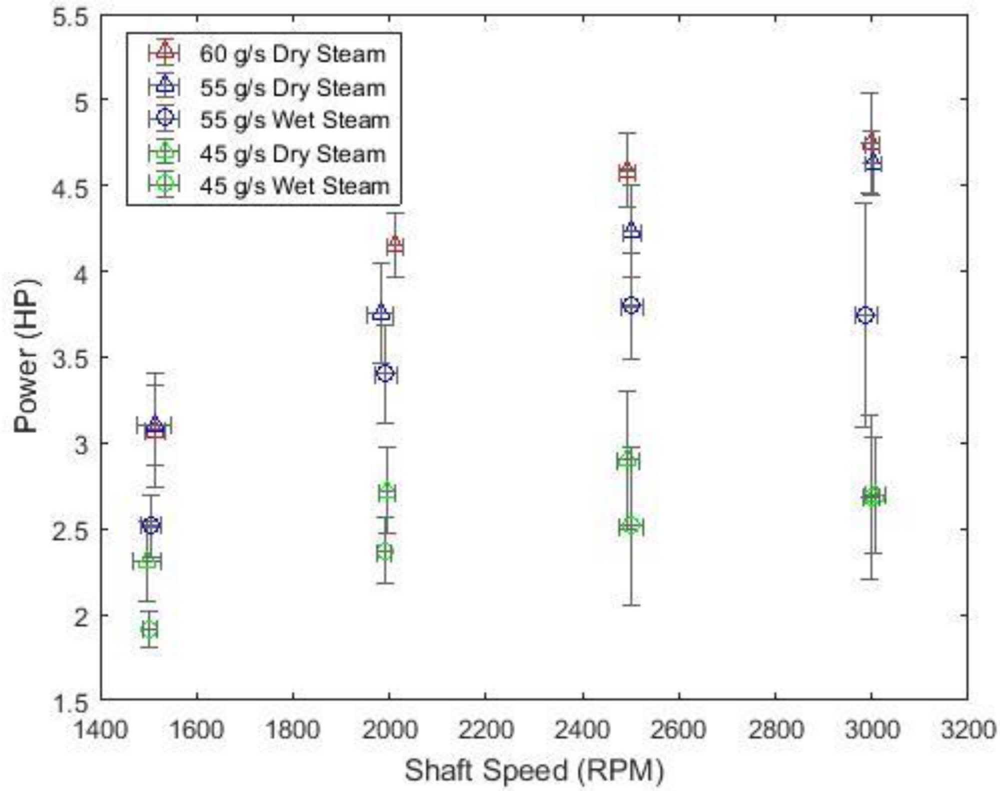


Figure 39: High-flow steam power summary data.

The wet steam tracked lower than the dry steam for equal steam injection rates, but most were within the margin of error. This shows a relatively good predictive capability with Baumann's rule of 1% quality corresponding to a 1% drop in power.

The turbine which was used is a single stage impulse turbine. This makes it well-suited to basic calculation methods. The only complicating design feature is the presence of reversing cups. The reversing cups redirect steam or air back through the turbine buckets three times after the first injection.

The relationship between nozzle exit velocity, rotor speed, and the force applied by the gas to the rotor, as stated by Church, is given in Eq. (8)[24]. For all tests with a given mass flowrate through the nozzle, acceleration due to gravity, mass flowrate from the nozzle, and gas exit velocity remain constant. Only the tangential velocity of the turbine wheel changes.

$$F = 2w(V_1 - W)/g \qquad (8)^{24}$$

F : steady force acting on the wheel

w : mass flowrate into nozzle

V_1 : velocity of gas exiting nozzle

W : tangential velocity of rotor

g : acceleration due to gravity

So for a given mass flowrate, the steady force exerted on the turbine rotor is a function only of the shaft speed. Furthermore, a linear relationship is expected. The force exerted on the rotor is directly proportional to the torque measured by the dynamometer.

A negative linear relationship between shaft speed and torque was noted for nearly all of the tests. The two exceptions were 60 g/s dry steam and 55 g/s wet steam. Both of these tests saw marked lowering of torque in the 1500 RPM tests.

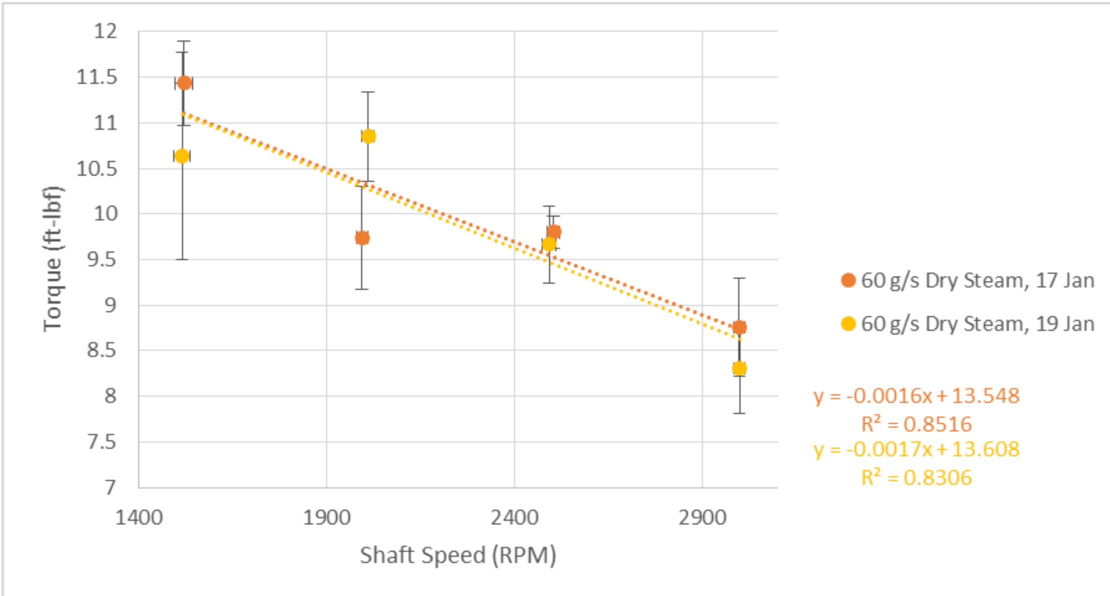


Figure 40: Comparison of two 60 g/s data sets, with trendlines.

The 60 g/s data set with the lowered torque was obtained on 19 January, 2017. To obtain a more complete understanding of the trend, this data was compared to a data set acquired on 17 January, 2017. Results are given in Figure 40. Based on this comparison, the obtained summary data yields a consistent trend, even with the inclusion of the lower torque at 1500 RPM.

7.3 Air Tests

Air test summary data is given in Figure 41 and Figure 42. Air tests showed a more pronounced lowering of power. The air tests differed from the steam tests in that addition of water to air resulted in an increase of work produced by the turbine. This may be due to a rise in the enthalpy into the turbine with the addition of water. Another possible contributor is the increased differential pressure across the nozzle caused by water injection. Water mass would act to obstruct and slow flow, but the resulting higher differential pressure would also provide more energy to be converted to kinetic energy. This indicates that for air, the higher differential pressure overcomes the losses from addition of water.

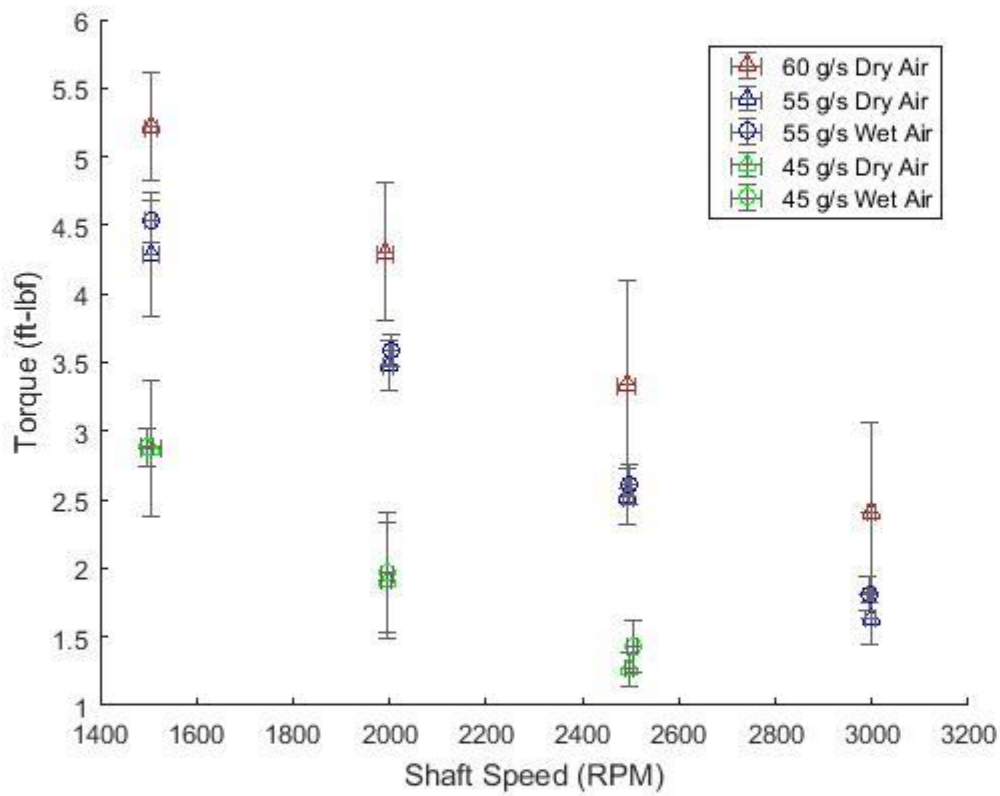


Figure 41: High-flow air torque summary data.

There was one tests for which the critical pressure ratio was not obtained across the nozzle. This was the 15 g/s dry steam test. For all other tests, the critical pressure ratio was reached for both air and steam. The 45 g/s air tests in Figure 42 constitute power near the maximum speed that can be achieved for this air flowrate. The turbine was unable to attain steady operation at 3000 RPM with 45 g/s dry air. Whereas the power peak is visible for the higher air flowrates, no peak is visible for the 45 g/s flow.

The torque plots of the air tests yield a linear pattern. The peak power for the 45 g/s air trials is not evident in Figure 42. Calculating power as a function of shaft speed yields an estimated peak at 1800 RPM.

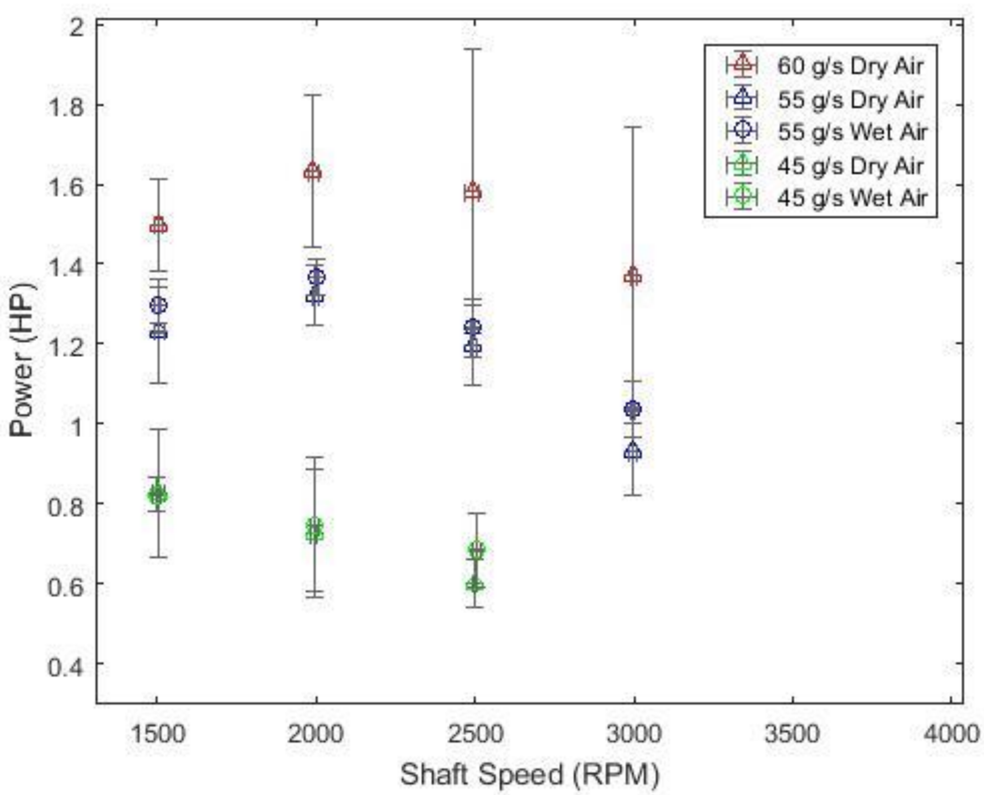


Figure 42: High-flow air power summary data.

7.4 Analytical Treatment

The use of reversing chambers added complexity to this test series. To simplify, analytical results treat the gas flow into the turbine buckets as a single flow, and the reversing chambers will be treated as negligible. Also, losses such friction, windage, and radiative heat losses are treated as negligible. With these assumptions, Eq. (8) can be used to estimate the nozzle exit velocity.

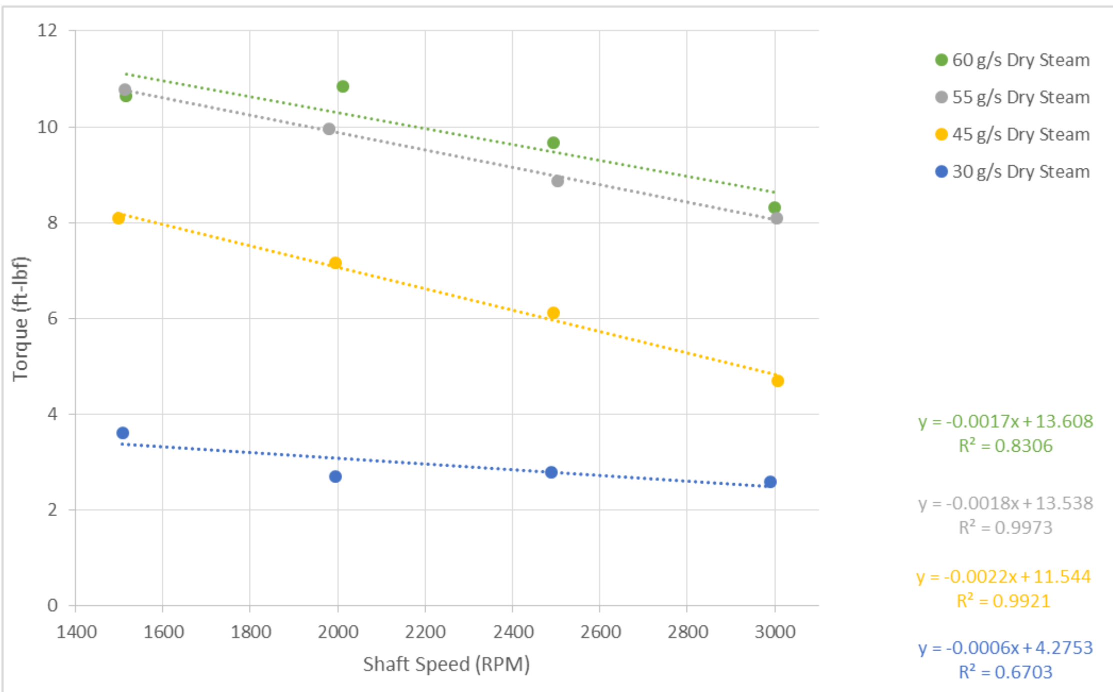


Figure 43: Dry steam torque, with trendlines.

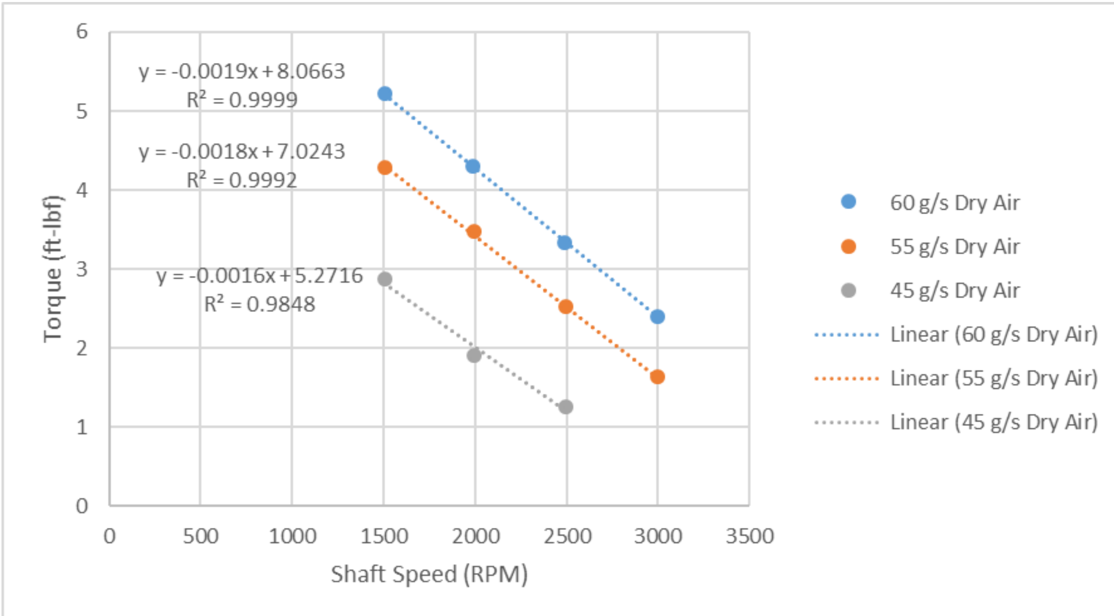


Figure 44: Dry air torque, with trendlines.

7.5 Isentropic Efficiency

Despite producing significantly less power for an equal mass flowrate, air in some cases had greater isentropic efficiency than steam. This is visible in the tests with the maximum flowrate, in Figure 45.

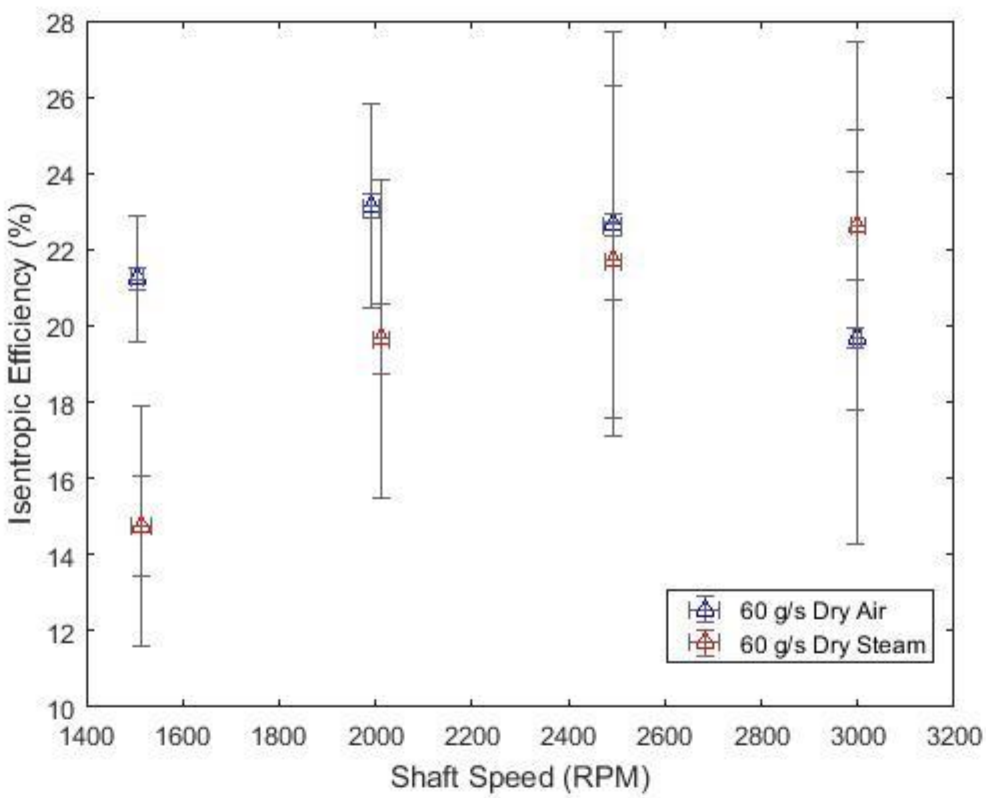


Figure 45: Isentropic efficiency of dry air and dry steam, 60 g/s injection rate.

Isentropic efficiency is calculated using Eq. (9).

$$\eta_{th} = \frac{\dot{W}_{sh}}{\dot{m}(h_1 - h_{2s})} \qquad (9)[21]$$

η_{th} : isentropic efficiency

$\dot{W}_{sh}$: rate of shaft work

$\dot{m}$: mass flowrate

h_1 : enthalpy of fluid into turbine

h_{2s} : isentropic enthalpy at exhaust

Shaft work and mass flowrate are measured directly. Inlet enthalpy is derived using temperature and pressure of injected fluids. Isentropic exhaust enthalpy is derived using entropy of injected water, and pressure measured at the turbine exhaust. For steam, both enthalpy terms are obtained by steam tables using pressure and temperature as read by instruments. For air, the enthalpy terms are obtained using instrument data and ideal gas calculations, with Eq. (10).

$$s_2 - s_1 = s_2^\circ - s_1^\circ - R \ln \frac{P_2}{P_1} \qquad (10)$$[21]

s_2 : entropy at turbine exhaust

s_1 : entropy at turbine inlet

s_2° : tabulated entropy at exhaust

s_1° : tabulated entropy at inlet

R : ideal gas constant for air

P_2 : pressure at exhaust

P_1 : pressure at inlet

The air is assumed to travel through the turbine isentropically, so the left hand side of Eq. (10) cancels to zero. Isentropic efficiency for air with a liquid component was not calculated. The addition of water with the air resulted in elevated inlet pressures. This resulted in a calculated s_2° term below the usable range of the ideal gas properties for air. This elevated pressure may have been a result of the water partially blocking the nozzle passage.

Though the power peaks of steam occur above the test speeds attained in this test series, efficiency peaks are visible for dry steam at 55 g/s in Figure 46 and 45 g/s in Figure 47. The turbine was unable to attain 3000 RPM using 45 g/s, and so only three air efficiency points are given in Figure 47.

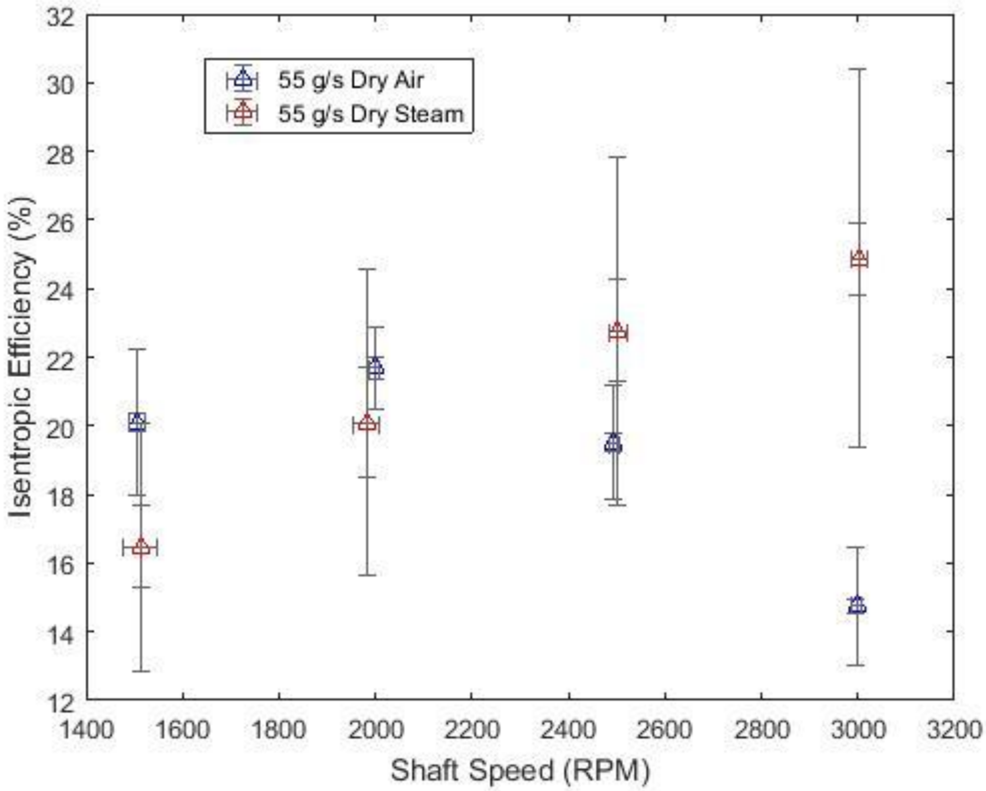


Figure 46: Isentropic efficiency of dry air and dry steam, 55 g/s injection rate.

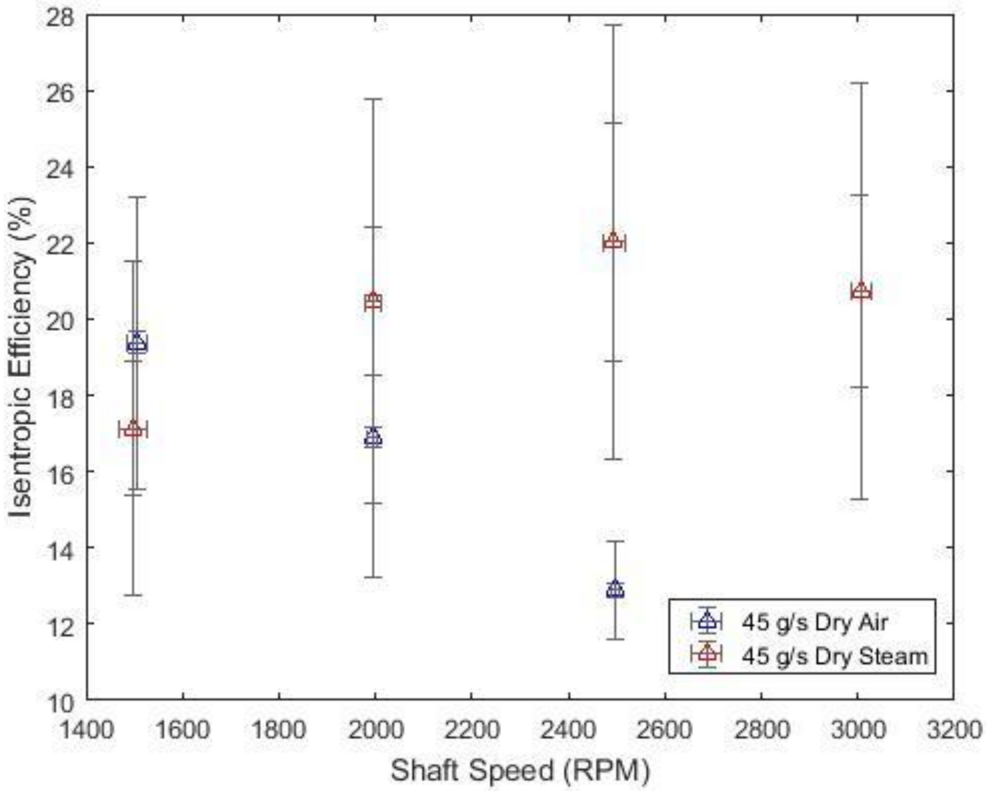


Figure 47: Isentropic efficiency of dry air and dry steam, 45 g/s injection rate.

Steam has a greater store of energy (measured by enthalpy) than air for an equal mass. Because of this, steam tests produced more power than air, yet did not have a higher efficiency.

7.6 Low-flow Tests

Tests with lower than 30 g/s gas flowrate were conducted. At this point, the operability limits of the turbine were reached. The turbine was unable to be loaded at less than 15 g/s of steam, or 30 g/s of air. The turbine could sustain a test at 2000 RPM with wet air at 30 g/s, but not with dry air at the same rate. This is in agreement with the trend of wet air tests delivering slightly greater power than dry air tests. Steam results are given in Figure 48 and Figure 49. Air results are given in Figure 50 and Figure 51.

The data yielded from this test series showed linear trends in torque with respect to speed, with flattening torque at the high end of the operable speed band. Mass flowrate, steam quality, and nozzle throat size, pressure ratio, and shaft work can all be used to validate computer models for tangential-flow impulse turbines.

Torque lowers with increasing shaft speed. The working fluid imparts motion to the rotor because it is directed against the surfaces of the rotor buckets. With greater shaft speeds, the velocity of the working fluid with respect to the bucket surfaces is lower, and so a lesser torque is imparted to the wheel. However, the power may rise with increasing RPM in spite of the lowering torque. Power is a function of both torque and shaft speed, as seen in Eq. (3). If the increasing shaft speed overcomes the lowering torque, power increases.

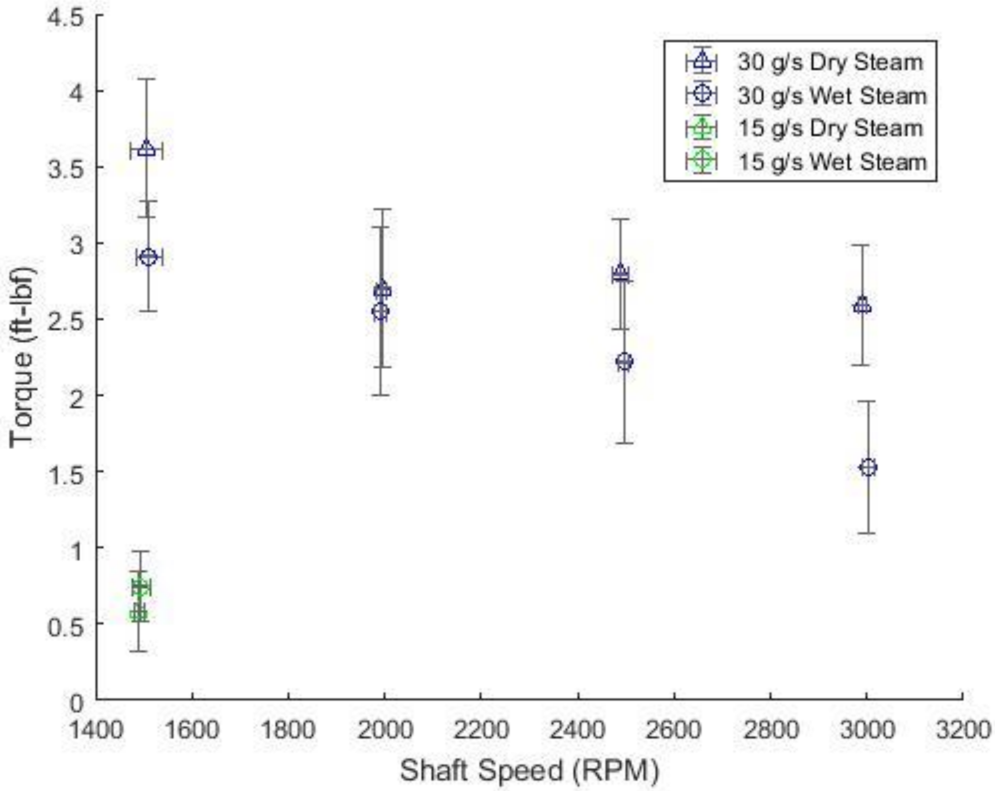


Figure 48: Low-flow steam torque summary data.

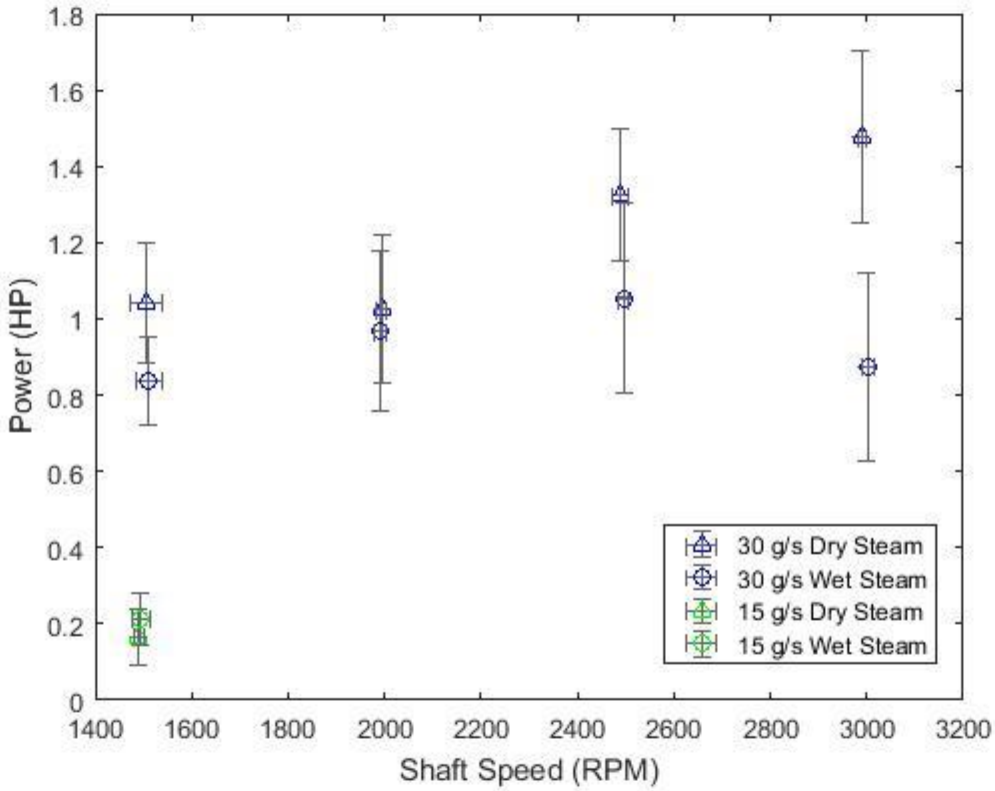


Figure 49: Low-flow steam power summary data.

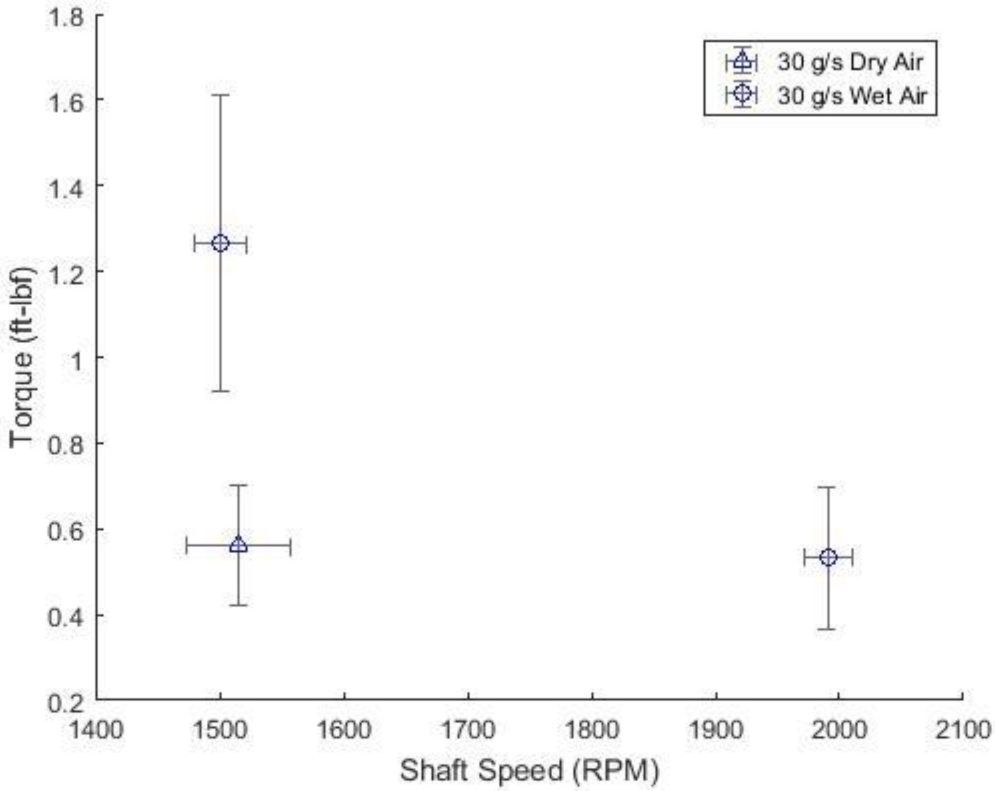


Figure 50: Low-flow air torque summary data.

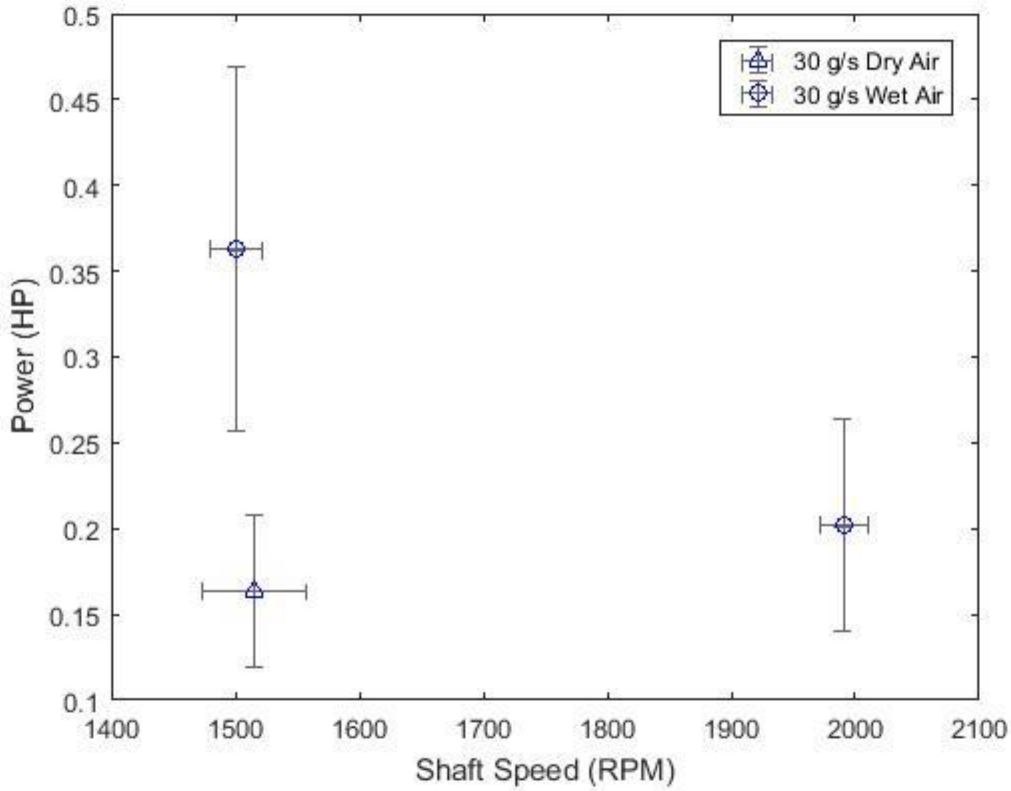


Figure 51: Low-flow air power summary data.

8 CONCLUSIONS

The study was motivated by the events of Fukushima Daiichi. The extended operation of the RCIC system in Fukushima Daiichi Unit 2 in the absence of power supplies has raised the question: how would the RCIC system operate under conditions of two-phase steam injection? To better understand this phenomenon, experiments were conducted using a ZS-1 Terry turbine, with two-phase flow injection. The turbine used a single nozzle, with a throat diameter of 0.380 inches. The gas phase for each test comprised either air or steam. Tests were conducted using both dry gas, and gas with injected liquid water. Tests were accomplished with total mass injection from 15 g/s to 60 g/s. These tests were conducted at turbine speeds from 1500 RPM to 3000 RPM.

Power and torque values were obtained for wet and dry steam and air flows which can be used to validate computational models involving Terry turbines. Isentropic efficiency curves were able to be constructed for wet and dry steam flows, and for dry air flows. For wet air flows, isentropic efficiency curves were not able to be produced. The addition of water resulted in a high differential pressure across the nozzle. Because of this large differential pressure, ideal gas approximations were unable to be applied to yield isentropic efficiency.

The data collected in this test series will be used to validate computational turbine model results. Inlet and exhaust temperature and pressure can be applied as boundary conditions, and resulting torque, power, and efficiency compared between experimental and computational turbines.

For an equal mass flowrate, steam produced significantly more power and torque in a Terry ZS-1 turbine than air in all tests. This is a result of greater enthalpy difference across the turbine during steam operations. The approximation of Baumann that a 1% lowering of quality producing a 1% lowering of efficiency fit the data of this experimental series well.[9]

Future work involves further testing of the ZS-1 Terry turbine used in this test. Turbine performance will be measured with the reversing chambers removed to determine their contribution to turbine power. Additionally, further validation data will be collected using a GS-1 turbine, subjected to air/water injection.

REFERENCES

1 United States Nuclear Regulatory Commission Human Resources Training & Development. *GE BWR/4 Advanced Technology*, Chap. 6.1: Emergency Core Cooling Systems and RCIC. 2014. NRC Accession Number ML14140A178.

2 Leland, W. S. *Steam Turbines.* American Technical Society, Chicago, IL: 1917.

3 Greene, S. R. *The Canary, the Ostrich, and the Black Swan: A Historical Perspective on our Understanding of BWR Severe Accidents and their Mitigation.* Nuclear Technology, 186 (2), pp.115-138, 2014.

4 International Atomic Energy Agency. *The Fukushima Daiichi Accident.* Technical Volume 2, Safety Assessment. IAEA, Vienna, Austria: 2015.

5 Tokyo Electric Power Company, Inc. *Evaluation of the Situation of Cores and Containment Vessels of Fukushima Daiichi Nuclear Power Station Units-1 to 3 and Examination into Unsolved Issues in the Accident Progression, Progress Report No. 2*. TEPCO, Inc., Tokyo, Japan: 2014.

6 Yamanaka, Y., Mizokami, S., Watanabe, M. and Honda, T. *Update of the First TEPCO MAAP Accident Analysis of Units 1, 2, and 3 at Fukushima Daiichi Nuclear Power Station.* Nuclear Technology, 186 (2), pp.263-279, 2014.

7 Moriya, K. and Sato, K. *Fukushima Daiichi NPP Accident: Plant Design and Preliminary Observations*, International Congress on Advances in Nuclear Power Plants, Nice, France, 2011.

https://www.sfen.fr/content/download/30420/1606953/file/3-ICAPP-0503P_Sato.pdf

8 Barrett, K. E. *Sales Aid Memo #12, Terry Wheel Water Slug Test*. The Terry Steam Turbine Company, 1973.

9 Baumann, K. *Recent Developments in Steam Turbine Practice*. Journal of the Institution of Electrical Engineers, 48 (213), pp.768-842, 1912.

10 Kim, S. I., Park, J. H., Ha, K. S., Cho, S. and Song, J. *Analysis of Fukushima Unit 2 Accident Considering the Operating Conditions of RCIC System.* Nuclear Engineering and Design, 298, pp.183-191, 2016.

11 Bonneville, H. and Luciani, A. *Simulation of the Core Degradation Phase of the Fukushima Accidents using the ASTEC Code*. Nuclear Engineering and Design, 272, pp.261-272, 2014.

12 Suzuki, H., Naitoh, M., Takahashi, A., Pellegrini, M. and Okada, H. *Analysis of Accident Progression with the SAMPSON Code in Fukushima Daiichi Nuclear Power Plant Unit 2*. Nuclear Technology, 186 (2), pp.255-262, 2014.

13 Lopez, H., Erkan, N. and Okamoto, K. *Two-Phase Flow Degradation on Fukushima-Daiichi Unit 2 RCIC Turbine Performance*. Journal of Nuclear Science and Technology, 53 (6), pp.821-830, 2016.

14 Akagawa, K. and Asano, Y. *Performance of Pelton-Type Turbine Driven by Gas-Liquid Two-Phase Flow.* Bulletin of the Japan Society of Mechanical Engineers, 29 (247), pp.106-112, 1986.

15 Solom, M. A. *Experimental Study on Suppression Chamber Thermal-Hydraulic Behavior for Long-Term Reactor Core Isolation Cooling System Operation*. Ph.D. Dissertation. Texas A&M University, College Station, TX: 2016.

16 Wynne, N. A. *Flooding Experiments with Steam/Water and Air/Water at Elevated Pressure in a Large Diameter Vertical Tube*. Thesis. Texas A&M University, College Station, TX: 2015.

17 Foxboro. *Instruction Book 3477: 83 F-A and 83W-A Vortex Flowmeters-Analog/Pulse*. 2000.

18 Badger Meter. *M-Series M2000 Electromagnetic Flow Meter User Manual*. 2016.

19 Yamatake Corporation. *MagneW 3000 PLUS Smart Electromagnetic Flowmeter Detector Model MGG18/19, MGS18, User's Manual.* CM2-MGG200-2001 (Rev. 4). 2004.

20 Omega, *Revised Thermocouple Reference Tables, TYPE T Reference Tables N.I.S.T. Monograph 175 Revised to ITS-90.* http://www.omega.com/temperature/Z/pdf/z207.pdf

21 Çengel, Y. A. and Boles, M. A. *Thermodynamics: An Engineering Approach.* 4th ed. McGraw-Hill, Boston, MA: 2002.

22 Bevington, P. R. and Robinson, D. K. *Data Reduction and Error Analysis for the Physical Sciences*. 3rd ed. McGraw-Hill, Boston, MA: 2003.

23 Knoll, G. F. *Radiation Detection and Measurement.* edited by Jennifer Welter, Debra Matteson, Elaine S. Chew and Tom Kulesa, 4th ed. John Wiley & Sons, Inc., Hoboken, NJ: 2010.

24 Church Jr., E. F. *Steam Turbines.* 3rd ed. McGraw-Hill Book, New York, NY: 1950.

APPENDIX A

OPERATING PROCEDURES

A.1 AIR TESTS

A.1.1 Initial Conditions

Steam Generator is at atmospheric pressure.

Steam Generator level is between 50 cm and 55 cm by sight glass level.

Turbine oil level is between low and high level marks on both sight glasses.

Feedwater tank level is greater than 10 cm by sight glass level.

Power is available to all instruments.

A.1.2 Startup

Shut V-16 (SG Vent) and V-13 (SG Vacuum Breaker Isolation).

Start up the air compressor system in accordance with B.2.

Drain the steam generator if necessary in accordance with B.5.2.

Start the Water Injection Pump in accordance with B.2.1.

Open V-75 (Exhaust Drum Drain Valve) to drain exhaust drum.

Pressurize the steam generator to 95 psig.

Check V-5 (RCIC Facility Isolation) open.

Cycle V-7b (Main Steam Line Low Point Drain) to drain trapped condensate from main steam line.

Verify hose is connected to load control valve.

Open or check open the water supply valves to the dynamometer hose.

Crack open V-74 (Dyno Load Control Valve) to allow a trickle flow of water into the dynamometer.

Check tripped V-41 (ZS-1 Trip and Throttle Valve).

Check shut V-42 (ZS-1 Nozzle Inlet Valve).

Cycle V-35 (MS to Feedwater Storage Tank Air Space) and V-36 (SRV Sparger Isolation) open, then shut to blow down trapped condensate in RCIC steam line.

Open V-72 (Turbine Branch Isolation Valve).

Latch open V-41 (ZS-1 Trip and Throttle Valve).

Place hygrometer on service in accordance with B.1.

With Steam Generator and Air Compressor tank pressurized, bring the turbine speed to 1000 RPM.

Latch the trip throttle valve in the open position.

Fully open the nozzle inlet valve.

Crack open V-1 (Main Steam Cutout Valve). The compressor will cycle on. Throttle V-1 (Main Steam Cutout Valve) to allow the air storage tank to repressurize to near 175 psig.

Throttle V-1 (Main Steam Cutout Valve) to obtain desired turbine speed.

Start the water injection pump and throttle to attain the desired mass injection rate.

Load turbine using V-74 (Dyno Load Control Valve) to maintain desired speed.

A.1.3 Shutdown

Admit full air flow through turbine to remove moisture deposits.

Shut V-72 (Turbine Branch Isolation Valve).

Trip turbine using V-41 (ZS-1 Trip and Throttle Valve).

Shut V-61 (Feedwater Storage Tank Recirc Throttle).

Secure water injection pump in accordance with B.2.2.

Shut V-82 (Feed Pump Suction).

Secure the low pressure air compressor in accordance with B.3.

Warning: verify the area in vicinity of the steam generator vent is clear of personnel before venting.

Crack V-16 (Steam Generator Vent) to vent the Steam Generator.

Shut V-1 (Main Steam Cutout Valve).

Shut hygrometer isolation and V-2 (Flooding Instrument Isolation).

Shut V-16 (SG Vent).

Open V-13 (SG Vacuum Breaker Isolation).

Shut dynamometer water supply valves.

Cycle V-74 (Dyno Load Control Valve) open, then shut.

A.2 STEAM TESTS

A.2.1 INITIAL CONDITIONS

Steam Generator is at atmospheric pressure.

Steam Generator level is between 55 and 60 cm by sight glass level.

Turbine oil level is between low and high level marks on both sight glasses.

Feedwater storage tank level is greater than 10 cm by sight glass level.

A.2.2 STARTUP

Begin data logging on the data acquisition system in accordance with section B.4.1.

Warning: Failure to perform this step can result in damage to hygrometer. Shut or check shut V-2 (Flooding Instrument Isolation).

Shut or check shut V-1 (Main Steam Cutout Valve).

Shut V-16 (SG Vent) and V-13 (SG Vacuum Breaker Isolation).

Shut or check shut V-90 (SG Air Inlet from Compressor).

Warning: Steam generator pressure must not be allowed to exceed 130 psia at any time.

Energize all steam generator heaters.

Vent SG for 20 seconds when SG pressure reaches 30 psia.

Repeat venting when SG pressure reaches 60 psia.

Secure SG heaters when SG pressure reaches 95 psia.

Fill the 55-gallon turbine exhaust drum to 2/3 full using potable water.

Check shut V-6 (Flooding Facility Isolation), V-34 (RCIC Sparger Isolation), V-35 (MS to Feedwater Storage Tank Air Space), V-36 (SRV Sparger Isolation), and V-72 (Turbine Branch Isolation). Check open V-5 (RCIC Facility Isolation). Check shut V-7b (Main Steam Line Low Point Drain) and V-7c (Main Steam Line Air Hose Isolation).

Crack open V-1 (Main Steam Cutout Valve).

Drain condensate from low point by cracking V-7b (Main Steam Line Low Point Drain) until steam is admitted.

Open V-36 (SRV Sparger Isolation).

Monitor main steam header heatup using DAQ, and shut V-36 (SRV Sparger Isolation) when warmup is complete.

Check V-41 (ZS-1 Trip and Throttle Valve) tripped and check V-42 (ZS-1 Nozzle Inlet) shut, then open V-72 (Turbine Branch Isolation).

A.2.3 SHUTDOWN

Shut V-42 (ZS-1 Nozzle Inlet).

Warning: verify the area in vicinity of the steam generator vent is clear of personnel before venting.

Open V-16 (SG Vent) to vent

Start up LPAC in accordance with B.3.

Secure Water Injection Pump in accordance with B.2.2.

When SG fully vented, shut V-16 (SG Vent) and open V-90 (SG Air Inlet from Compressor) to pressurize SG with air.

When air bubbles are audible, shut V-63 (Feed Control Valve).

Open V-1 (Main Steam Cutout Valve).

Cycle open, then shut V-35 (MS to Feedwater Storage Tank Air Space) and V-34 (RCIC Sparger Isolation).

Admit trickle flow to dyno by cracking open V-74 (Dyno Load Control Valve) and open V-42 (ZS-1 Nozzle Inlet) to spin turbine with air.

Shut V-42 (ZS-1 Nozzle Inlet). When turbine has coasted to a complete stop, secure potable water flow to V-74 (Dyno Load Control Valve) by shutting supply valves on upstream end of supply hose.

Shut V-72 (Turbine Branch Isolation) and trip V-41 (ZS-1 Trip and Throttle Valve).

Raise the steam generator level to between 55 and 60 cm by sight glass in accordance with B.5.1.

Shut V-16 (SG Vent) and V-9 (Main Feed Isolation), then open V-13 (SG Vacuum Breaker Isolation).

Secure air compressor in accordance with B.3.

APPENDIX B

OPERATING INSTRUCTIONS

B.1 HYGROMETER

B.1.1 INITIAL CONDITIONS

Steam line is free of steam.

Warning: exposing the hygrometer to steam will result in equipment damage.

B.1.2 STARTUP

Open hygrometer isolation valve.

Shut or check shut flooding facility isolation valve.

Crack open V-2 (Flooding Instrument Isolation).

B.1.3 SHUTDOWN

Shut hygrometer isolation valve.

Shut V-2 (Flooding Instrument Isolation).

B.2 WATER INJECTION PUMP

B.2.1 Startup

Energize the Water Injection Pump Cooling Fan

Check V-9 (Main Feed Isolation) shut.

Open V-82 (Feed Pump Suction), shut V-81 (Flooding Pump Suction) and V-80 (Flooding Pump Discharge).

Crack open V-63 (Feed Control Valve) and fully open V-61 (Condensate Storage Tank Recirc Throttle).

Open V-53 (Feedwater Storage Tank Upper Recirc); shut or check shut V-54 (Feedwater Storage Tank Lower Recirc).

Energize Water Injection Pump. Check that discharge pressure rises.

Cycle V-66 (Feed Pump Recirc Globe Valve) shut, then open ½ turn if necessary to prime pump.

Check V-66 (Feed Pump Recirc Globe Valve) ½ turn open.

Shut V-61 (Feedwater Storage Tank Recirc Throttle).

Shut V-63 (Feed Control Valve). Verify pump discharge pressure is greater than SG pressure.

Open V-9 (Main Feed Isolation).

B.2.2 Shutdown

Shut V-63 (Feed Control Valve) and V-9 (Main Feed Isolation).

Secure power to Water Injection Pump.

Shut V-82 (Feed Pump Suction).

B.3 LOW PRESSURE AIR COMPRESSOR[16]

B.3.1 INITIAL CONDITIONS

Visually inspect the air compressor; verify moving parts are clear from obstruction, and that wiring is in good condition.

Crankcase oil level is between low and high level marks on dipstick.

Compressor drive belts are free of cracks, frays, tears or other signs of wear.

All fasteners are tight with the exception of floor mounting nuts.

Compressor wiring is in good condition.

Scheduled maintenance has been performed.

Isolation valves leading to the pressure regulator are checked open.

B.3.2 STARTUP

Turn the air dryer switch to the ON position. Allow the refrigerated air dryer to run for at least five minutes prior to starting the air compressor.

Plug in the auto drain valve.

Shut V-89 (Air Line to Hose).

If pressurizing the SG, open V-90 (SG Air Inlet from Compressor).

If not pressurizing the SG, shut or check shut V-90 (SG Air Inlet from Compressor).

Shut or check shut V-1 (Main Steam Cutout Valve).

Shut V-16 (SG Vent).

Caution: the SG cannot be pressurized above 130 psia. Ensure the air pressure regulator is set to a pressure lower than 105 psig during compressor operations.

Shut the air compressor breaker in the 480 VAC electrical panel.

Monitor pressure on the air regulator and/or the steam generator pressure gage. Verify the regulator maintains air pressure at less than 110 psig. Adjust the regulator to obtain desired pressure.

Note: Air compressor automatically turns off when tank reaches 175 psig, and cycles on at 125 psig.

Note: Hissing sound from the air compressor pressure switch is normal after automatic shutdowns. This is caused by air leaving the unloader valve, and lasts for 3-5 minutes.

Note: The auto drain valve opens once every 45 minutes.

The air supply system is ready for use.

B.3.3 Shutdown[16]

Open the air compressor breaker in the 480 VAC electrical panel.

Vent the compressed air line. This can be done by throttling V-89 (Air Line to Hose).

Note: Wait at last five minutes after compressor is turned off and line is depressurized to secure the refrigerated dryer. This is to ensure there is no condensate in compressed air piping.

Turn air dryer power switch to the off position.

Unplug the auto drain valve.

Shut or check shut V-90 (SG Air Inlet from Compressor).

B.4 DATA ACQUISITION SYSTEM

B.4.1 STARTUP

Log into the data acquisition system PC.

Energize the remote monitors near V-1 (Main Steam Cutout Valve) and turbine.

For steam/water turbine operations, open C:\Users\vierowsummer\My Documents\N_Luthman\Z-1 Facility v2 Folder\Z-1 Facility Steam.vi.

For air/water turbine operations, open C:\Users\vierowsummer\My Documents\N_Luthman\Z-1 Facility v2 Folder\Z-1 Facility Air.vi.

Power on the DC power supply and adjust output to 24.0 V.

Power on the SCXI chassis.

Energize Circuit 30 to supply power to tachometer and load cell.

Energize feed line magnetic flowmeter.

Begin data acquisition via the LabVIEW interface.

Enter the filename for the data to be taken.

Switch the Write Data Toggle Switch to the "Yes" position.

Begin writing data to file by selecting the "START" button on the LabVIEW interface.

B.4.2 SHUTDOWN

Terminate data writing by selecting the "STOP" button on the LabVIEW interface.

Terminate interface by clicking “END EXECUTION” button on the LabVIEW interface.

Secure the SCXI chassis.

Secure the DC power supply.

Secure power to Circuit 30.

Secure power to the feed line magnetic flowmeter.

Secure the remote monitors near V-1 (Main Steam Cutout Valve) and turbine.

Log out of the data acquisition system PC.

B.5 STEAM GENERATOR

B.5.1 RAISING LEVEL

Start the Water Injection Pump in accordance with B.2.1.

If the steam generator is at atmospheric pressure, open V-16 (SG Vent). If steam generator is pressurized, check shut V-16 (SG Vent).

Throttle V-63 (Feed Control Valve) to fill Steam Generator.

Monitor Steam Generator level during filling.

When level is between 55 and 60 cm in sight glass, shut V-9 (Main Feed Isolation), V-63 (Feed Control Valve), and V-16 (SG Vent).

B.5.2 LOWERING LEVEL

Secure the Water Injection Pump in accordance with B.2.1.

Pressurize the steam generator to 80 psig using the air compressor. If necessary, start up the air compressor in accordance with B.3.

Fully open V-61 (Feedwater Storage Tank Recirc Throttle).

Crack open V-63 (Feed Control Valve).

Check open V-53 (Feedwater Storage Tank Upper Recirc) or V-54 (Feedwater Storage Tank Lower Recirc).

Open V-9 (Main Feed Isolation).

Throttle V-63 (Feed Control Valve) to regulate flow from steam generator to feedwater storage tank.

When steam generator level is at desired level, shut V-63 (Feed Control Valve) and V-9 (Main Feed Isolation),

Warning: Ensure the area in vicinity of steam generator vent is clear of personnel prior to operating V-16. Vent steam generator by opening V-16 (SG Vent).

B.6 ZS-1 TURBINE

B.6.1 INITIAL CONDITIONS

Steam generator is pressurized with steam or air.

Feed Injection system is operating.

For steam tests, exhaust drum is filled approximately 2/3 full.

For air tests, exhaust drum is drained.

B.6.2 TEST INSTRUCTIONS

Warning: Failure to admit flow to dyno can damage seals. Admit trickle flow to the dyno by cracking open V-74 (Dyno Load Control Valve).

For first test, latch V-41 (ZS-1 Nozzle Inlet) open. For subsequent tests, check V-41 (ZS-1 Nozzle Inlet) latched open.

Fully and rapidly open V-42 (ZS-1 Nozzle Inlet). When fully open, V-42 (ZS-1 Nozzle Inlet) must be maintained ½ turn off its backseat to prevent valve binding.

For steam tests, energize steam generator heaters as appropriate to maintain steam generator pressure during test.

Throttle V-1 to obtain desired gas flowrate.

Open V-49 (Water Injection Flowmeter Discharge). Throttle V-68 (Water Injection Throttle) to obtain desired water injection rate.

Load turbine at target speed by throttling V-74 (Dyno Load Control Valve).

When test is complete, shut V-41. Shut V-74 (Dyno Load Control Valve) gradually. Maintain at least a trickle flow of water to dyno at all times that shaft is revolving. When turbine has fully coasted down, shut V-74 (Dyno Load Control Valve).

APPENDIX C

SYSTEM VALVES

The following is a list of valves used in the facility. They are referenced in APPENDIX A, APPENDIX B, Figure 23, Figure 24, and Figure 25.

Table 8: System valves

Valve Number	Valve Name
V-1	Main Steam Cutout Valve
V-2	Flooding Instrument Isolation
V-3	SG Relief
V-4	SG Backup Relief
V-5	RCIC Facility Isolation
V-6	Flooding Facility Isolation
V-7b	Main Steam Line Low Point Drain
V-7c	Main Steam Line Air Hose Isolation
V-8	Main Steam Line Pressure Transmitter Fill Isolation
V-9	Main Feed Isolation
V-10	SG/Hot Water Tank Cross Connect
V-11	SG Fill Isolation
V-12	SG Vacuum Breaker
V-13	SG Vacuum Breaker Isolation

Table 8 Continued

Valve Number	Valve Name
V-14	SG Water Level Variable Leg Isolation
V-15	SG Level Indicator Vent
V-16	SG Vent
V-17	SG Air Connector Isolation
V-18	SG Level Indicator Drain
V-19	SG Drain
V-20	SG Water Level Reference Leg isolation
V-21	SG DP Transmitter Reference Leg Drain
V-22	SG DP Transmitter Variable Leg Drain
V-23	SG Blowdown Drum
V-24	DI Inlet
V-25	DI Outlet
V-26	DI to Hot Water Tank
V-27	Hot Water Tank Vent
V-28	Hot Water Tank Recirc Cutoff
V-29	Hot Water Tank Drain
V-30	Hot Water Tank Pressure Transmitter Isolation
V-31	Hot Water Tank Pressure Transmitter Gage Access
V-32	Hot Water Tank Pump Suction Cutout

Table 8 Continued

Valve Number	Valve Name
V-33	Hot Water Tank Pump Discharge Cutout
V-34	RCIC Sparger Isolation
V-35	MS to Feedwater Storage Tank Air Space
V-36	SRV Sparger Isolation
V-37	RCIC Sparger Gage Isolation 1
V-38	RCIC Sparger Gage Isolation 2
V-41	ZS-1 Trip and Throttle Valve
V-42	ZS-1 Nozzle Inlet
V-43	Feedwater Storage Tank Relief
V-44	Feedwater Storage Tank Backup Relief
V-45	Feedwater Storage Tank Vacuum Breaker
V-46	Feedwater Storage Tank Airspace Gage Valve
V-47	Feedwater Storage Tank Level Indicator Vent
V-48	Feedwater Storage Tank Reference Leg Isolation
V-49	Water Injection Flowmeter Discharge
V-50	Feedwater Storage Tank Vent to Blowdown Drum
V-51	Steam Line Tank Side Gage Line Fill Access
V-52	Feed Line Vent
V-53	Feedwater Storage Tank Upper Recirc

Table 8 Continued

Valve Number	Valve Name
V-54	Feedwater Storage Tank Lower Recirc
V-55	Feedwater Storage Tank Sight Glass Drain
V-56	Feedwater Storage Tank Variable Leg Isolation
V-57	Feedwater Storage Tank Variable Leg Gage line
V-58	Feedwater Storage Tank Reference Leg Gage Line
V-59	Feedwater Storage Tank to Feed Line Isolation
V-60	Feedwater Storage Tank Drain
V-61	Feedwater Storage Tank Recirc Throttle
V-62	Water Injection Pump Discharge Relief
V-63	Feed Control Valve
V-64	Feed Pump Suction PT Isolation
V-65	Feed Pump Suction PT Gage Line
V-66	Feed Pump Recirc Globe Valve
V-67	Feed Pump Recirc Ball Valve
V-68	Water Injection Throttle
V-69	Water Injection Ball Valve
V-70	Steam Line Tank Side Gage Isolation
V-71	Feedwater Storage Tank Blowdown Drum Drain
V-72	Turbine Branch Isolation

Table 8 Continued

Valve Number	Valve Name
V-73	Turbine Exhaust Drain
V-74	Dyno Load Control Valve
V-75	Exhaust Drum Drain
V-76	Feed Pump Suction Line Drain
V-77	Exhaust Drum Level Tube Isolation
V-80	Flooding Pump Discharge
V-81	Flooding Pump Suction
V-82	Feed Pump Suction
V-89	Air Line to Hose
V-90	SG Air Inlet from Compressor

APPENDIX D

UNCERTAINTY ANALYSIS

Some test parameters required instrument error to be carried forward. For instance, steam mass flowrate is calculated from data collected by three instruments: a pressure transmitter (I-7), a thermocouple (T-41), and a vortex flowmeter (I-6). Uncertainty from all instruments are given in Table 1, on page 53.

D.1 GAS FLOW

The vortex flowmeter (I-6) has an associated instrument uncertainty of ±1% of reading for flow rates in accurate range. This range is all flows with a Reynolds number greater than 20,000. All tests with both air and steam had Reynolds numbers greater than this value.

D.1.1 Steam

The portion of testing where instrument uncertainty contributes the largest change in the mass flowrate measurement is at low pressures: 14.7 psia, and 100°C. Instrument I-6 has an associated instrument uncertainty of 0.1% of the Upper Range Value (URV). The upper range value is 130 psia, so instrument uncertainty is ±0.13 psia. Uncertainty of the thermocouple at 100°C is ±0.5°C. Using ideal gas calculations, the density of steam can be approximated using Eq. (11).

$$\rho = \frac{PM}{RT} \qquad (11)$$

ρ : density of gas

P : absolute pressure

M : molar mass

R : ideal gas constant of gas

T : absolute temperature

From the ideal gas approximation, the instrument uncertainty of P (P is proportional to ρ) contributes ±0.884% to the uncertainty of density. Temperature (in Kelvin for eq (5)) has a 1/T relationship to density. The instrument uncertainty of the thermocouple contributes ±0.134%.

The total uncertainty for this steam flow measurement is 1.341%

D.1.2 Air measurements

Air flow measurements are similar to steam flow measurements, except air temperature is lower, which causes the instrument error of the thermocouple to provide a higher contribution.

Typical temperatures for an air test were approximately 25°C. For this case, instrument uncertainty of the thermocouple is still ±0.5°C. Uncertainty of the thermocouple contributes ±0.168% to uncertainty of density.

Flowmeter and pressure instrument uncertainty are the same as in the steam example. Total uncertainty for the mass air flow measurement is ±1.345%.

D.2 WATER FLOW

Water injection mass flowrate was measured by a Badger M2000 magnetic flowmeter (I-12). Instrument uncertainty of this meter is ± 0.25 percent of rate. Once again, density is a function of temperature. However, at this point pressure has a very small effect on density. Change in temperature and at this point contributes approximately 0.00074%/°C to the change in density. The uncertainties of the flowmeter and thermocouple taken in conjunction result in approximately 0.252% total error for mass flowrate in the Badger M2000.