TURBINE OIL DEGRADATION AND ITS EFFECTS ON PERFORMANCE OF A TERRY TURBINE IN NUCLEAR APPLICATIONS

A Thesis

by

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ABSTRACT

In 2011, during the Fukushima Daiichi Nuclear Power Plant accident, a steam turbine driven safety system, Reactor Core Isolation Cooling (RCIC), operated under conditions it was previously expected to fail during, surpassing its expected run time by approximately sixty hours. This opened for questions such as why the expected run time was so short, whether the system could be relied on for longer run times during beyond design conditions, and why the turbine failed when it did.

This specific steam turbine is a Terry designed turbine, used in both Boiling Water Reactors and Pressurized Water Reactors, but there are little data available on the performance of the turbine and even less data available on why its operating conditions are set the way they are. In order to address the previous questions of the turbine behavior at beyond-design-basis conditions and turbine failure modes, the focus was placed on hypothesized reasons for turbine failure. Specifically, the failure mode regarding beyond-design-basis conditions for the oil lubrication system during extended periods was to be observed. The focus of this research is looking at the changes of turbine oil while exposed to heat and the turbine's bearing degradation due to noted changes of the turbine oil. A new facility needed to be designed in order to test degradation at a variety of temperatures and other conditions for a prototype RCIC turbine and smaller sized Terry turbines.

A new facility was designed in the Nuclear Heat Transfer Systems Laboratory at Texas A&M University to carry out these studies. In this thesis research, the facility was constructed and operated gathering initial data successfully to show proper performance for acquiring new data which will be used to improve the reliability of the Terry turbine driven systems in nuclear applications. A 72-hour heated oil test was conducted. Data on the change of oil color (the oil

darkened considerably), particulate/residue in the oil after sampling (as measured in a high-accuracy scale), and bearing performance on a Model ZS-1 Terry turbine were acquired.

DEDICATION

To God for all that I am capable of is due to His work within me and to Donald and Deirdre Peck for the immeasurable love and support.

ACKNOWLEDGMENTS

This would not have been possible without the help of many individuals who all deserve thanks. Dr. Kirkland and Dr. Solom for guidance and continuous help. The members of the NHTS Lab who helped operate equipment at all hours of the day and night. Workers of Revak-Keene Turbomachinery for allowing the sharing of their expertise and the refurbishment of turbines. The entire BWR Owner's Group and Terry Turbopump Expanded Operating Band Committee for industry input and data.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis committee consisting of Professor Kirkland and Professor Kimber of the Department of Nuclear Engineering and Professor Delgado of the Department of Mechanical Engineering.

Use of a high precision scale to obtain data was allowed by Dr Charles Folden and his student Kevin Glennon who operated the scale and provided advice.

Dr Solom of Sandia National Laboratory and Dr Delgado aided in the design by recommending specific equipment in order to meet the needs of this project.

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NOMENCLATURE

BWR	Boiling Water Reactor
NHTS	Nuclear Heat Transfer Systems
OEM	Original Equipment Manufacturer
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling
RPM	Rotations Per Minute
RPV	Reactor Pressure Vessel
TC	Thermocouple
TDAFW	Turbine Driven Auxillary Feedwater
TTExOB	Terry Turbine Expanded Operating Band
VFD	Variable Frequency Drive

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1. INTRODUCTION

On March 11, 2011, an earthquake measuring 9.0 hit off the coast of Japan, the strongest recorded for the country. This earthquake, later deemed "Great East Japan Earthquake," resulted in the formation of a tsunami that hit land 30 – 40 minutes after the shock. At a six-unit nuclear power plant in the area, Fukushima Daiichi, the first wave hit 41 minutes after the shock and a second wave 8 minutes later. These two waves caused flooding of up to 5-meter-deep on site.[1]

This flooding resulted in a beyond design basis accident at the power plant as it damaged "pumps, electrical distribution panels, backup batteries, and diesel generators." [3] With no offsite power and the little remaining onsite backup power draining, the plant began to lose instrumentation, lighting, and communication. Safety systems responsible for adding coolant to the reactor were not able to operate. However, one system unexpectedly did not fail, despite the loss of needed power, and continued to operate in its "as is" state reached before the loss of power. This system was the reactor core isolation coolant (RCIC) system. RCIC ran for approximately 70 hours in Unit 2 until failure and approximately 20 hours in Unit 3 until the system was shutdown intentially[2]. This performance of RCIC has gained attention as RCIC was previously assumed to last no longer than 12 hours under similar conditions and the failure mode is still not known due to the inaccessibility of the turbine room and lack of instrumentation during the accident. However, calculations have been performed to know rough conditions to help hypothesize failures, aiming focus towards the Terry turbine that drives the RCIC system as the reason for exceeding expectations and potential failure at the end[3].

1.1 Terry Turbines in Nuclear

RCIC is a safety system specific to boiling water reactors (BWR) that provides makeup water to the reactor pressure vessel (RPV) during indications of low water level in the RPV. The system includes a steam driven turbine, powered by steam generated in the RPV, directly drives a pump that takes water from the condensate storage tank and feeds it into the feedwater paths[4]. During the Fukushima Daiichi accident, RCIC is projected to have operated well into beyond design conditions, causing professionals, members of the Terry Turbine Expanded Operating Band (TTExOB) Committee, to look at what the Terry turbine driven system is capable of in order to expand its operating band as well as the operating band of other Terry turbines used in the nuclear power industry. This research will apply to RCIC in BWRs as well as the Turbine Driven Auxiliary Feedwater (TDAFW) system in pressurized water reactors (PWR)[5].

This Terry turbine is a steam turbine driven by a steam jet from a nozzle, hitting a bucketed wheel that reflects the steam 180 degrees into reversing chambers and another bucket. This force rotates the shaft that sits inside bearings lubricated by oil slinger rings. Figure 1, modified from Leland's *Steam Turbines*, on the following page shows a cut out of a Terry turbine, revealing the bucketed wheel, reversing chambers, and journal bearings with oil slinger rings[6]. There are two different size Terry turbines, the Z series and the G series. The Z series is the smaller of the two with an 18 in diameter wheel while the G series has a 24 in diameter wheel.

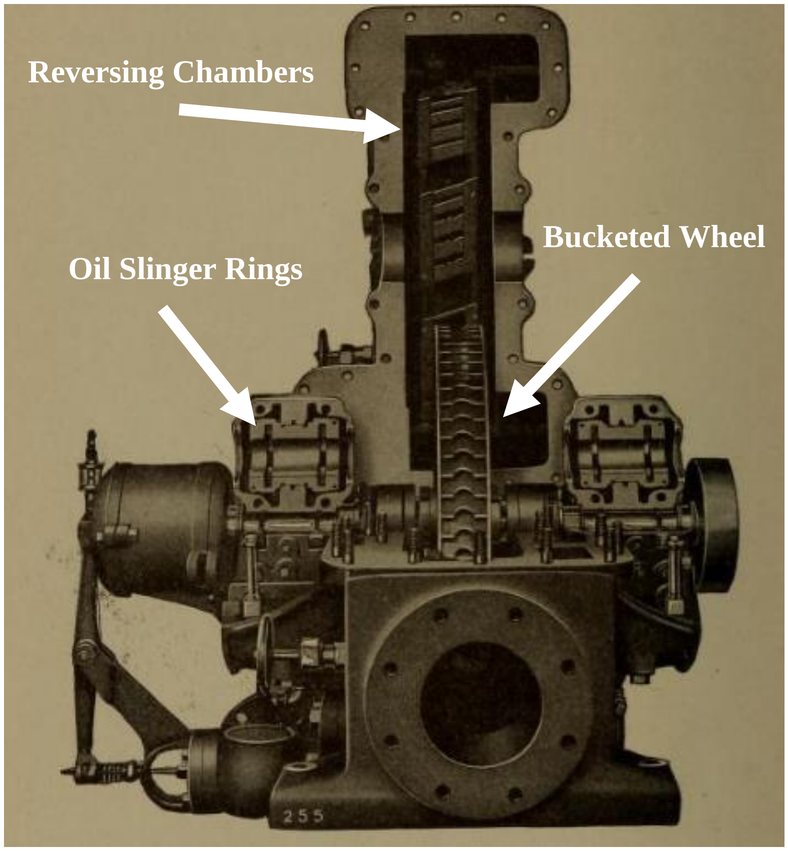

Figure 1: Cutout of a Terry turbine modified from Leland, W. S. *Steam Turbines*. American Technical Society, Chicago, IL: 1917.

1.2 Project Motivation

In speculations of what could have caused RCIC to fail, one culprit is the Terry turbine's oil and bearings facing degradation that led to a mechanical failure of the shaft[3]. Due to this dilemma, this research designed a system to test oil degradation and bearing wear from oil degradation at beyond design conditions for extended periods of time, matching RCIC's lifespan during the nuclear accident. This new data will go towards evaluating the current operating condition bands of the Terry turbines in nuclear, such as temperature and lifespan, and possibly providing new evidence that the Terry turbine can operate over a wider band of operating conditions than currently used.

1.3 Project Objectives

The objectives of this research are as follows:

- Develop methods to evaluate oil degradation and bearing wear
- Construct a new facility capable of collecting data to monitor and track oil degradation and bearing wear for two different sized turbines
- Collect data to show the success of the new facility and methods
- Allow for flexibility in order for future work to be completed

1.4 Importance of Work

The importance of this original work is that, to the author's knowledge, there is not currently recorded data available to show the effect of oil degradation and elevated oil temperatures on bearing degradation of a Terry turbine in the nuclear industry. This new testing facility will give the opportunity to observe and record the performance of both G and Z size Terry turbines in which the data can go towards improving nuclear power's safety.

2. LITERATURE SURVEY

2.1 History of Terry Turbines

Revak-Keene Turbomachinery Services is a business out of LaPorte, Texas that specializes in steam turbine refurbishment, sales, and servicing. They sell a variety of steam turbines to fit their costumers' needs and one style of turbine they have decades of experience with is the Terry turbine. The author was not able to find data that was of the caliber that the management team of Revak-Keene could provide.

In discussions with a turbine shop foreman, Thomas Saucedo Jr, Mr. Saucedo told of how the history of Terry turbines is an oral history that includes more stories and experience passed around more than actual reports. His repairmen would tell stories of Terry turbines they had serviced due to running misaligned, missing oil for a few weeks, or even running on liquid water instead of steam, but when asked for anything written or even photos there was no evidence. When asking if they had any books to reference, Mr. Saucedo again informed that the workers learn by refurbishing or servicing the turbines, not by books or reports (personal communications, December 4, 2018).

Lendell Keene, a man with forty years of experience, confirmed this through stories and his own personal suggestions for the project. Mr. Keene would explain the durability of the Terry turbines and more examples of how the turbines could withstand major misuse for months with the users seeing no performance changes. When explaining the conditions of RCIC's running during Fukushima Daiichi and the conditions Terry turbines see in the nuclear power industry, Mr. Keene was shocked at how conservative the nuclear industry was with their turbines and explained how they could handle so much more, but once again there was no physical data to prove these statements, only years of experiments (personal communications, October 2018).

2.2 Journal Bearings

The Terry turbine utilizes journal bearings to support the wheel driven shaft. The Z series utilizes a brass bearing while the G series utilizes a Babbitt bearing. Journal bearings are typically chosen for relatively low velocities, such as what the Terry turbines run at, for the simplicity in the lubrication system[7]. In the Terry turbines, oil is brought into the inner surface of the journal bearing through oil slinger rings which, when the turbine is running, creates a lubricant film. This film has a high enough pressure from the relative motion to create a wedge of oil that the shaft is in contact with. This allows for proper lubrication as long as there is oil in the reservoir and the turbine is spinning at operating speeds, a lack of lubrication allows for metal to metal contact of the bearing and shaft which creates wear on the surfaces. This wear occurs in the form of wiping the surface material or creating porous holes that can cause uneven clearances. The properties of the lubricant also matter as the viscosity needs to stay in an appropriate range (range depending on application) in order to maintain the film[7].

2.3 Lubrication

In order to reduce bearing and shaft wear, the proper oil is chosen for each application. After surveying a variety of nuclear power plant engineers through TTExOB it was noted the most commonly used oil was Mobil DTE™ 732. This specific lubricant is a turbine oil, created for use in steam turbines, such as the Terry turbines, due to its higher oxidation inhibitors which reduce the degradation of the oil when exposure to water compared to other oils. According to the MSDS, it has a viscosity of 31.5 cSt at 40°C and as the temperature increases the viscosity decreases to 5.68 cSt at 100°C[8].

2.4 Contribution to Literature

Data that comes out of this new facility will be able to confirm the statements from the Revak Keene team in a way that will be tracked for coming generations, no longer relying on the verbal communication of data. This data will also be directly available to the nuclear industry as the test procedures will be recorded meticulously along with calibration of the facility.

3. EXPERIMENTAL FACILITY DESIGN AND CONSTRUCTION

3.1 Experimental Facility Layout

The following section describes the experimental facility for the oil and bearing facilities within the Nuclear Heat Transfer Systems (NHTS) Laboratory.

3.1.1 Oil Facility Layout

The diagram below, Figure 2, shows a simplified layout for the oil facility. The major components are the fume hood, with hot plates, viscometer, and thermocouples (TC) inside, and the high precision scale at another location. The thermocouples record the oil reservoir temperature during heating and the viscometer is used to check viscosity at 40°C with the potential for online measurements. The high precision scale is used in the process of testing oil residue.

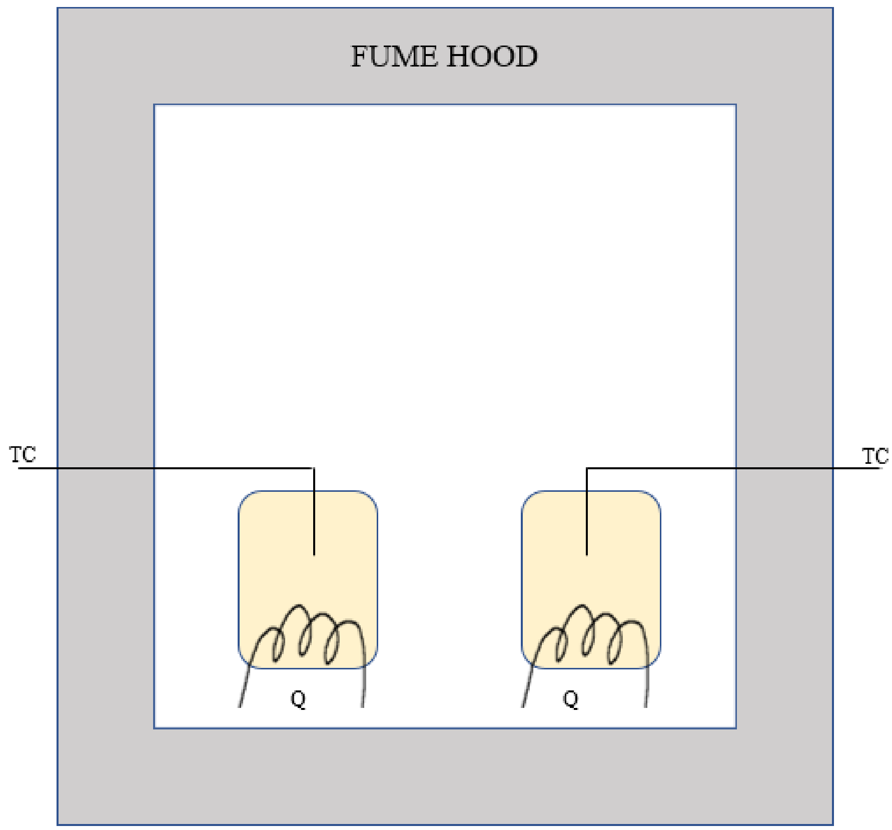

Figure 2: Oil facility diagram where Q denotes the heat adding hot plate and the yellow boxes denote the oil filled beakers.

3.1.2 Bearing Facility Layout

The diagram below, Figure 3, shows a simplified layout for the bearing test facility. The major components are the turbine, bearings, motor, variable frequency drive (VFD), torque meter, and safety coupling. The VFD controls the motor which spins the turbine shaft that is being monitored by a torque meter and tachometer connected with a safety coupling. The final layout is seen in Figure 4.

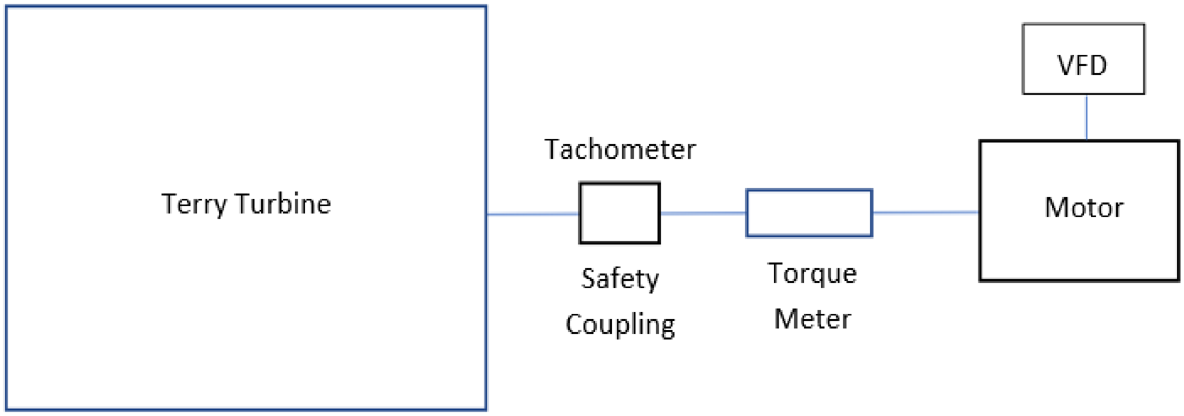

Figure 3: Bearing facility diagram

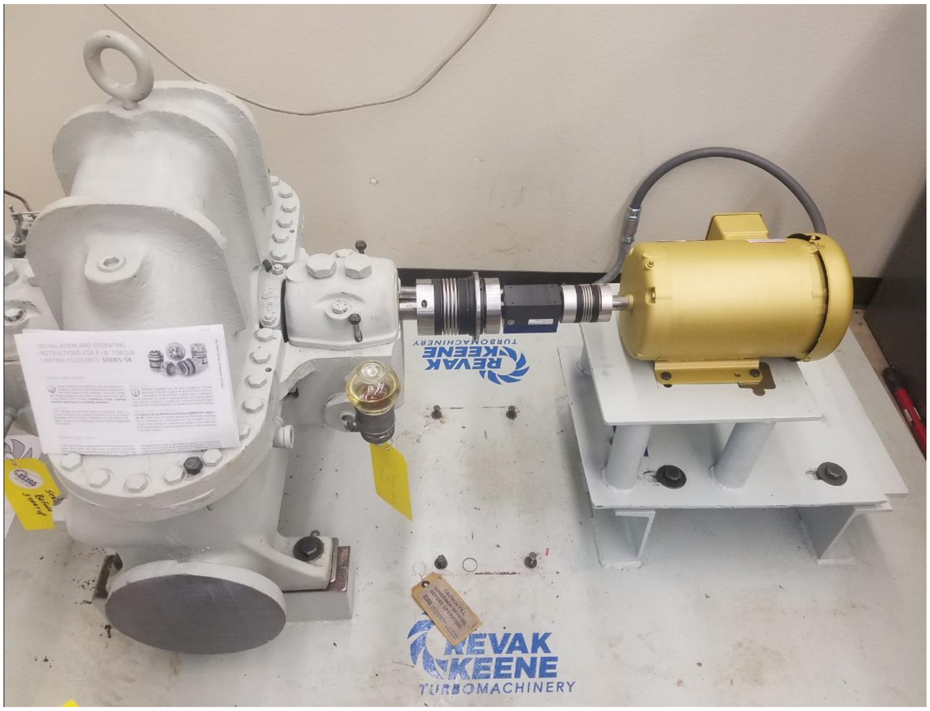

Figure 4: Bearing facility layout

3.2 Experimental Equipment

The following section details the major experimental equipment used in the oil and bearing test facilities.

3.2.1 Fume Hood

In order to meet safety requirements, set by Texas A&M University's Department of Environmental Health and Safety, following ANSI/AIHA Z9.5-2012, a fume hood was installed in order to do the oil testing. Specifically, a Labconco Protector® Premier® Laboratory Fume Hood, 10040 series, was installed. This 4 ft wide unit was installed with features such as chemical resistant work surface, required face velocity of over 100 cubic foot per minute while sash is half open, proper storage cabinet for chemicals, and external blower to limit noise inside the building[9]. Figure 5 shows the hood set up within NHTS.

Figure 5: NHTS fume hood

3.2.2 Hot Plates

Hot plates were chosen for the oil testing based off of their heating area and power rating. The Thermo Scientific Type 2200 “Large-Capacity Hot Plate” was chosen due to its 12 in x 12 in heating surface that would fit either one large beaker or multiple smaller beakers and aluminum top plate. It also included a favorable controller with stated control of the surface temperature to ±3°C at 371°C. Two hot plates were purchased in order to perform multiple tests at once or double the capacity of one particular test, as shown below in Figure 6[10].

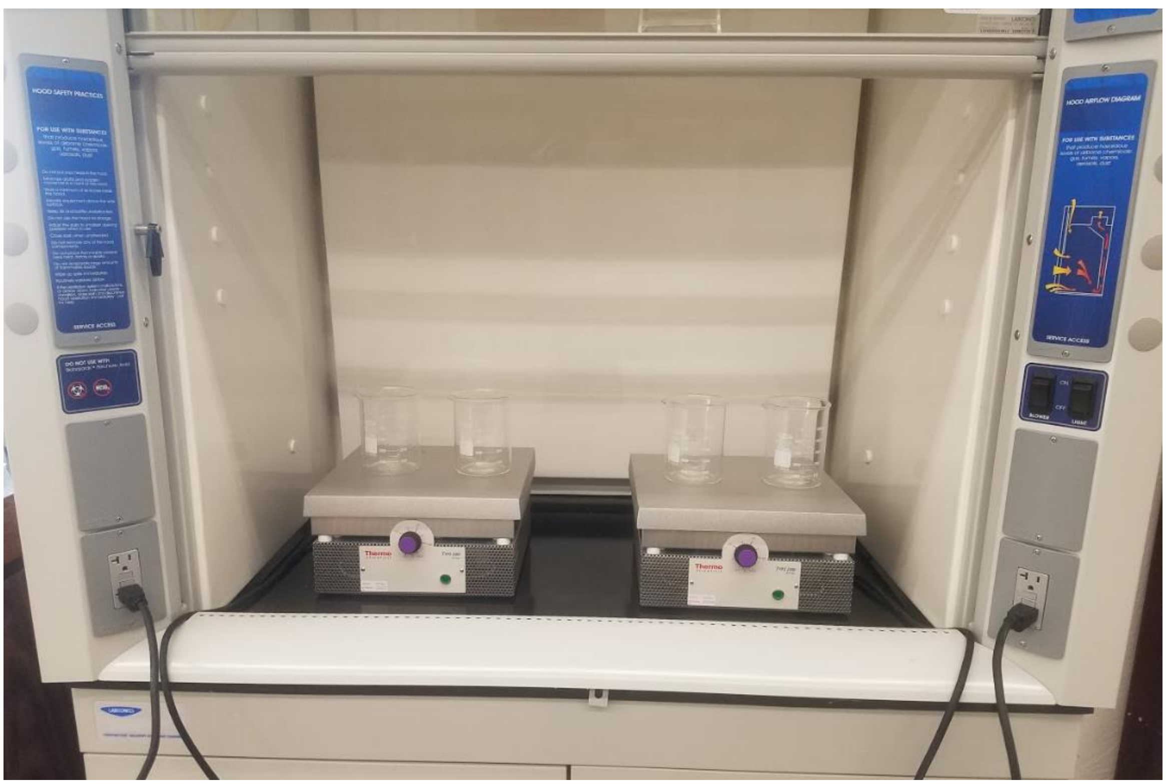

Figure 6: Hot plate set up allowing for multiple beakers

3.2.3 High Precision Scale

In order to maintain high precision of weighing low mass items, such as filter paper, a high precision scale was needed. The scale used in this experiment was from the lab of Dr. Folden and Dr. Chirayath in the Department of Nuclear Engineering. The chosen scale was a Mettler Toledo XP105DR with a readability of 0.1 mg and repeatability of 0.04 mg during its coarse range with a maximum capacity of 120 g, but at finer ranges, like what are expected for this project, the readability is 0.06 mg and repeatability of 0.007 mg for samples up to 100 mg. The scale is shown in Figure 7 sitting on a marble slab to dampen any outside movements that would alter data collection[11].

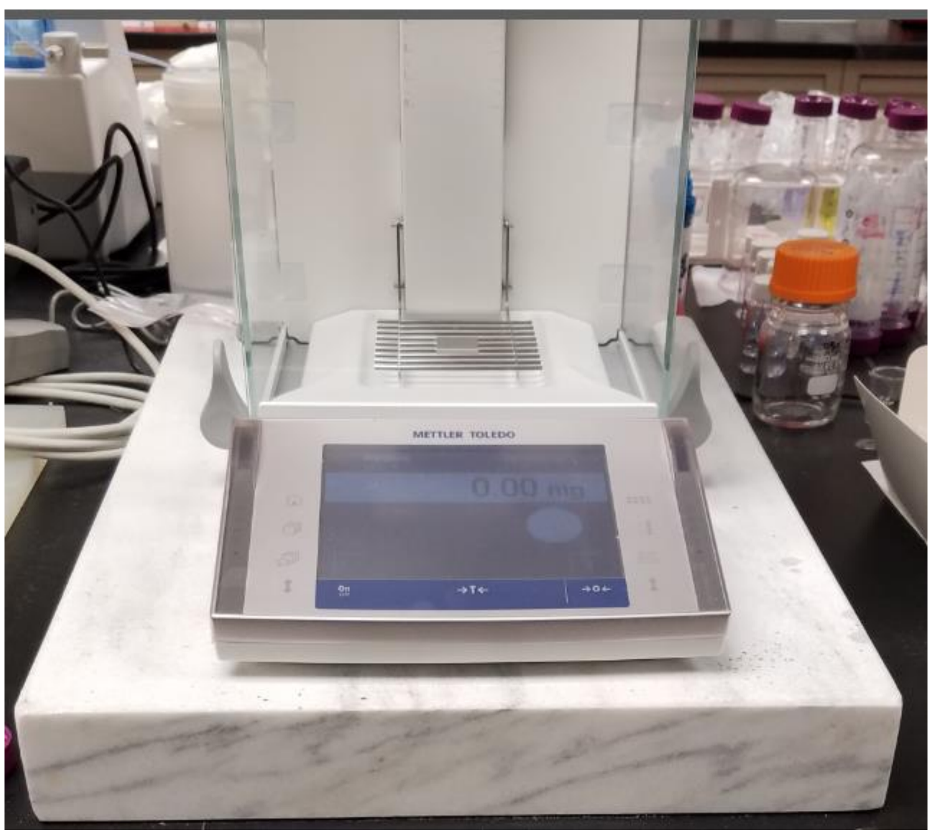

Figure 7: Mettler Toledo high precision scale

3.2.4 Terry Turbines

This new facility was designed in order to test both Z series and G series Terry turbines. First, a refurbished ZS-1 Terry turbine, named “The Duke”, was purchased from Revak-Keene, seen in Figure 8 below. This turbine includes an 18 in wheel and is rated for 3600 rpm. It was air tested to ensure operability before leaving the Revak-Keene facility and was serviced by their technicians once it arrived at the NHTS Lab, including alignment and oil flush. Figure 8 also shows the location of the governor end and the oil bubbler, both which will be referenced later.

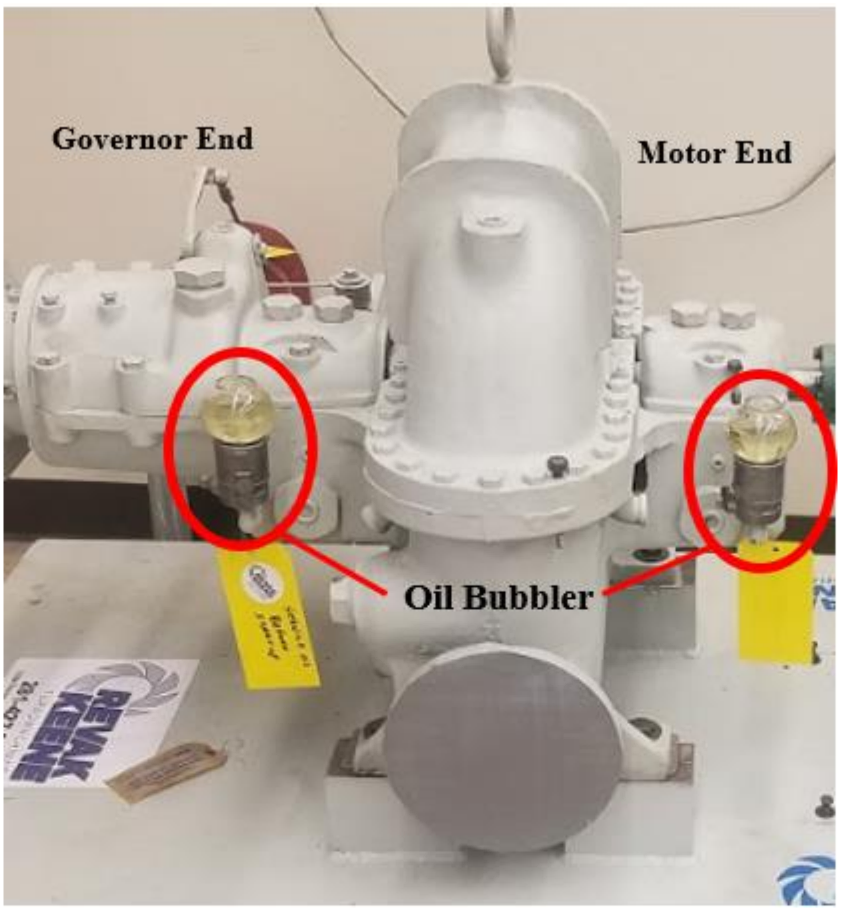

Figure 8**:** Labeled ZS-1 Terry turbine ("The Duke")

Seen on the turbine are two oil bubblers, a method of oil level indication that works via a set “spider” that sits on the surface of the oil. When the oil level is lower than the setting the bubbler drains oil into the reservoir until the spider rises again, shown in Figure 9.

Figure 9: Spider used for oil level setting inside oil bubblers

Another Terry turbine to be added to the facility was a GS-2 loaner from Exelon’s Clinton Power Station (CPS) that was refurbished by Revak-Keene. This turbine is larger than the ZS-1, having a 24 in wheel and is rated for 4000 rpm, but it is not currently rated for steam use. It was also air tested and inspected before leaving the facility and was only approved for air testing, no steam. Figure 10 on the following page shows the wear of the turbine when it was delivered to Revak-Keene versus its refurbished condition. During the refurbishment process the turbine wheel had any rust sanded off, had a protective coating applied, and the rotor shaft balanced. The oil system was drained and refilled while the bearings were either replaced or re-Babbitted to Original Equipment Manufacturer (OEM) standards.

Figure 10: GS-2 Terry turbine from CPS before (top) and after (bottom) refurbishment by Revak-Keene Turbomachinery

3.2.5 Bearings

While the turbines were delivered to NHTS with bearings already installed, an extra set was delivered with each. In Terry turbines, the bearings are journal bearings with oil slinger rings that as the shaft turns, the rings turn and bring oil from the oil reservoir into the bearing. The slinger rings sit 3/8 inches into the reservoir to maintain constant lubrication to the bearings.

For the Z series Terry turbine, the bearings are brass, Figure 11, with oil slinger rings. However, for the G series, the bearings are a steel tube with a thin Type 2 Babbitt lining, Figure 12, still with oil slinger rings. Both sets of bearings were manufactured to OEM standards by Revak-Keene's Bearing Shop, ensuring the bearings are of the same quality of those within a nuclear application. The G series bearings were also arranged to be re-babbitted, if needed, to repair the bearings to required quality.

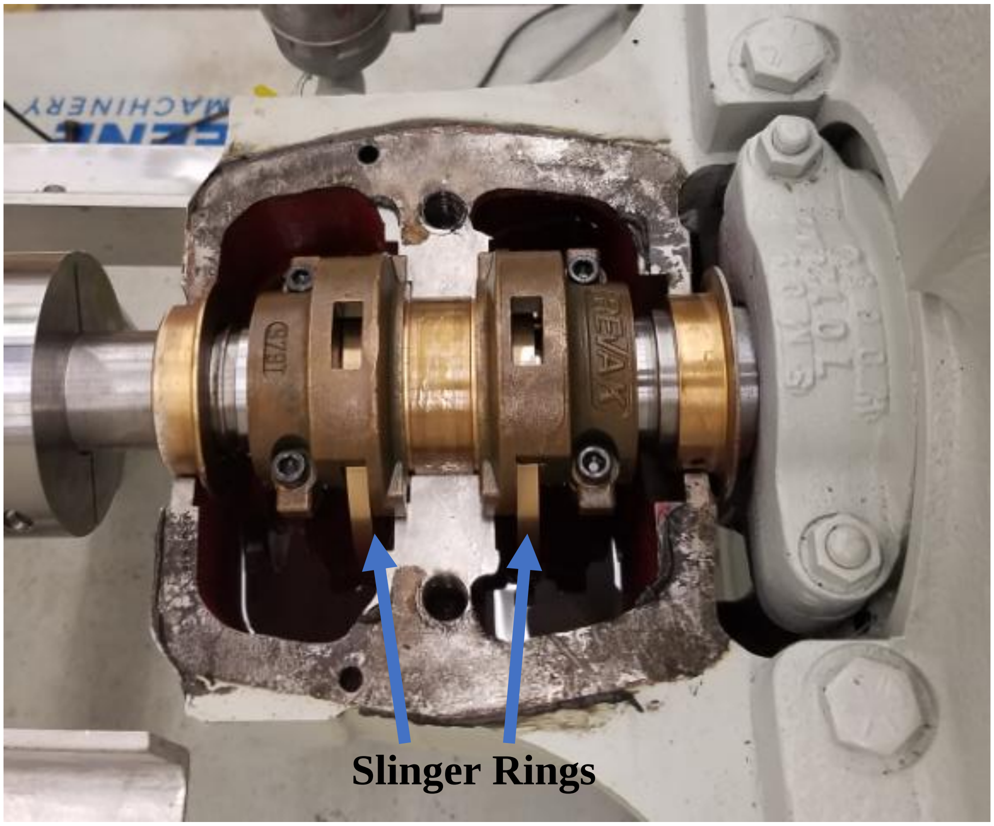

Figure 11: Brass bearings inside a ZS-1, The Duke, with labeled slinger rings

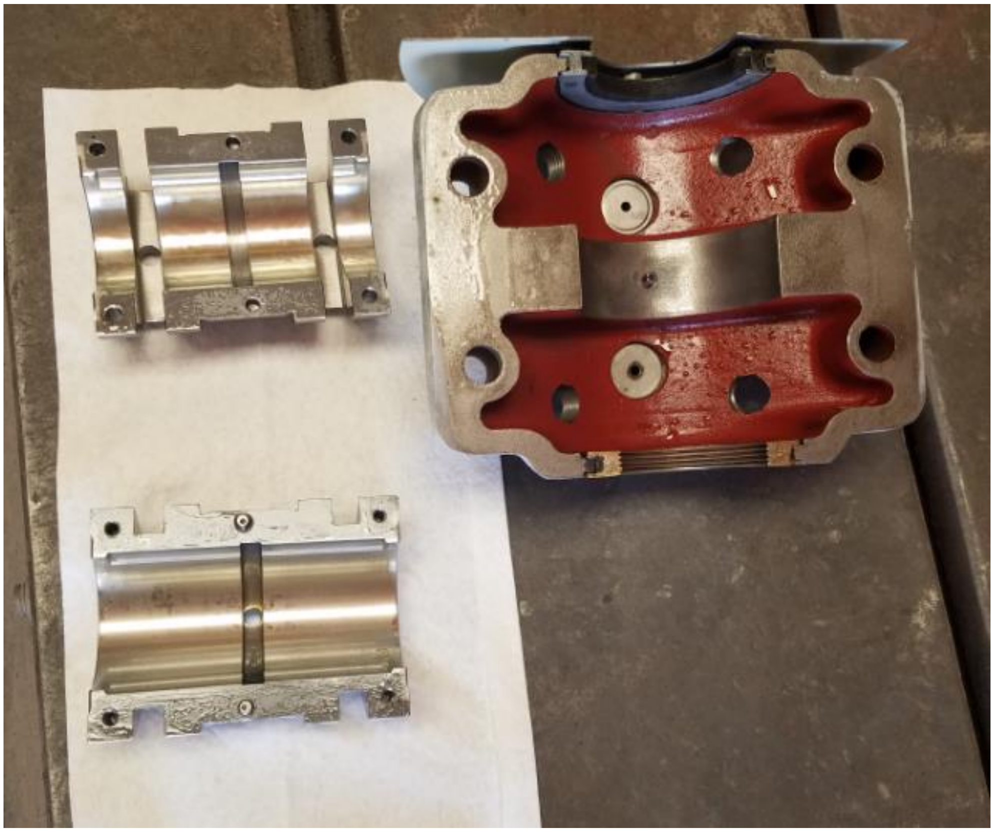

Figure 12: Disassembled steel and Babbitt G bearings

3.2.6 Drive Motor

In order to drive the turbine shaft, the Baldor EM3555T motor was installed, shown in Figure 13. This 2 hp motor has the necessary range of up to 3490 RPM at 60 Hz; the range was chosen based off of input from the US nuclear power industry. This three-phase, 230V, motor is also inverter-rated so that it can be controlled by a VFD for easy operating and changing of speeds mid-test[12].

Figure 13: Baldor EM3555T motor

Revak-Keene also manufactured mounts for the motor. The first mount attached to the skid for the ZS-1, taking the place of a pump, is shown in Figure 14. A separate mount was also manufactured to properly align the motor to the GS turbine, Figure 15.

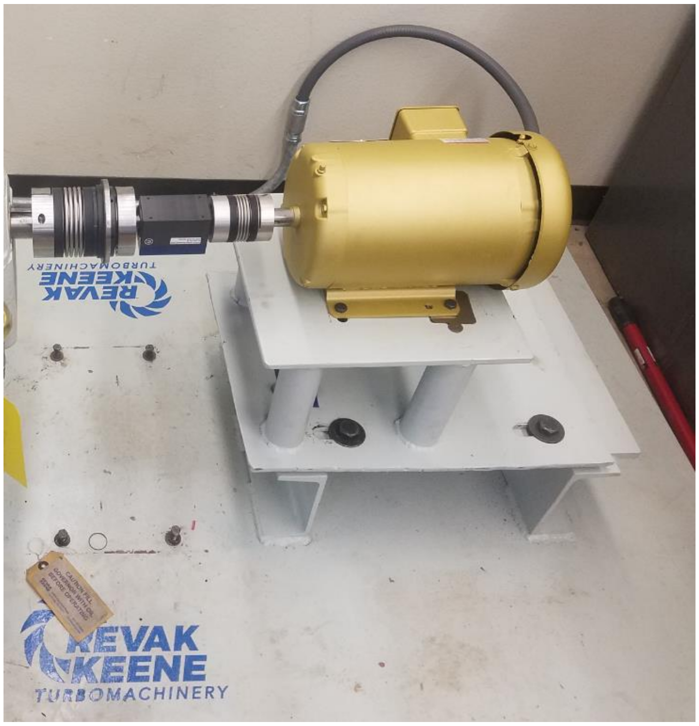

Figure 14: Motor on the mount for the ZS-1, The Duke

Figure 15: Motor mount for the G series bearing testing

3.2.7 Variable Frequency Drive

A Galt G320-00070UL-01 VFD, Figure 16, was installed to a 280V circuit and the Baldor motor in order to use it as a speed controller. The VFD is rated to control 230V, 2 hp, 3 phase devices by adjusting the frequency sent to the selected motor. Appendix C shows the recommended settings for the bearing test operation in order to properly set up the VFD for the desired motor and test. The VFD can also be controlled through analog signals, but either hand control or analog control still includes the proper trip functions to ensure no overload is sent to the motor[13].

The speed and frequency are directly related so the necessary frequency for the desired speed in RPM can be determined using Eq. (1).

$$f = \frac{Desired\ RPM * 60}{3490} \tag{1}$$


Figure 16: Galt 320 VFD

3.2.8 Safety Coupling

Custom couplings were necessary to connect the motor system to the turbine due to the difference in shaft diameters of the turbines and the shaft diameters of the torque meter created in metric units. With the risk of bearing failure and therefore shaft seizing, a safety coupling was chosen. The SK2 from R+W, Figure 17, has a disengagement torque of 19.25 Nm. When this torque is exceeded the coupling disconnects the shafts using a ball spring apparatus. An internal disc spring holds an actuation ring up to a ring of steel balls set into a designed location, but when the set torque is exceeded, the disc spring flips over and removes pressure from the actuation ring so the balls are no longer held in place, disconnecting the two shafts[14].

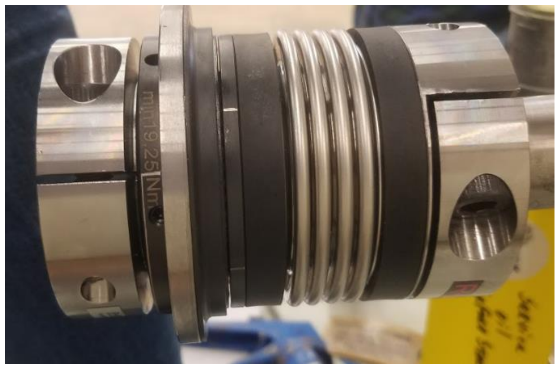

Figure 17: R+W SK2 safety coupling

This disengagement protects the torque meter and motor from experiencing damaging torque and protects researchers as the chance of any parts breaking off and flying decreases dramatically. The safety coupling is under a rotating part guard for additional protection, shown in Figure 18.

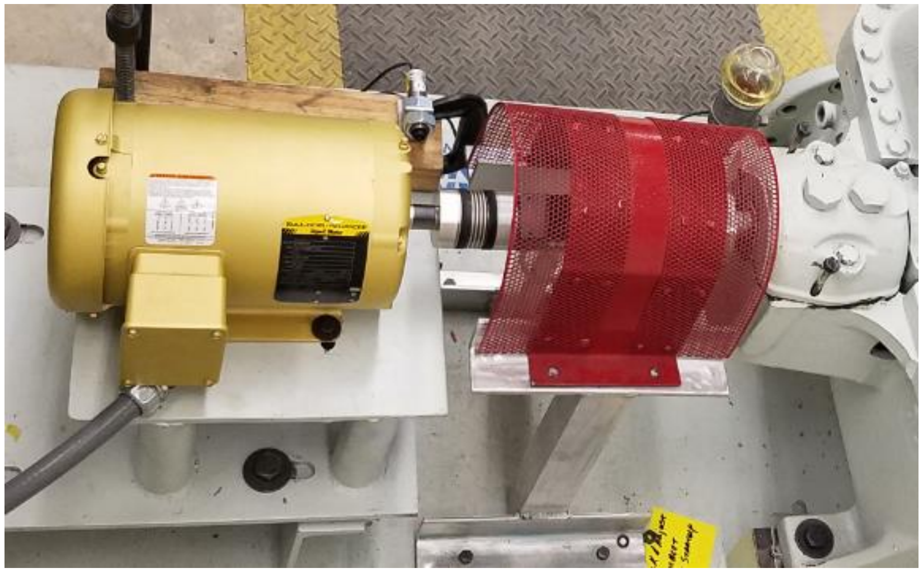

Figure 18: Couplings protected by a rotating parts guard on the ZS-1 bearing test set up

After disengagement, it is an easy process to reset the coupling; the coupling can be re-engaged by lining up the cut marks on each half and applying a uniform force, method seen in Figure 19, along the shell towards the turbine to “unflip” the disc spring, reset the steel balls, and close the gap between shafts[14].

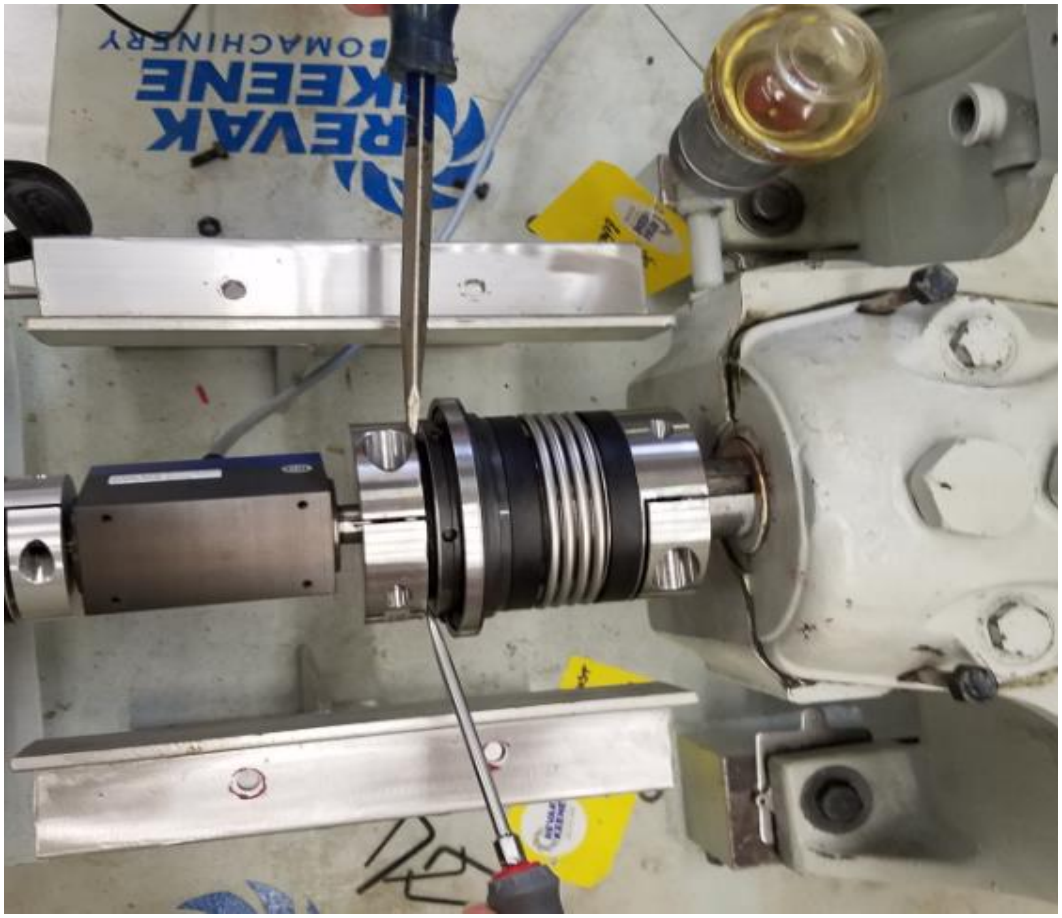

Figure 19: Demonstration of re-engaging the SK2 safety coupling with proper alignment and force points

3.2.9 Data Acquisition System

In order to read the analog signals transmitted by instrumentation and convert the signal to online data to monitor, a data acquisition system (DAQ) is required. The DAQ is made up of hardware and software paired together in order to best fit this new experiment's needs. The DAQ setup used was part of the NHTS Lab before this new facility, but software was altered for the new instrumentation[15].

3.2.9.1 Hardware

The NHTS Lab utilizes a National Instruments (NI) SCXI system made up of the SCXI-1000 chassis that is set up for four modules with 32 inputs for either voltage or thermocouples and a cold junction sensor input from the terminal block. These modules were chosen for their lowpass filters capable of blocking out additional electrical noise. The system is currently set up for two SCXI-1002, 2 Hz bandwidth, a SCXI-1102B, 200 Hz, and a SCXI-1102, 10 kHz. This chassis is connected to a data acquisition card, NI PCIe-6341, in the PC via shielded cable[15].

This setup allows for thermocouples to be directly wired into the terminal blocks, but current outputs require additional hardware, specifically a 249 Ohm resistor within the current loop. The 249 Ohm resistor was chosen during the DAQ set up over a 250 Ohm resistor to add a buffer for any offsignal high signals. This 249 Ohm resistor allows for a voltage drop to be measured by the DAQ system by input terminals wired to each side of the resistor[15].

3.2.9.2 Software

Utilizing what was previously set up on the lab's DAQ PC, LabVIEW 2015 32-bit ran on a 64-bit Microsoft Windows 7 Professional. The LabVIEW Virtual Instrument (VI) was altered from previous lab arrangement VI's, but still utilized the functionality while managing CPU. The block diagram within the LabVIEW VI was kept predominately the same as previous NHTS versions in regards to how data were recorded, averaged and paired with its standard deviation within an array. During data collection, 200 samples per second are read and averaged in order to obtain 10 data points per second along with the corresponding standard deviation[15].

For this data collection method, while the mean and standard deviation are stored, for current signals, the mean also goes into a calibrated block to convert the raw signal into a value that corresponds to the user input calibration and conversion performed for the particular instrumentation the signal came from, this is discussed more in 4.4 Calibration. The new value, in appropriate units, is then stored in an array with the raw mean and uncertainty. For thermocouples, the DAQ is already programmed to process internally, cutting the need for the calibration block[15].

While the mean, standard deviation, and, if necessary, converted signal are outputted into a text file for later analysis, they are also displayed in live time for online monitoring of the experiment paired with alerts in case the system begins operating outside the desired conditions[15]. For the oil system, it is important that the temperature is displayed to ensure that the oil bath is at the desired temperature while in the bearing facility it is important that the speed is appropriate, torque is consistent, and the temperature is as desired as well.

Due to these complexities, two separate programs were created in order to specialize each facility and open the potential of utilizing two separate DAQ systems if that option becomes available. Figure 20 and Figure 21 on the following pages show the front panel display of the LabVIEW programs for the oil and bearing facility, respectively, in which the conditions of interest are also displayed.

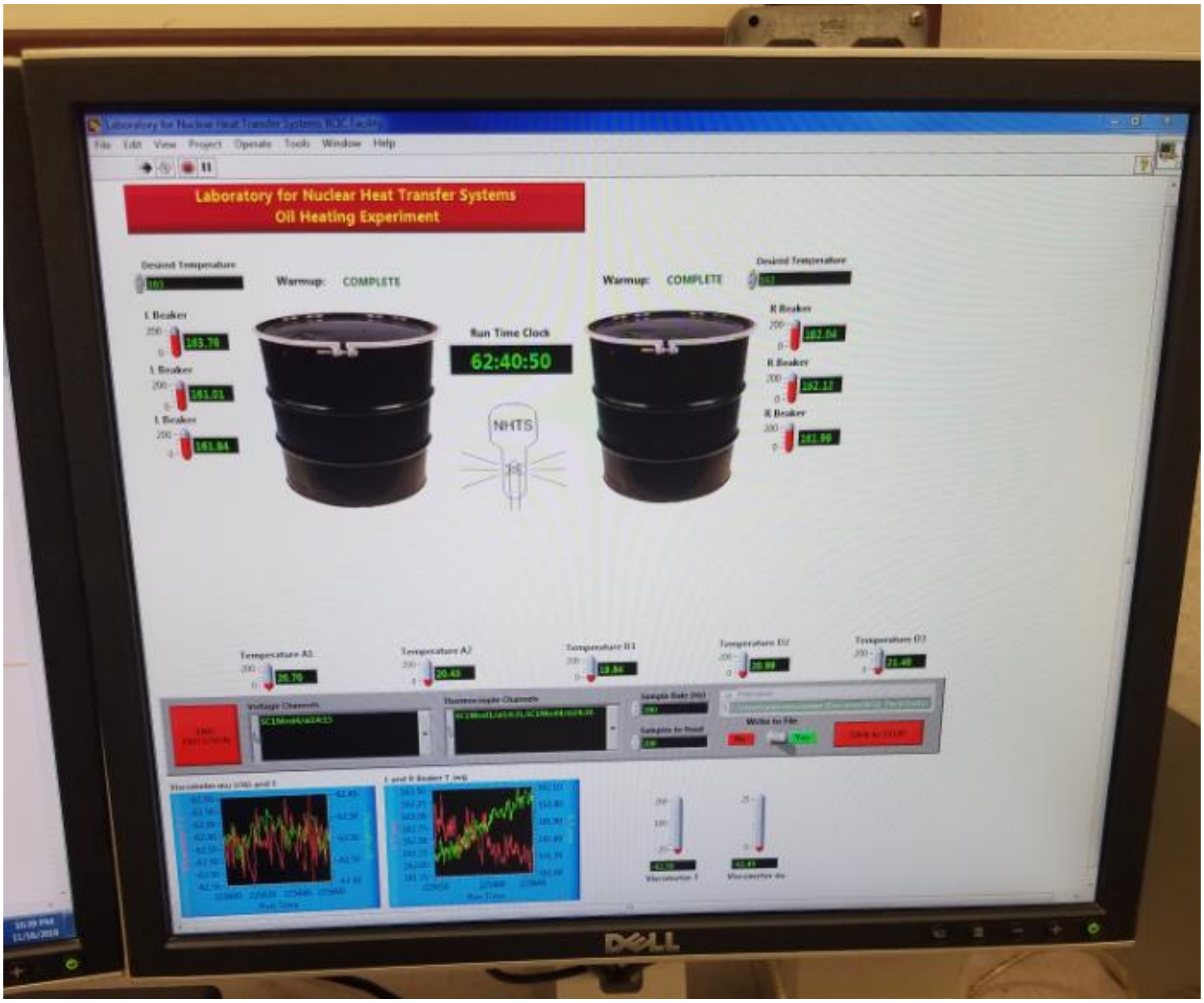

Figure 20: Front panel interface for the oil facility's LabVIEW program

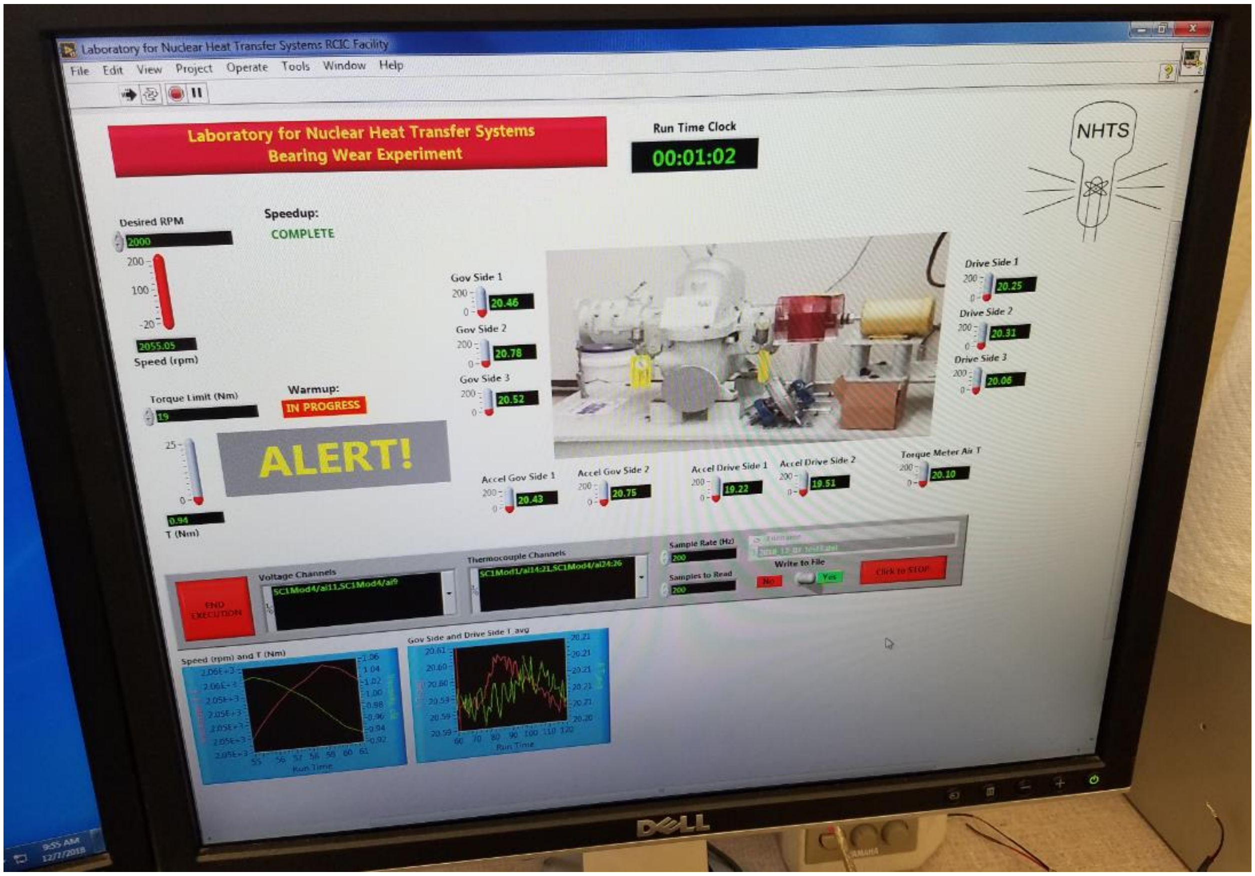

Figure 21: Front panel interface for the bearing facility's LabVIEW program

3.3 Instrumentation

This section details the instrumentation used within the experimentation. Table 1 lists the instruments with their associated properties.

Table 1: Instrument p10roperties

Instrument	Manufacturer	Model	Range	Instrument Error
Viscometer	Brookfield	FAST103	-20°C - 200°C 1-3,300 cSt	4% of reading
Torque Meter	HBM	T21WN	0-20 Nm	0.2% of reading
Tachometer	Monarch	ACT-3X	5-250,000 RPM	± 0.001% of reading
Thermocouples	Omega	Type T; SLE	0-350°C	±0.5°C or 0.4% of reading
Accelerometer	PCB	320C33	±50 g pk; 1-4000 Hz	100mV/g sensitivity (±10%)

3.3.1 Viscometer Probe

A Brookfield, Model FAST103LXX2AXA, In-Line Viscometer was acquired in order to test the online and offline viscosity of oil samples at temperatures up to 200°C. This Brookfield Model AST100 Immersion Probe viscometer operates by measuring the resistance to a center probe's torsional oscillation powered by magnetic coils within the housing. The resistance is measured by recording the phase shift in frequency of the probe and converting that into a scaled 4-20 mA value corresponding to a viscosity range. It is capable of measuring up to 3,300 cSt at a temperature range of -20°C to 200°C[16].

3.3.2 Torque Meter

A T21WN torque meter from HBM, Figure 22, was chosen in order to record the torque on the shaft during the test. This specific torque meter is capable of outputting torque, angle of the shaft from a referenced location, and rotational speed using either a frequency or voltage output. The measurable torque limit is 20 Nm and the maximum speed is 19,000 RPM. Voltage output was chosen for compatability with the DAQ[17].

Figure 22: HBM T21WN torque meter

3.3.3 Tachometer

In order to ensure the turbine is rotating at the appropriate speed, a Monarch ROLS-W laser sensor is used as a tachometer. Figure 23 shows its installation, recording the speed of the motor's shaft by the laser indicating when a white strip on the motor shaft passes the set location. The laser records the speed and outputs a 4-20mA signal that is sent to a Monarch ACT-3X that displays the speed as well as sending the 4-20mA signal to the DAQ. This tachometer is capable of measuring 250,000 RPM with resolution set by the Monarch ACT-3X[18,19].

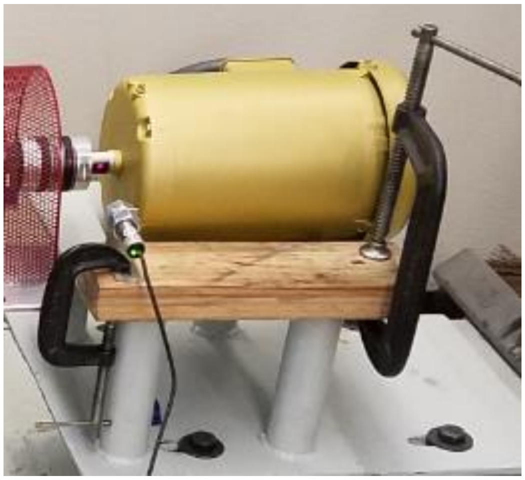

Figure 23: Tachometer alignment on the motor

3.3.4 Thermocouples

Thermocouples are used throughout both test facilities to record different temperatures such as oil reservoir temperature, ambient temperature, temperature near instrumentation to ensure safe operation, and, for the GS Bearing test, actual bearing temperature. The thermocouples chosen for these experiments were Omega type T thermocouples with special limits of error, ±0.5°C. Sheath lengths of 18 in and thicknesses of 0.062 in were chosen for easy manipulation into the desired locations[20].

3.3.5 Accelerometer

In order to measure the vibration of the turbines due to misalignment or bearing wear, accelerometers were chosen. Specifically, as seen in Figure 24, a PCB 320C33 high sensitivity ICP® accelerometer. These unidirectional accelerometers will be distributed with two for each bearing housing to provide reading of vibration in two directions to track misalignment. The high sensitivity of 100mV/g, as well as 1 to 4000 Hz frequency range with a broadband resolution of 0.0003 g rms, was chosen in order to pick up even minor vibrational changes in the turbine housing. ICP style is important in order to for the accelerometer to be able to properly communicate with the DAQ[21].

Figure 24: PCB 320C33 accelerometer

3.4 Calibration

In order for data to be reliable, it is needed to know that the equipment is reliable. This is done through calibrations. Due to this facility being new, most of the equipment was also new and came with calibration documentation. A previously designed LabVIEW VI was used in order to perform additional calibrations through two-point calibration for the viscometer, torque meter, and tachometer. This was done by having the instrumentation transmit a full signal, 20mA, as well as a zero signal, 4mA, over at least a 100 s time frame and taking the average. Next, Eq. 2, two-point calibration equation, was applied due to the linearity of the analog output to the conversion of analog to digital[15].

$$y = a \times (x - b) \quad (2)$$

The results of the calibration for the equipment used in the preliminary tests are shown in Table 2 and also programmed into the appropriate LabVIEW program.

Table 2: Calibration data for the instruments

Instrument	a	b
Viscometer (Temperature)	0.2510	0.9959
Viscometer (Viscosity)	0.2511	0.9957
Tachometer	0.2510	0.9948
Torque Meter	0.02510	0.0995

In regards to the thermocouples, since new thermocouples were used, wire length was relatively short, and LabVIEW is proficient at reading thermocouples, the special limits of error were assumed sufficient with minimal to no degradation or drift. In order to ensure this was a safe assumption, the connections and wiring were done meticulously being sure to properly ground the electronics. The current DAQ card, NI PCIe-6341 X Series data acquisition card, was also calibrated less than two years ago, falling in the ANSI/NCSL Z540-1-1994 NI compliance standard[15]. Calibration certificates for the DAQ system as well as the instruments are physically and digitally stored.

4. SHAKEDOWN TESTING AND FACILITY IMPROVEMENTS

4.1 Shakedown Testing

4.1.1 Oil Facility

During shakedown testing for the oil facility, water was boiled to determine if there was a consistent temperature distribution across the hot plate as well as deciding how necessary insulation would be to keep heat from escaping the beaker. This was done by simply filling multiple beakers with 250 mL of water and placing a thermocouple in each while turning the hotplates on to the same setting. The temperature was monitored as a function of location as well as a function of whether there was insulation or not. A sample test was also ran with oil.

In the end, it was decided that the insulation was necessary, otherwise it would take hours to even boil water, and that the location on the hot plate did not matter but the location of the hotplate within the fume hood did affect the results due to the air flow through the fume hood. The back of the fume hood had a greater flow due to the design path of air flow, this created a larger heat loss of the heat plate if the hot plate was further back.

Unexpectedly, during the oil shakedown test, after 12 hr, the temperature readings began to dramatically change on LabVIEW, the temperature readings began to decrease even though the heat source was being increased. Initially the terminal block was only grounded on the channels surrounding the used channel so as a precaution all of the channels were grounded and another test was run with no issues.

4.1.2 Bearing Facility

For the bearing shakedown testing, it started with a tear down and replacement of the bearings per the procedure created from shadowing Revak-Keene. Initial bearing alignment testing was done by manually rotating the turbine shaft without the bearing housings on then with the bearing housing on. Manually rotating ensured the shaft was not seized.

Next, the experiment was run at room temperature following procedure, but only running for a few minutes at a time. Throughout this testing the VFD was controlled by manually changing the frequency with the front knob and also by setting the proper frequency and hitting "run" to find an acceleration time that does not trip the unit. During this testing the tachometer was also used to ensure the Monarch ACT-3X, DAQ, and VFD were all reporting the same values.

4.2 Modifications

4.2.1 Oil Facility

Modifications to the oil facility included adding insulation to the oil beakers to limit the heat loss from the fume hood air flow as well as grounding all unused channels in the DAQ system in order to fix the inaccurate responses that were seen. The procedure was also updated to note the ideal location of the hot plate within the hood and sash height.

4.2.2 Bearing Facility

Modifications to the bearing facility included altering the VFD operating settings to the proper acceleration time (90 s) and the decision to run the VFD by setting the proper frequency and hitting "run" versus controlling by the knob.

4.3 Post-Shakedown Repairs

No repairs were necessary after shakedown testing.

5. TESTING

5.1 Oil Testing

In order to prove the new facility adequate for its purpose of testing oil degradation over extended periods of time an initial experiment was performed, following procedures found in Appendix A. Taking input from the TTExOB Committee, it was decided to perform a 72 hr test in which the oil temperature would be raised to (163 ± 5) °C, corresponding to a target temperature of 325°F, and maintained until the 72 hr was complete. Due to safety concerns, two individuals were required to be in the NHTS Lab at all times with one person being the lead to ensure the temperature stayed within its appropriate band. Although all personnel had access to the procedures, the lead was specifically trained on how to properly use the equipment to ensure reliability when the facility designer was not working.

The oil was chosen to be Mobil DTE 732, a turbine oil commonly used in the nuclear power industry for Terry turbines. Two 2500 mL beakers were filled to 2250 mL, insulated, and placed on the hotplates with three thermocouples each, Figure 25. After the 72 hr, the hotplates were turned off and insulation was cut off in order for the oil to cool down quicker. Once the oil was cooled a visual inspection would occur and samples would be taken for the filter residue test.

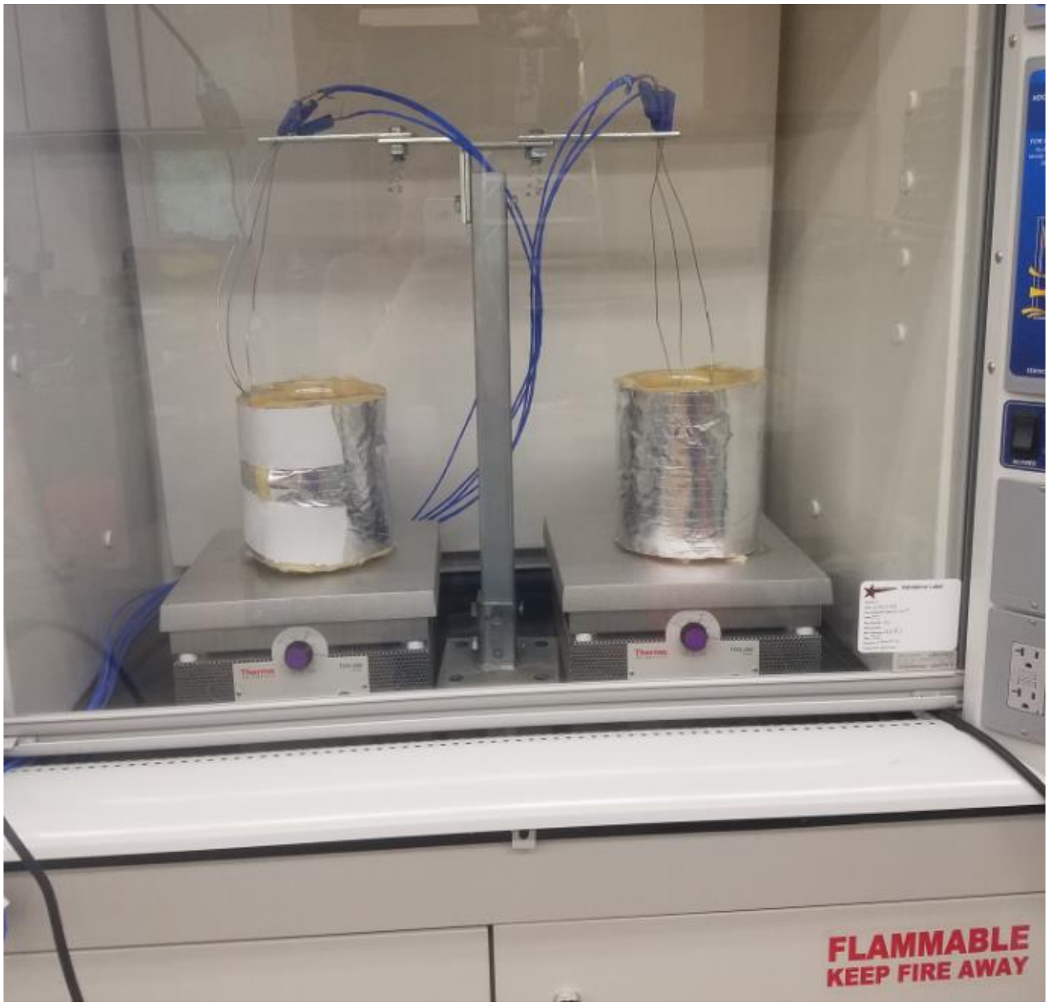

Figure 25: Equipment set up during oil test

5.2 Bearing Testing

To showcase the new testing facility capable of tracking the bearing degradation of a Terry turbine, a baseline 6 hr test was chosen at a mid-range speed, 2000rpm, following the procedure found in Appendix B. The bearings would undergo an initial and final visual inspection while the torque was recorded by the DAQ. The visual inspection would be looking for change in bearing or shaft finish as well as consistent wear while the torque readings would indicate a change of clearances if torque began to increase.

6. RESULTS AND ANALYSIS

6.1 Uncertainty Analysis

The presence of uncertainty is acknowledged in these results and gathered using standard deviations where appropriate. The sources of uncertainty include: instrument capabilities, operator inputs and variance from operator to operator, aleatory sources such as atmospheric fluctuations over the 72 hr time frame, and conversion from analog to digital signal, assumed negligible. The instrument capabilities were accounted for in Table 1 (Section 3.3) and accounted for in plots with error bars where applicable.

For example, the torque plot includes the uncertainty in the instrumentation measurements while other data, such as filter residue results, uncertainty was calculated and shown through standard deviation methods in order to add conservativism and record aleatory uncertainty in the method.

The standard deviation was calculated using the following equations, Eq. (3) and Eq. (4).

$$\bar{x} \equiv \frac{1}{N}\sum x_i \qquad (3)$$ [20]

$$s^2 \equiv \frac{1}{N-1}\sum \left(x_i - \bar{x}\right)^2 \qquad (4)$$ [20]

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

x_i : individual measurement value

N : number of measurements

s : sample standard deviation

In the filter residue test, calculations were done to find differences therefore uncertainty was propagated to obtain a derived uncertainty for each of these results. Eq. (5) was used to propagate uncertainty during addition/subtraction.

$$\sigma_u = \sqrt{\sigma_x^2 + \sigma_y^2} \qquad (5)^{23}$$

x, *y*: direct measurements

u: derived measurement

σ: uncertainty in measurement

6.2 Oil Test

The results of the oil test include a temperature plot showing how the constructed facility handled maintaining the required temperature as well as comparison of the physical color change of the oil and numerical results of a filter residue test.

Figure 26 and Figure 27 on the following pages show the temperature distribution of each individual beaker over the 72 hr time period illustrating the success in maintaining the oil temperature within ±5°C of the desired temperature.

The effects of changing atmospheric conditions and multiple different operators had to be accommodated during testing. This was done by teaching the operators about the equipment. The operators were always attentive to the experiment, but when the sun set or rose, the operators were even more attentive as they were expecting the change. During each shift there was one operator designated as the lead who was trained specifically on how to operate the hot plates as well as any backup measurement methods. The second operator was trained on the equipment, but was more there for safety and as a peer check role to ensure the experiment was being followed out per the given procedure.

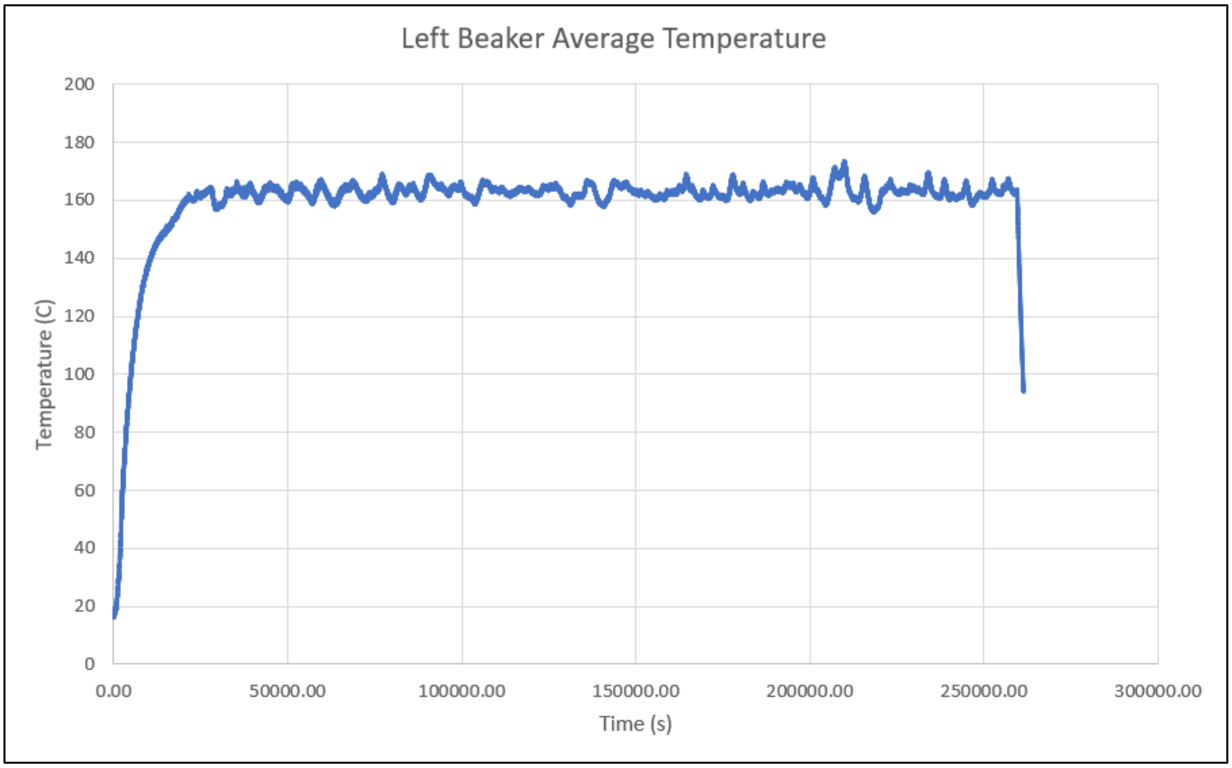

Figure 26: Left beaker average temperature over 72 hr

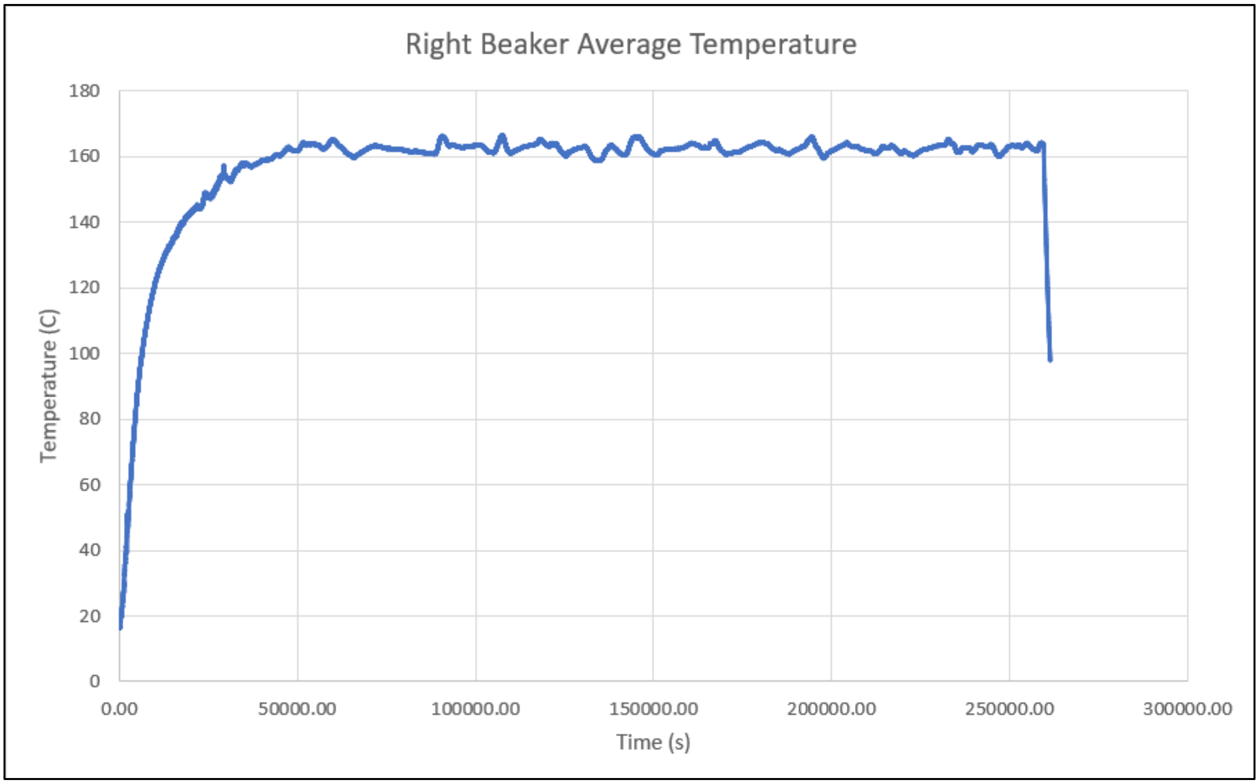

Figure 27: Right beaker average temperature over 72 hr

During the experiment it was noted that the thermal expansion of the oil was noticeable, increasing the volume up to 2500 mL, compared to the 2250 mL at the starting temperature. The other easily noticeable change was the color change of the oil. Figure 28 shows the tested oil next to a small beaker of new oil, noting the color difference and the residue mark showing thermal expansion.

Figure 28: Visual comparison of the tested oil to new oil

The tested oil is cloudy due to particulates suspended in it. Figure 29 shows the particulates left on filter paper after 25 mL of oil was drained through it while Figure 30 shows the difference in color of the filter paper after particulates were trapped in it. In Figure 31, the oil in the Erlenmeyer flask is noticeably clearer due to the particulates being filtered out.

Figure 29: Particulates on filter paper after the oil residue test

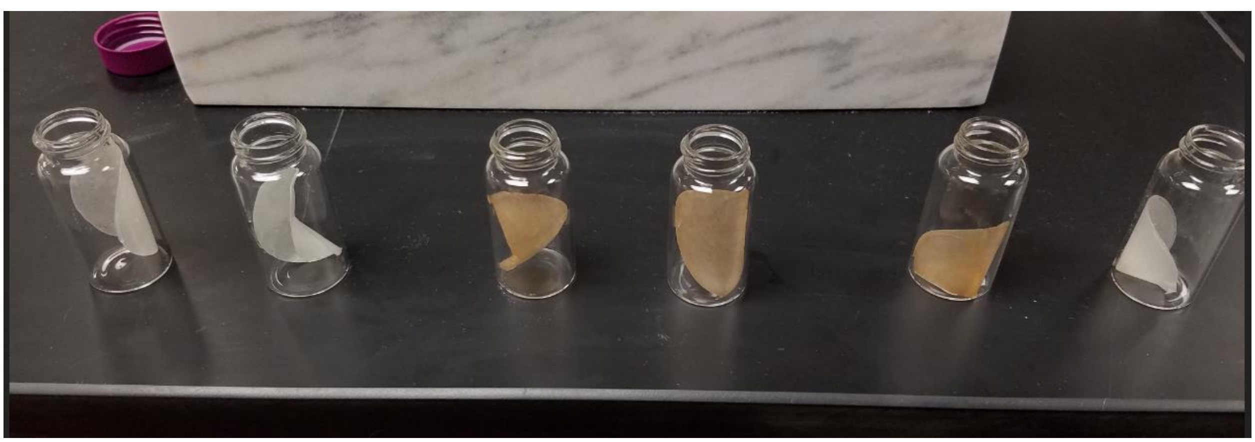

Figure 30: Comparison of filter paper after having new oil and tested oil drained through the filter

Figure 31: Oil after being through the oil residue test

The abundance of particulate in the oil residue was quantified by measuring the particulate mass filtered from six different 25 mL oil samples. Table 3 and Figure 32 show the measured masses, where samples 1 through 3 are from the used oil and samples 4 through 6 are from the new oil. Although the scale has a readability of ±0.03 mg, it was not performing to this accuracy. Therefore, a conservative approach was taken and standard deviation was calculated for the four measurements of each sample and propagated through the calculations.

Table 3: Oil residue test results stating the filter and vial mass before and after filtration

	Mass 1 (mg)	Mass 2 (mg)	Mass 3 (mg)	Mass 4 (mg)	Mean (mg)	Difference (mg)
Sample 1						
Before	13206.35	13206.13	13206.09	13206.15	13206.18±0.116	
After	13320.54	13320.29	13320.11	13319.95	13320.22±0.253	114.04±0.28
Sample 2						
Before	13186.71	13186.11	13185.72	13185.5	13186.01±0.530	
After	13322.66	13322.45	13322.34	13322.25	13322.43±0.177	136.42±0.56
Sample 3						
Before	13203.9	13203.7	13203.79	13203.5	13203.72±0.169	
After	13335.94	13335.68	13335.43	13335.45	13335.63±0.239	131.90±0.29
Sample 4						
Before	13211.36	13211.13	13211.12	13211.06	13211.17±0.132	
After	13321.64	13321.25	13320.91	13320.89	13321.17±0.352	110.01±0.38
Sample 5						
Before	13166.99	13166.85	13166.62	13166.42	13166.72±0.252	
After	13289.53	13289.24	13288.93	13288.8	13289.13±0.327	122.41±0.41
Sample 6						
Before	13122.69	13122.08	13121.72	13121.34	13121.96±0.574	
After	13230.57	13230.19	13229.98	13229.8	13230.14±0.331	108.18±0.66

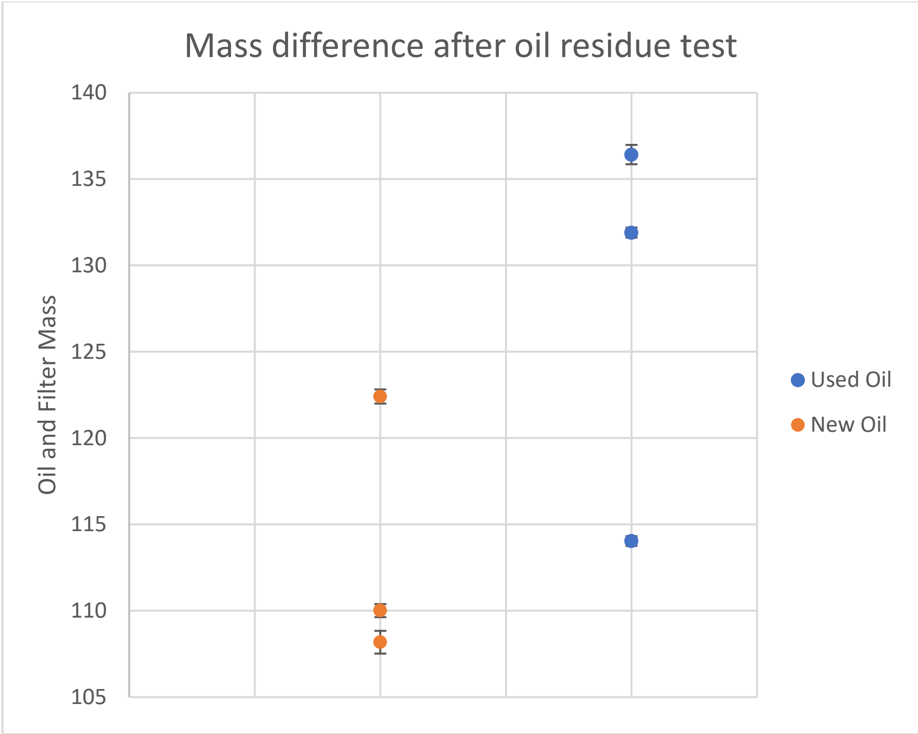

Figure 32: Oil residue results, difference of mass, plotted for comparison

Looking at Figure 32, it is seen there is a noticeable difference in the new and used oil, even though there are outliers. Over the range of mass being measured, any little change can greatly affect these values, such as oil slipping past the filter if the filter is not completely set or amount of oil that stays inside the volumetric pipette during transfer. However, overall a change of the oil is seen showing a success of the new testing facility and procedure. This encourages the continuation of this facility to gather further data to supply data for the nuclear industry.

6.3 Bearing Test

Throughout the 6 hr test for bearing wear, interest was not just on the before versus after condition of the bearings, but also on the turbine and motor behaviors while coming to speed. Figure 33 shows that the rotational speed was nearly constant throughout the test duration with negligible drifting. From 2270 seconds to the test end, the rotational speed rose from a minimum of 2033 rpm to 2039 rpm. Figure 34 shows the motor's response to the 34.38 Hz setting of the VFD, the plot shows the setting of speed at approximately 2040 rpm instead of the calculated 2000 rpm, likely due to the lack of load on the motor encouraging slipping. This data will be used in the future to help characterize the slip of the motor. Figure 35 shows how small the load of the turbine is by plotting the maximum torque of the experiment during the first 300 seconds of the test start up.

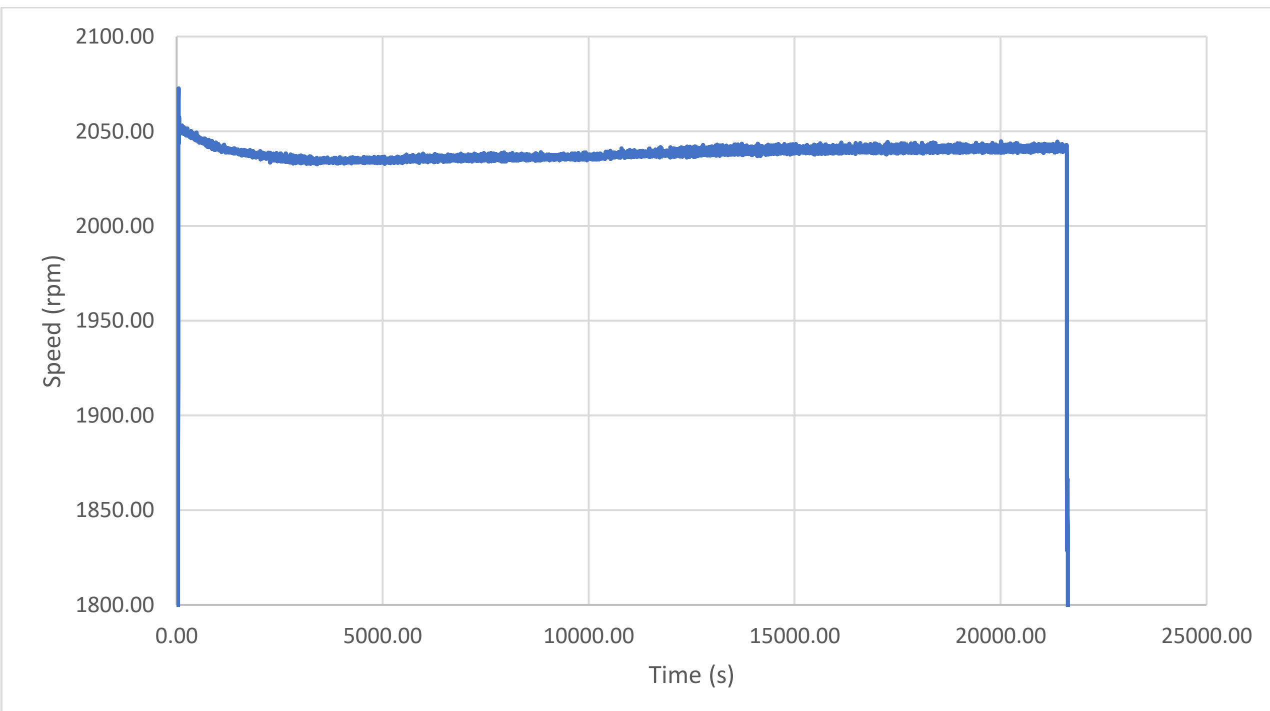

Figure 33: Motor speed versus time during bearing test

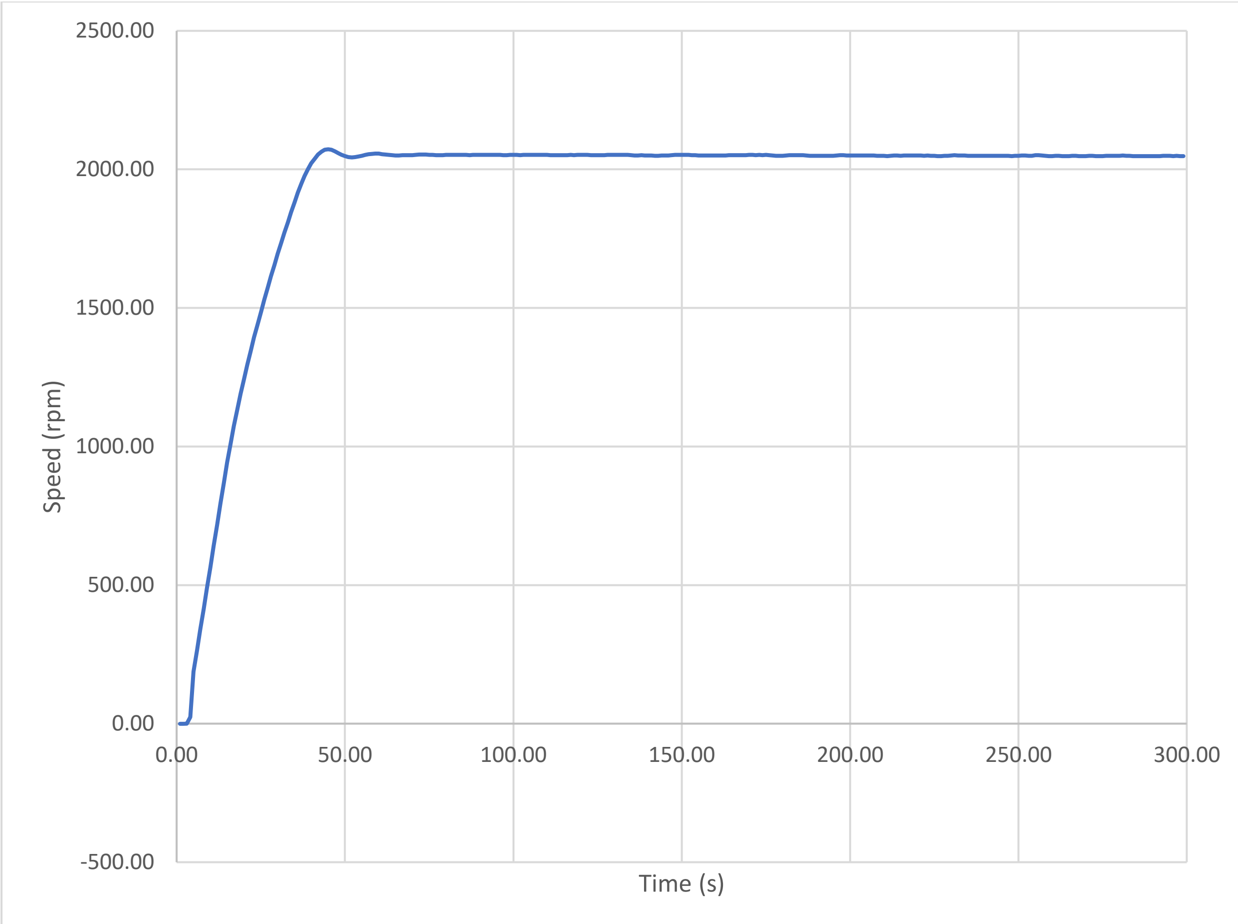

Figure 34: Speed versus time during bearing test start up

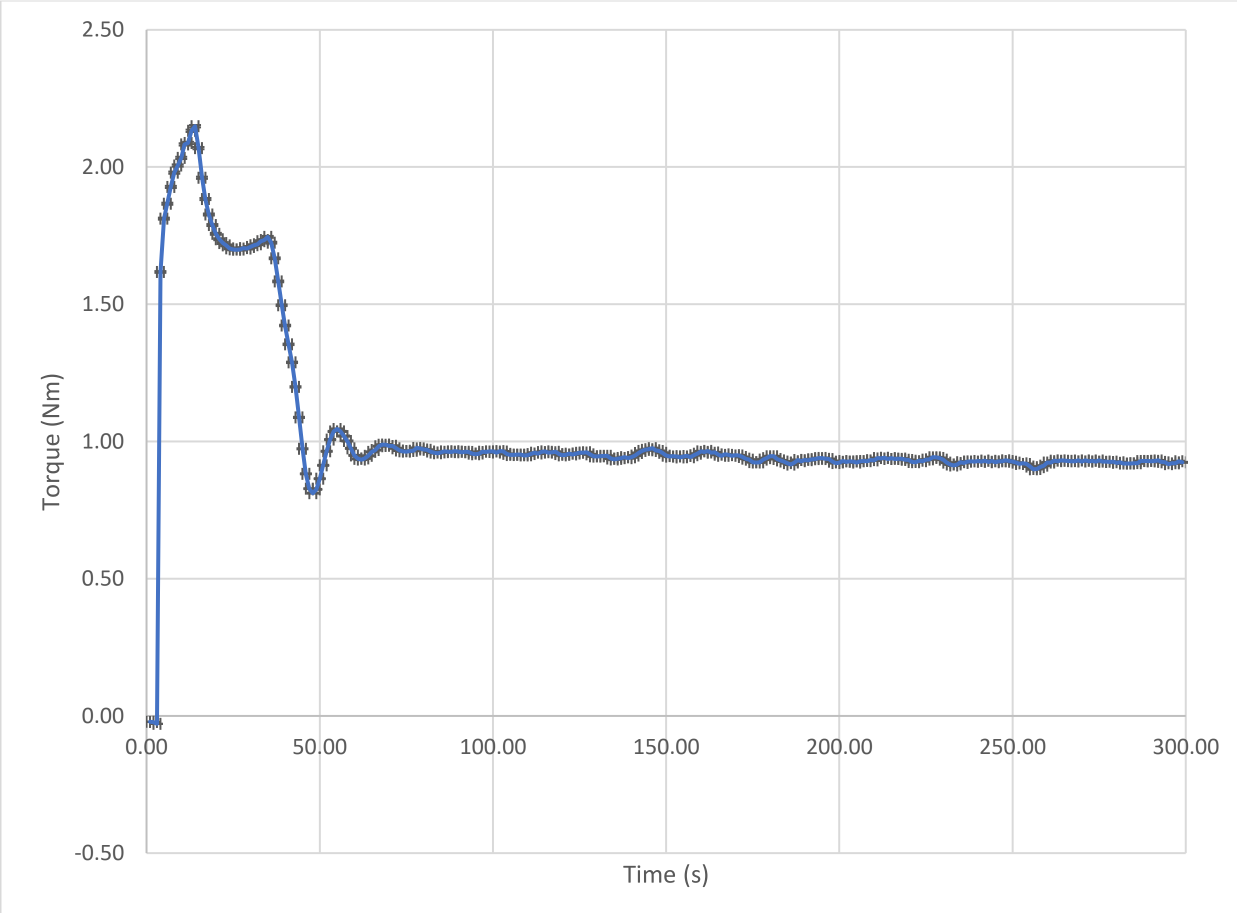

Figure 35: Torque versus time during the bearing test start up

The torque recorded is substantially lower than the 19.25 Nm that would trip the safety coupling, motor, and torque meter. The consistency of data proved this method's reliability for longer tests and for applying a larger load, such as a GS Terry turbine, to the motor. A check of the bearings' condition after the test revealed no noticeable wear compared to the pre-test inspection. The absence of noticeable wear indicates that more experiments with higher loads and speeds could safely be tried.

Figure 36 and Figure 37 show the initial versus final condition of the bearings for the governor and motor ends. The visual inspection was done in order to look for wear to the bearings including pitting, wiping, or excess wear that was not centered; centered wear is allowable as that is where the shaft sits and overtime will gradually wear, but uncentered shows damage to either the bearing or shaft.

Figure 36: Visual inspection of the bearing before (left) and after (right) the bearing test for the governor end

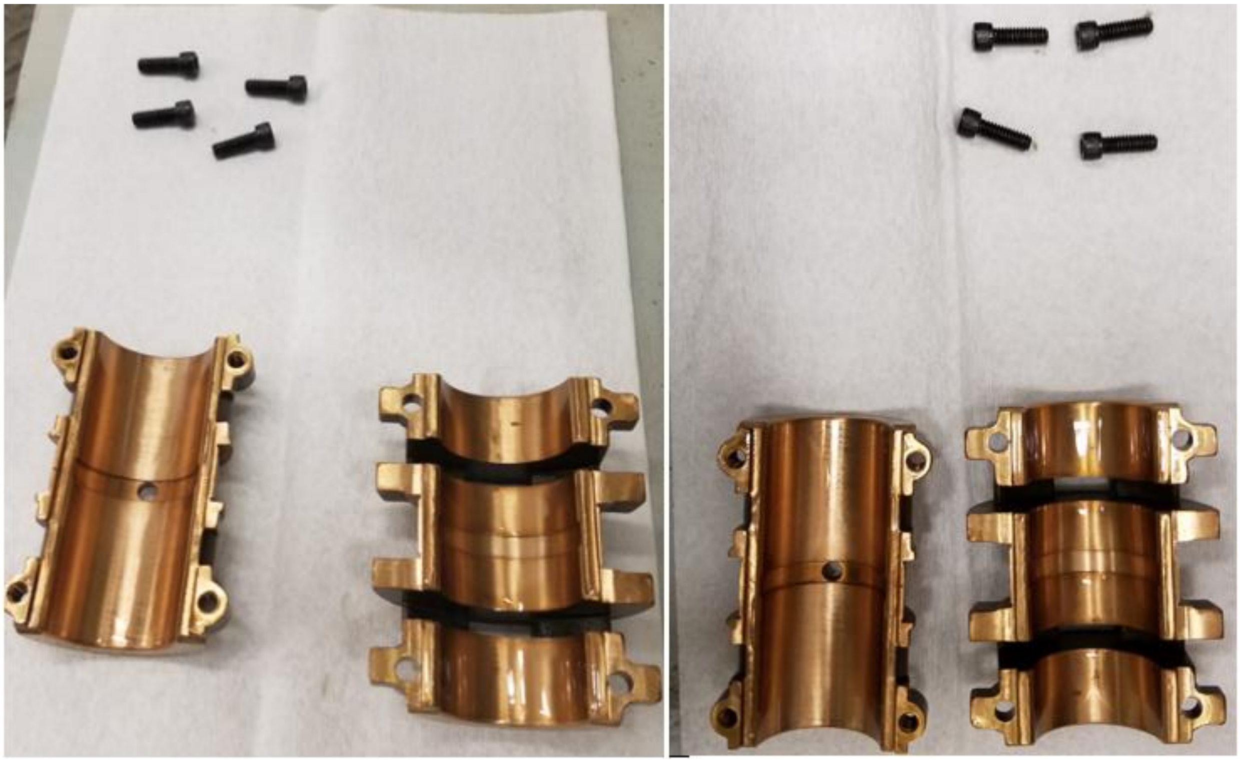
Figure 37: Visual inspection of the bearing before (left) and after (right) the bearing test for the motor end

6.4 Future Work

With the success of the newly developed testing facility and testing methods, future work to be done includes longer durations of oil heating and bearing operation with degraded oil, the introduction of air to the oil during heating, the introduction of water to the oil during heating, bearing testing with the GS Terry turbine in place of the ZS-1 turbine, and varying operating temperature for both the oil and bearing tests. The proposed future testing for this facility to show the degradation over a wide variety of conditions are shown in the tables below. Table 4 elaborates on the oil testing while Table 5 and Table 6 focus on the proposed bearing tests.

Table 4: Proposed future oil testing matrix

Lo: Low air flowrate H: High air flowrate x: No air				
Temp*** (F)	0% wet	1% wet	5% Wet	10% Wet**
160	x,Lo,H	x,Lo	x,Lo	x,Lo
180	x,Lo,H	x,Lo	x,Lo	x,Lo
200	x,Lo,H	x,Lo	x,Lo	x,Lo
250	x,Lo,H	*x,Lo	*x,Lo	x,Lo
270	x,Lo,H	*x,Lo	x	x
290	x,Lo,H	*x,Lo	x	x
310	x,Lo,H	*x,Lo	x	x
390	x	-	-	-

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

**10% Wetness test series is optional

***±2F

Table 5: Proposed future ZS-1 turbine bearing testing matrix

S: 12 hours			
Temp** (F)	1000 rpm	3000 rpm	Alternating
250	S*	S*	S*
290	-	S*	-

*Testing can stop once 3hr of constant vibration has occurred (12hr max)

**Temperature will be measured at oil inlet location

Table 6: Proposed future GS turbine bearing testing matrix

L: 72 hours S: 12 hours			
Temp** (F)	Lo-Speed	Hi-Speed	Alternating
160	L	S	-
180	L	L	S
200	S	S	-
250	L	S	S
290	-	S	-

**Temperature will be measured at oil inlet location

7. CONCLUSION

The purpose of this research was to develop, construct, and gather data from a new facility that would be capable of collecting quality data on oil changes due to heating and turbine bearing performance with degraded oil, data that has not been previously available to the nuclear power industry. Through preliminary testing, the new facility was proven capable of providing quality data for both the oil heating tests and the bearing tests. Quality data were collected and the results showed the tests were not pushing the limits of the facility so more rigorous testing could be performed. As for the data, turbine oil heated to 163°C (325°F) for 72 hours was shown to dramatically change color and contain measurable number of particulates. The ZS-1 bearings, when lubricated with used oil, did not show any signs of damage or change in performance.

These experiments have confirmed the success of the thesis objectives and allowed for the future work to continue in order to test oil degradation over a wider operating band and testing bearing degradation with both the Z series and G series Terry turbines in order to produce never available before data to the nuclear power industry.

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APPENDIX A

OIL TEST OPERATING PROCEDURE

Set up

1. Set beaker of oil on hotplate and wrap with insulation
2. Insert labeled thermocouples
3. Start Labview program (filename: Oil Facility 2015 - MS_EDITS_R3.vi) for Heated Oil Experiment
4. Set hotplate to 350C and turn on the fume hood blower

WARNING: From this point on the fume hood sash should remain no more than 4" open

5. Start timer and monitor until temperature of the oil is at desired temperature
6. Adjust hot plate if needed to maintain the oil at desired temperature

    NOTE: Audial alarms will go off if temperature drifts outside of acceptable limits

7. After 72 hours, turn off hotplate and cut off insulation
8. Once temperature is below 80C, turn off Labview program

Sampling

1. Using a volumetric pipette and while wearing safety gloves and googles, pull 25mL of oil into the pipette
2. Let pipette drip over the beaker before moving the pipette and dispensing the oil
3. Dispense the oil in a beaker and seal the beaker
4. Label the beaker with the time and oil sample ID

Filter Residue Test

Day 1

1. Take oil samples, 5μm filter paper, funnels, and Erlenmeyer flasks to AIEN Annex Lab 019
2. Using the Mettler Toledo high precision scale while wearing gloves, help the current graduate student:
    a. ¨Record mass of scintillation bottle three times
    b. ¨Record mass of scintillation bottle and filter paper three times

¨NOTE: Only the graduate students of that lab are allowed to use the scale, do not touch unless authorized to do so. Ensure the student Zeros the scale between every sample and the glass case is fully closed

3. Take the weighed filter paper and place it in a labeled funnel with the scintillation tube next to it
4. Place funnel into an Erlenmeyer flask
5. Extract 25mL of the oil sample using a volumetric pipette
6. Dispense the pipette over the filter paper in the funnel
7. Let the oil drain overnight
8. Repeat for all the samples being sure the filter recorded number matches the funnel number

Day 2

1. Using a clean tweezers, pick up filter and fold it
2. Using the clean tweezers, place filter paper inside the scintillation tube
3. ¨Weigh and record mass of the scintillation tube and filter paper three times
4. Clean up all oil and any oil residue parts by placing in a box and taking back to NHTS for proper disposal

APPENDIX B

BEARING TEST OPERATING PROCEDURE

Set up

1. Set beaker of oil on hotplate and wrap with insulation
2. Insert labeled thermocouples
3. Start Labview program for Heated Oil Experiment
4. Set hotplate to 350C and turn on the fume hood blower

WARNING: From this point on the fume hood sash should remain no more than 4” open

5. Start timer and monitor until temperature of the oil is 325F
6. Adjust hot plate if needed to maintain the oil at 325F

   NOTE: Audial alarms will go off if temperature drifts outside of acceptable limits
7. After 72 hours, turn off hotplate and cut off insulation
8. Once temperature is below 80C, turn off Labview program

Testing

1. Before adding oil to the turbine, test its properties using Oil Residue Test and Acid Number Test
2. Open the bearing housings and check bearings for conditions, documenting with digital photos
3. If needed, add pre-tested oil to 3/8” above oil slinger rings
4. Set VFD to desired rpm and ensure settings are as seen in Appendix C
5. Open LabView Bearing Test program (filename: New Facility Draft_DP1.vi”) and set desired RPM
6. Begin data collection
7. Hit “RUN” on the VFD and record the time it started

   NOTE: Be aware of any rise of torque as it predicts bearing failure

   WARNING: If safety coupling trips, immediately turn off the VFD

Evaluating once time is done

1. Turn and VFD
2. Let turbine and motor decelerate
3. Once RPM is zero, “End Execution” of the LabView program
4. Disassemble and document condition of the bearings, documenting with digital photos
5. Flush the oil system and perform Oil Residue Test

APPENDIX C

VFD PROGRAMMING RECOMMENDATIONS

Recommended VFD Programming setting for the bearing facility found via Galt Manual and shakedown testing[11].

VFD Channel	Value
P0-0	2
P0-3	60
P0-4	60
P0-5	15
P0-11	60
P0-12	60
P0-14	4
P1-0	0
P2-1	1.12
P2-2	60
P2-3	3490
P2-4	230
P2-5	5
P4-0	3 or 4