Final Design Report

Nozzle Testing System for General Electric's Test and Research Development Centre

Project #: 15

MECH 4860

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Executive Summary

This report summarizes a design project initially submitted by General Electric Aviation to address their air atomizing nozzle troubleshooting needs at the Engine Test and Research Development Centre (TRDC) in Winnipeg, MB. Currently, the process to identify defective air atomizing nozzles solely by inspection is overly time consuming and ineffective. Therefore, the project's objectives were to design a test rig that will streamline the process of identifying defective nozzles, as well as measure the spray pattern output of the nozzles for testing and comparison purposes.

The client's needs for the test rig are for it to provide and control water and air flow to a minimum of one nozzle in a self-contained manner. The water and air flows must be provided at 180°F, and up to a maximum pressure of 100 psig. The rig must also simultaneously collect and record data for the flow properties and the output spray pattern. Project deliverables included in this report are preliminary drawings of the test rig, a parts list with approved vendors, a cost report, and operating instructions.

In order to develop a successful design, conceptual design solutions were first generated and screened for feasibility, and then more rigorous part evaluations and design calculations were performed for the selection of the final design components. For both the conceptual and final design stages, the test rig design was broken up into several main categories including the water and air delivery systems, the heating and insulation systems, the measurements and control system, and the overall frame assemblies.

For the water delivery system, the selected pump and motor combination is an Oberdorfer R103M rotary gear pump coupled to a half-horsepower Baldor CDP3326 DC motor. The water tank capacity is 50 gallons and is installed on casters to be separately portable from the rest of the rig. An adjustable pressure regulator is included to allow for a variable water pressure supply to the nozzle(s) under test. The piping material for both water and air flows is 304 stainless steel.

The selected air compressor for the final design of the air delivery system is Atlas Copco's oil-injected rotary-screw compressor, model GA7VSD$^+$ (P/N 8153-0383-21), coupled directly to a 10 horse power, Interior Permanent Magnet variable speed drive train. The air receiver tank volume is 60 gallons and is constructed out of stainless steel. An oil coalescing and oil vapor tower have been included in the set-up outside of the air compressor to treat the oncoming air. Downstream from the receiver tank is a pressure regulator and needle valve for the regulation of air pressure and flow rate.

The water heating system consists of a 30 kW industrial horizontal inline water heater with a built-in control module from Wattco. Air flow heating is accommodated via an inline 1.5 kW heater and a temperature control module from O.E.M. heaters. The selected inline heaters

allow for testing to commence on demand by eliminating the need for either pre-heating the system or maintaining the working fluids at temperature when the rig is not in use.

Measurement devices include a Flow Technology FT-8NENW-LEA-2 flowmeter, Emerson Rosemount 2088 G 2 S 22 A 1 pressure transmitters and Omega TJ36-CPSS-18G-6 T type thermocouples. The same sensors as those used at the TRDC were selected where possible to reduce GE's required efforts for implementation and calibration. The selected controller is an Automation Direct C0-02DD1-D modular PLC, which uses an external frequency to voltage converter and an InterConnecting Automation FC-LOG data logger. Measurement of 2-D spray pattern geometry is accomplished via a mounted GoPro Hero 6 that feeds images into a laptop running Oxford Laser's Envision Patternate spray analysis software. Optionally, a proposal to incorporate Oxford's VisiSize N60 system for droplet size and droplet velocity measurement is also included.

For mobility, the test rig design is separated into three different subassemblies: the primary rig frame, the air compressor assembly, and the water tank. The water tank is installed on casters, and a separate frame design has been developed for the air compressor due to its substantial weight of 732 lbs. The primary rig frame houses the remainder of the components and both frames are constructed from A513 2x2", 14 gauge rectangular steel tubing. The primary test rig weighs approximately 650 lbs, measures 6' long, 4'4" inches wide, and is 4'8" tall at its highest point above the air receiver tank.

The total cost of all components included in test rig is $49,900 CAN, and the optional VisiSize N60 droplet size and velocity measurement system can be procured for an additional $154k CAN if the cost is justifiable at the TRDC's discretion.

Overall, the baseline rig provides the TRDC with an effective means of collecting pressure, flow rate, and temperature data, as well as 2-D spray characteristics for their air atomizing nozzles. By testing up to three nozzles at a time, the rig quickly identifies malfunctioning nozzles and reduces the downtime associated with nozzle troubleshooting. Having selected components which are easy to install and operate, and are adjustable to meet the client's spray requirements, the team is confident that the recommended design will address GE's needs for an air atomizing nozzle test rig and spray measurement system.

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1 Introduction

This report summarizes activities undertaken as part of a design project initially submitted by General Electric Aviation (GE) to the University of Manitoba's IDEA program. The project was undertaken by a team of four mechanical engineering students in fulfillment of the University of Manitoba's mechanical engineering capstone design course, MECH 4860. The project includes the design of a test rig for the air atomizing water nozzles used at GE's Engine Test and Research Development Centre (TRDC). Deliverables included in this report are preliminary drawings of the test rig, a parts list with approved vendors, a cost report, and operating instructions for running the test rig.

The design project tasks were broken up into three phases. The initial phase of the design project included identifying GE's motivation and needs for the project, as well as the project's limitations, scope and schedule. The second phase included establishing a design methodology, as well as generating, evaluating and selecting concepts for further development. The third and final phase involved performing more detailed analyses and evaluations for the final part selection and the detailed design of the test rig.

The remainder of this report is organized as follows.

In section 2, key outcomes from the first phase of the design project are detailed. In particular, section 2 includes is a brief background on the sponsoring company and the project site, a description of the factors that initiated GE's project submission to the University of Manitoba's IDEA program, the project's overall objectives, as well as the scope of the project's deliverables. Also included is a compiled list of the design needs, and a brief overview of the methodology used throughout the design process.

Section 3 presents an overview of the recommended design, and a compliance matrix for the needs applicable to the overall rig.

Section 4 details the part selections within each design category, descriptions of how the various components meet the client's needs, and highlights the relevant design specifications within each subsystem.

Appendices A and B include the drawings and bill of materials deliverables for the design.

Appendix C contains specific results from the conceptual design phase of the project, including the scoring and screening matrices used for the down-selection of equipment. Engineering calculations are provided in Appendix D to validate the equipment selections where applicable.

Appendix F contains the compiled list of quotes and specifications for the design's parts and equipment, and Appendix G contains operating instructions for the test rig.

2 Background

General Electric Aviation (GE) is a leader in the development, manufacturing and testing of commercial and military jet engines, and holds an approximate sixty-percent share [1] of the aero engine market worldwide. GE's Aviation Engine Testing and Research Development Centre (TRDC) is located at the James A. Richardson International Airport, Winnipeg and was built with local partner StandardAero primarily for the testing and certification of GE's new engine lines per Federal Aviation Regulations (FARs). As part of the FARs, aircraft engines are subject to a wide range of rigorous tests from blade containment and rotor unbalance tests, to bird and icing ingestion tests [2]. Manitoba's winter climate is particularly agreeable for the icing tests. Therefore, the TRDC is the location of choice for the cold weather certification of GE's gas turbine engines. An overall view of the TRDC during one such engine test is given in Figure 1a. Icing certification tests performed at the TRDC utilize a spray mast located inside the wind tunnel downwind of the fans, as depicted in Figure 1b.

Wind tunnel

[redacted]

Supercooled water droplet cloud

Exhaust tube

Noise attenuation walls

Engine test stand

(a)

[redacted]

Horizontal spray bars

Spray nozzles

(b)

Figure 1: (a) Icing certification test in progress at the TRDC [3]; (b) View from outlet of wind tunnel.

The main components of the TRDC shown in Figure 1a include a newly upgraded [redacted] foot diameter wind tunnel capable of producing up to two thousand kilograms per second of airflow [4], and a test stand capable of holding back the one hundred thousand plus pounds of thrust from the GEnX and GE9X engines [5], as well as the exhaust tube and blast deflection walls for noise attenuation.

The spray mast shown in Figure 1b is instrumented with [redacted] air atomizing nozzles. These nozzles inject small droplets of water into the wind tunnel's air flow, simulating supercooled clouds in the atmosphere, as well as ground level fog icing conditions.

During icing testing, the spray cloud is ingested by the engine under test, and the water droplets freeze upon contact with the engine components, presenting several hazards. During the tests, ice builds on the engine surfaces until it reaches a critical mass and sheds. Ice buildup can unbalance the rotors in an engine, resulting in significant vibration and gear or bearing damage. Shedding ice chucks can also damage components on impact as they pass through the engine. The main purpose of the icing tests is to ensure that the engine can ingest sufficient amounts of supercooled water without any loss of performance and without sustaining any serious long-term damage. Ensuring the functionality of the spray nozzles is critical to confirm that required FAR icing conditions are met during certification testing.

The close-up image of Figure 2 shows the components that constitute a spray nozzle in more detail, including the receiving block that the interchangeable nozzles thread into during assembly. Also shown in the picture is the receiving block's drain plug hole which can be used to remove water from the system to stop the system from freezing up when not in use. A difference between the pictured configuration and the actual nozzle configuration when in use is a missing spray cap that gets installed prior to operation.

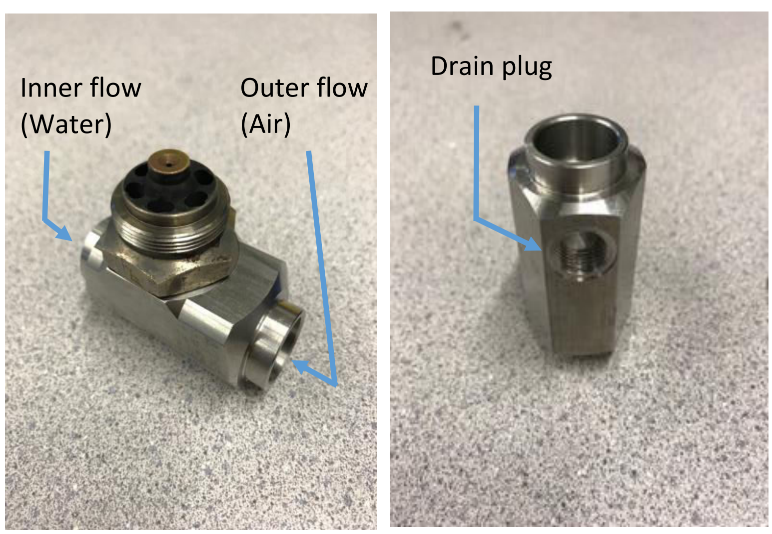

Figure 2: Spray nozzle and base connection assembly. (a) Isometric view; (b) Underside.

2.1. Problem Statement and Objectives

Approximately 2-3 times an icing season, anomalous water pressure readings are measured by the sensors outfitted on the spray bars inside the TRDC's wind tunnel. These abnormal readings have been traced back to malfunctioning nozzles that are either broken, leaking, or clogged. Currently, GE has no way of testing the functionality of the spray mast nozzles without running the entire wind tunnel which is an expensive and time-consuming process. Then, even with the full system running, measurements are limited to only the data for an entire spray bar consisting of up to 16 individual nozzles. Troubleshooting practices currently include the removal, inspection, rearrangement and replacement of every nozzle on the malfunctioning spray bar. To aid in the troubleshooting of suspect or malfunctioning nozzles, GE requested that the group design a rig capable of testing nozzles independently from the operation of the wind tunnel.

The primary objective of this project was to design a rig capable of testing a minimum of one nozzle at a time by controlling the inlet water and air flows to specified temperatures, flow rates and pressures. It is critical that the rig accurately simulates the real test conditions so that inconsistencies in flow properties can help determine if the nozzle is defective.

Secondary objectives of the design are for the rig to:

- Test up to three nozzles simultaneously
- Characterize spray patterns emitted from the array for different types of nozzles
- Easily allow the change out of nozzles
- Reduce the time and cost it takes to identify a malfunctioning nozzle
- Be safe and easy to use to avoid injury or damage to the rig or surrounding equipment
- Be easy to move and small enough to store such that it does not waste space at the facility when not in use
- Be designed in a way that minimizes cost and the difficulty of maintenance.

2.2. Scope

The scope of this project is to prepare a preliminary design for a nozzle testing system at the GE TRDC. The actual construction, installation, and operation of the rig are excluded from the current project's scope, and will be managed by GE or their subcontractors as applicable. Project deliverables include a report detailing the final design concept for the test rig complete with preliminary engineering drawings, a parts list with approved vendors, an estimated budget for the overall design, and procedural documentation consisting of operating instructions and the identification of any safety hazards. The depth of design applicable for each deliverable is summarized in the following subsections.

2.2.1. Electrical Control Systems and Wiring

Due to time constraints and a lack of the design team's expertise in this field, the detailed configurations and programming of the electrical control systems for the test rig is not within the scope of the project. Recommendations are provided regarding type of logic controller to be used, ensuring that it contains compatible I/O for the measuring devices sourced for the test rig. However, the specific program and/or GUI for running the rig is out of the project's scope. A validated wiring parts list is not required. GE has agreed to this scope limitation, and have stated that their instrumentation group can perform the wiring design and programming of the system once it has been built.

2.2.2. Drawings

Preliminary drawings of all major components requiring custom fabrication are provided in Appendix A of this report. These drawings have been prepared by student members of Engineers Geoscientists Manitoba, and therefore have not been officially reviewed nor stamped by a professional engineer.

2.2.3. Parts List and Cost Report

A parts list with names and quantities of all components included in the design is provided in Appendix B of this report. The parts list includes approved vendors and estimated costs for all major components. Construction, installation, and operating costs of the design are not presented as these details will be managed by GE and their subcontractors at the time of build. However, due effort has been made to ensure that the rig can be easily manufactured without the need for specialized tooling.

2.2.4. Procedural Documentation

A standard operating procedures bulletin is provided in Appendix G. The design team recommends that the client post these instructions on the test rig after construction is completed. The bulletin also identifies safety hazards and any safety measures to be performed during normal operation of the test rig.

2.3. Client Needs and Target Specifications

Through communication with staff members at the GE TRDC, the group developed a list of the client's needs as well a list of metrics to quantify values to aid in designing a rig that meets these needs.

The following tables present the final list of the client's needs along with their relative importance ratings assigned by the team, and the final list of metrics along with targeted ideal and marginal values.

TABLE I. CLIENT NEEDS IDENTIFIED BY THE MECH 4860 DESIGN TEAM

#	Need	Importance (1-5) 1 = low, 5 = High
1	Design measures flow rate of water near nozzle(s)	5
2	Design measures pressure of air near nozzle(s)	5
3	Design measures spray angle	5
4	Design measures overall pattern	3
5	Design collects and logs data	4
6	Design delivers adequate power to all components	3
7	Design transmits data	3
8	Electrical systems are protected from water	5
9	Design measures water temperature	3
10	Design measures droplet size	2
11	Design is safe for user(s)	5
13	Design is compatible with range of nozzles types	1
14	Design performs under required environmental conditions	4
15	Design is structuraly stable under test	4
16	Design is easily portable	2
17	Design is easy to assemble / disassemble	2
18	Design is affordable	2
19	Design fits required dimensions	1
20	Design has sufficient space for performing maintenance	3
21	Design is made from durable compents	3
22	Design is manufacturable with compatible compents	4
23	Design contains operating instructions	3
24	Design contains instructional work procedure (SOP)	4
25	Design can be shut down in case of an emergency	5
26	Design runs for length of test without intervention	5
27	Design uses standard components where possible	4
28	Design regulates water flow rate	5
29	Design regulates air pressure supplied to nozzle(s)	5
30	Design regulates water pressure supplied to nozzle(s)	5
31	Design is capable of testing a single nozzle	5
32	Design is capable of testing mutiple nozzles simultaneously	3
33	Design can determine if a nozzle is defective	5
34	Working fluids can be removed from system	3
35	Design has accessible water supply	4
36	Design supplies water to desired flow rate and pressure	4
37	Design supplies air to desired pressure	4
38	Pipe dimensions are economical	4
39	Pipe dimensions are able to withstand 1.5 times design specifications	4
40	Design heats water to required temperature	5
41	Design stores required amount of water	4
42	Design considers drainage of water	1
43	Design heats air to required temperature	5

Table I lists all client needs identified by the design group as being important to ensure a successful design. The importance rating to the right of the need was determined by the design group, using discussions with the client to gauge the client's priorities for the project needs. A rating of 5 indicated the need was a top priority for the group, whereas a rating of 1 indicated the need was a lower priority and should not have been the primary focus for the group's efforts.

From Table I, the group was able to prioritize the following while designing the test rig:

- Measurement of water flow, water and air pressure, and spray angle (needs 1, 2, and 3)
- Safety in terms of protecting the electrical system from water (need 8), the overall safety for users (need 11), and the incorporation of emergency shut-down procedures and controls (need 25)
- Autonomy (need 26) and control of water flow, air pressure and water pressure (needs 28, 29 and 30)
- Testing a single nozzle at a time (need 31)
- Determining a defective nozzle (need 33)
- Target water flow rate and pressure, air pressure, and water and air temperature (needs 36, 37, 40 and 43).

From there, the group developed a list of metrics and attributed a target specification ('Ideal Value' in Table II) to each metric, accompanied by a minimum acceptable value ('Marginal Value' in Table II), to determine the overall success of the final design as well as give the group a range of values for the evaluation of conceptual designs.

TABLE II. METRICS DETERMINED BY THE MECH 4860 DESIGN TEAM

#	Metric	Units	Marginal Value	Ideal Value
1	Water flow through nozzle	gpm	0.3012	0.317
2	Height	ft	10	5
3	Length	ft	5	2
4	Water pressure near nozzle	psi	71.25	75
5	Air pressure near nozzle	psi	85.5	90
6	Data collection rate	bps	500	1000
7	Power supply	Watt	3600	1800
8	Water temperature	°F	175	180
9	Air temperature	°F	175	180
10	Safety rating	Subj	8	9.5
11	Serviceability	Subj	7	10
12	Minimum operating temperature	°F	60	40
13	Mobility	Subj	7	10
14	Manufacturability	Subj	7	10
15	Component and manufacturing cost	$CDN	20,000	9,000
16	Time to access operating instructions	sec	90	10
17	Duration for complete emergy stop	sec	5	1
18	Reliability rating	Subj	7	10
19	Water storage size	gal	30	50
20	Supply water pressure	psi	85	75
21	Supply air pressure	psi	100	90
22	Data storage	MB	0.5	2
23	Troubleshooting time	min	90	60

Details on how the group established the ideal and marginal values shown in TABLE II can be found in Appendix E.

2.4. Design Methodology

Having defined the problem as well as the needs and metrics for the design, the team came up with a systematic way of generating and evaluating conceptual solutions. The chosen methodology was broken up into seven steps whereby the overall rig design in broken down into subsystems, concepts are generated for each subsystem and down-selection processes are applied. The full description of the concept selection methodology and the rationales for the specific part screening decisions are provided in Appendix C. An overview of the final design is presented in the next section, and the descriptions of the individual subsystems per the design methodology are provided in section 4.

3 Final Design Overview

A CAD model rendering of the integrated design is shown pictorially in Figure 3. Exploded views and drawings of the test rig subsections are available in Appendix A, and a full bill of materials and cost breakdowns for all included parts are available in Appendix B.

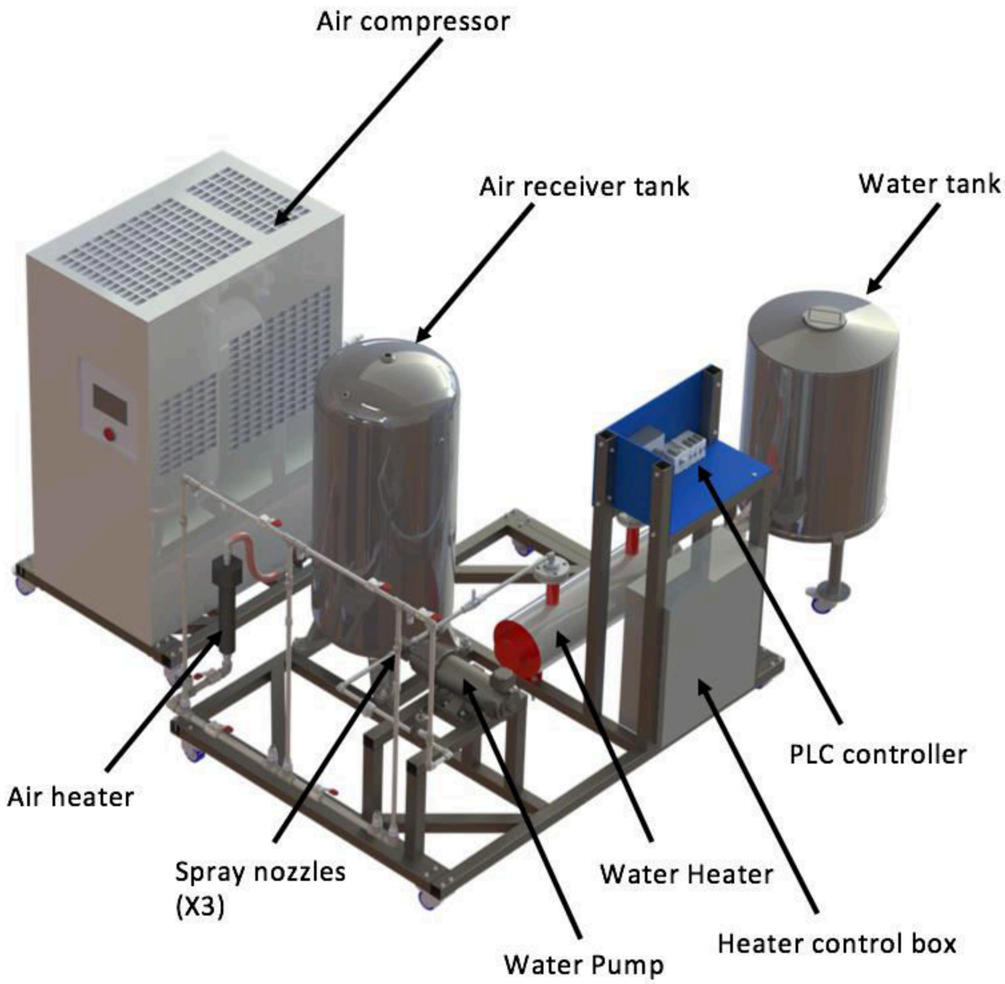

Figure 3. Integrated CAD model rendering of the test rig

Figure 3 shows the layout of the nozzle test system with all major components installed. All of the components can accommodate testing either one, two, or three nozzles at a time. The front of the test rig contains the spray mast, complete with ball valves and pressure sensors. Flowmeters and thermocouples are also installed in the pipe routing system to provide the necessary data for spray condition verification and nozzle troubleshooting. The spray nozzles themselves are located approximately three feet off the floor, so that the wide-angle spray can develop adequately before contacting and condensing on the ground.

Near the back of the rig, control components are installed in an easily accessible location. The PLC, data logger, water pump controller, and air heater controller are also housed behind HDPE plates which protect against water damage and provide convenient mounting locations. The air compressor contains an integrated controller, and is installed on a separate frame to account for its significant weight.

Overall, a three-piece design was produced to meet the client's need for a mobile test rig. Each assembly is installed on rolling casters and can be moved by two staff members. Detailed descriptions of each design subsystem are provided in the following section. For reference, specific requirements verification matrices are provided in Appendix E.

TABLE III reiterates the target design specifications and presents the actual or estimated value of the final design. More details on the actual value are provided in Appendix E.

TABLE III. ACTUAL VALUES OF FINAL DESIGN COMPARED TO TARGET SPECIFICATIONS

#	**Metric**	**Units**	**Marginal Value**	**Ideal Value**	**Actual Value**
1	Water flow through nozzle	gpm	0.3012	0.317	0.317
2	Height	ft	10	5	5
3	Length	ft	10	2	9
4	Rated water pressure	psi	60	100	150
5	Air pressure near nozzle	psi	85.5	90	90
6	Number of Power Supply Circuits	#	3	1	3
7	Maximum Power Supply Current	A	100	15	75
8	Maximum Power Supply Voltage	V	240	120	240
9	Water temperature	°F	175	180	180
10	Air temperature	°F	175	180	180
11	Safety	Subj	8	9.5	9
12	Serviceability	Subj	7	10	8
13	Minimum operating temperature	°F	60	40	60
14	Mobility	Subj	7	10	8
15	Manufacturability	Subj	7	10	9
16	Component Cost	$CDN	50,000	9,000	49,900
17	Duration for complete emergy stop	sec	5	1	0
18	Reliability	Subj	9	10	10
19	Water storage size	gal	30	50	50
20	Data storage	MB	0.1	2	4
21	Troubleshooting time	min	90	60	63

4 Final Component Selections and Detailed Design

Detailed descriptions of the rig's various subsystems are provided in the following subsections. In order, the sections considered are the rig's:

- Water delivery system
- Air delivery system
- Heating systems
- Measurements and control systems
- Spray pattern characterization systems
- Frame assembly

4.1. Water Delivery System

The water delivery system addresses the client's needs to have a supply of pressurized water to the nozzles under test. For the design process, the system was broken down into four separate subcategories: the water pump, the pump motor, the piping system, and the water storage tank. A liquid pressure regulator, a water filter, and a pressure relief valve are also incorporated into the final design to ensure the safety and smooth operation of the spray system.

The final component selections are presented in the following subsections, while the detailed conceptual design process can be found in Appendix C. Where applicable, component selections are justified using technical data provided by the respective manufacturer or through engineering calculations performed by the design team.3

4.1.1. Water Pump

The selected water pump for the test rig design is an Oberdofer R103M gear pump. The following figure demonstrates the pump's operating curves and the required flow rates for one and three nozzle spray configurations.

Figure 4. R103M pump performance curves [6].

The solid red and dashed blue lines denote the required flow rates for the one and three nozzle configurations, respectively.

Figure 4 shows that the R103M pump is suitable for a three-nozzle configuration at a flow rate of approximately 1 gpm using standard motors in the 1400-1800 RPM range. At this flow rate, there is more than sufficient pressure available from the pump since the targeted operating points for nozzles are within the 25-75 psi range. The technical brochure provided by Oberdorfer [5] is provided in Appendix F, and the full recommended part number is R10316CA-C1. This full part number provides the following material and coupling options:

- 316 SS housing, covers and shafting
- W88 drive gear and W88 idle gear
- Teflon encapsulated silicone O-ring cover seals
- Carbon graphite resin bearings
- 56C Close coupled adapter

With the above noted options, the pump's maximum working fluid temperature is 450˚ F. This easily accommodates the 180˚ F requirement for the test rig.

Motion Canada has local distributing facilities for Oberdorfer pumps and has provided a quote for an R10316CA-C1 pump at $4,385 CAN. The full quote is included in Appendix F.

Referring back to, the plot also shows that a 0.5 hp motor will be sufficient to run the pump in a three-nozzle configuration. Therefore, a 0.5 hp power rating target was used for assessing motor concepts and selecting a motor for the final design.

4.1.2. Water Pump Motor

Important factors specific to selecting the water pump motor were the motor's required power supply, the output torque and rotational speed provided by the motor, and the motor's capability to meet the pump requirements for one, two, or three nozzle configurations.

From the Baldor product line, a 0.5 hp DC motor has been selected that meets the pump's rotational speed and power requirements as shown in Figure 4 of the previous section. The base motor part number is CDP3326, and the motor is shown in Figure 5.

Figure 5. Selected water pump motor: Baldor CDP3326 [7]

Like the 1 hp pumps currently used at the TRDC, the CDP3326 is a permanent magnet DC motor. It is rated to 180 V on the armature, rotational speeds of up to 1750 RPM at 0.5 hp, and comes in a NEMA frame size of 56C, which matches the close coupled adapter supplied with the water pump. The CDP3326 weighs 30lbs and is priced at 845 USD [7]. For reference, the motor's specification sheet is provided in Appendix F.

An enclosed AC to DC motor speed controller has been sourced from McMaster Carr (P/N 7793K51) to provide the necessary electrical transformation and supply to the motor. The controller allows for the adjustment of speed through an analog dial, providing the capability to test at varying water flow rates for the different nozzle configurations.

4.1.3. Piping System

In terms of piping material, 304 stainless steel was selected for both the water and air flow components of the design. Stainless steel is costlier than some of the other alternatives considered, but meets the necessary performance requirements for the design in terms of pressure, temperature and contamination or corrosion resistance. It is costlier than some of the other alternatives considered, but incorporates well with the chosen pump fittings for ease of installation. In addition, GE TRDC mainly uses stainless steel for their piping applications, and have thus proven manufacturing and pipe routing capabilities for this material.

Detailed design decisions after selecting the piping material included the assembly method, the cross-sectional pipe dimensions, and the required support locations. These decisions are presented and validated throughout the remainder of this section.

First, the design team measured the inner diameter of the spray nozzle base provided by the TRDC as 0.70”. Therefore, according to ANSI/ASME 36.19M [8], the corresponding nominal stainless steel pipe size is 3/8”, with an outer diameter of 0.675”.

Schedule 40S piping was selected to accommodate the use of threaded fittings for the system routing. Threaded fittings provide an easier to assemble solution when compared to butt-weld fittings. The selected pipes and fittings are threaded according to National Pipe Thread Taper (NPT) specifications. These fittings are slightly tapered at 1.7899° [9] to provide a tight seal as the taper forces the threads to compress on one another. However, to ensure a leak-free seal, nickel-filled PTFE tape should also be wrapped around the threads before assembling the fittings to reduce the chances of the threads seizing [10].

Per the calculations performed in Appendix D, the minimum pipe wall thickness required for the maximum design pressure of 100 psig is 0.003”, and the wall thickness of the selected 40S piping is 0.091”, providing ample margin against pipe bursting. The limiting factor of the piping system design is in the selected Class 150 pipe fittings. The selected fittings are all rated to a minimum of 150 psig at the design’s working fluid temperature of 180°F, providing a factor of safety of 1.5 against the maximum design pressure.

Calculations were also performed to estimate the maximum allowable length of unsupported pipe that can be run off a fitting. The results from Appendix D demonstrate that up to 6’ 6” of 3/8” schedule 40S piping (or an equivalent bending load from other fittings) can be run between supports.

4.1.4. Water Storage Tank

The design's water storage tank is also constructed from 304 stainless steel. Other than material, the major design factor to consider for the water tank was its overall size. The size of the water tank determines the length of time that spray nozzles can be tested continuously, as well as the frequency of required fill-ups.

To calculate an effective tank size, input parameters are the number of nozzles that need to be tested sequentially, the average test duration, and the mass flow rate of water during the tests. Given that the longest spray bar on the TRDC wind tunnel contains [redacted] nozzles, and the test rig is able to troubleshoot up to three at a time, up to [redacted] sequential tests would need to be performed before the faulty nozzle on the bar can be identified. The client has estimated that on average, it should take roughly ten minutes of spray time to identify a faulty nozzle. In combination with the approximately 1 gpm flow rate through the test rig with three nozzles installed, this results in an estimated tank size of 50 gallons before a faulty nozzle on the largest spray bar can confidently be identified.

Using the density of water (8.3 lbm/gal at 70°F), the water weight for a 50-gallon tank was estimated as $8.3 \times 50 = 415$ lbs. This mass provides some concern for the mobility of a fully integrated design since general operational health and safety guidelines suggest a maximum load of 500 lbs on four wheeled push carts [11]. Therefore, the concept of having a detachable cart for the water tank was pursued.

A vertical tank concept was selected over a horizontally oriented tank to provide low-pressure gravity fed flow to the inline heater and water pump. The final water tank design has been sourced from Mixer Direct, and is pictured in Figure 6, below.

[redacted]

Figure 6. 50-Gallon, Stainless Steel Water Tank [12]

Important parameters for the water tank are that it:

- Is made from 16 ga. 304SS with a #2B surface finish
- Has a straight tank height of 36”, and an overall height of 48”, which provides approximately 12” of clearance to the floor
- Comes with two rigid casters and a swivel caster installed for mobility.
- Has a one piece removable lid with a 2” male NPT fitting for refilling. An identical drainage port is provided on the bottom. Camlock couplings are added to the ports for compatibility with the fittings available at the TRDC.
- Has a 1 ½” outlet to the rest of the test rig’s piping system. A braided stainless steel hose is used to facilitate the main outlet’s connection with the test rig.
- Has an estimated cost of $4,032 USD (See QT001384 in Appendix F)

To demonstrate the camlock coupling to the test rig, a CAD model rendering of the water tank outlet and the inlet to the test rig is shown in Figure 7, below.

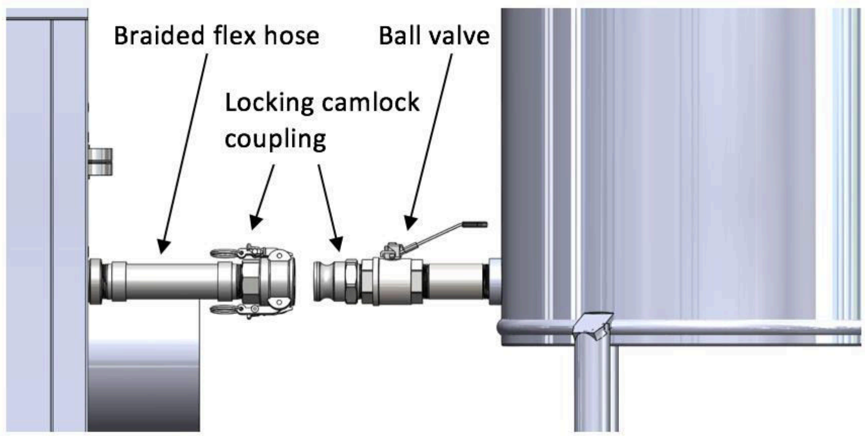

Figure 7. Water tank coupling method

As shown in Figure 7, the water tank coupling method allows for easy connection to the spray rig. A braided flex hose allows some degree of misalignment to facilitate the connection, and the camlock couplings can be locked to ensure a reliable connection when the spray rig is operating. When the tank is emptied, the connection is easily unlocked and the tank can be moved to the main water tank on site or to the deionized water delivery truck for refilling.

4.1.5. Pipe Routing, Fittings, and Supports

A rendering of the CAD model for the piping system from the pump to the spray nozzles is provided in Figure 8.

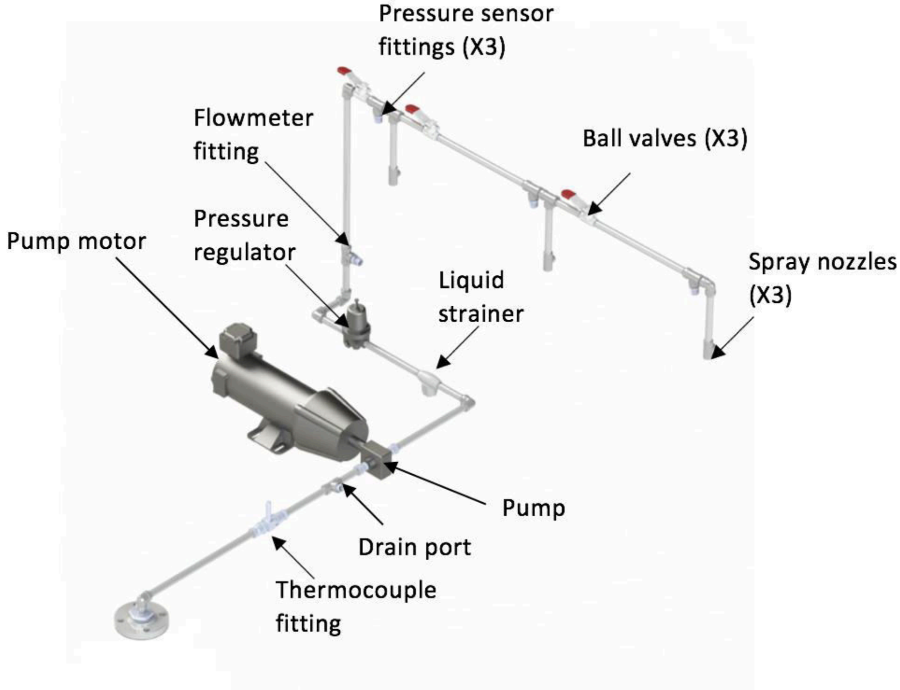

Figure 8. Pipe routing from heater to spray nozzles

Examples of the various fittings used in the pipe routing system are shown in Figure 8. A liquid strainer is used to remove any solids in the flow that could contaminate or block the spray nozzle outlets. A pressure regulator (adjustable from 25 to 125 psi) is used to ensure a smooth spray and to protect against unsafe over pressurizing of the line. Tee fittings are used to connect the rig's pressure sensors near each spray nozzle, and ball valves allow for variability in testing one, two, or three nozzle configurations at a time. The specific part numbers of all of the fittings and piping used in the overall system are detailed in the bill of materials provided in Appendix B.

4.1.6. Water System Design Summary

As part of the design process, five primary subsections of the rig's water system were considered. Critical components such as the pump and motor have been specified and sourced out from the same manufacturers that supplied the equipment currently used at the TRDC. The general pipe material and cross-section, the water tank, and the fittings for the assembly have been selected along with the design of the overall pipe routing. The bulleted list below provides a summary of the water system design:

- The selected water pump system consists of Oberdorfer's R103M gear pump, coupled to a CDP3326 DC motor manufactured by Baldor.
- All piping on the test rig is designed as 304 stainless steel which is durable and compatible with the selected pump adaptors.

- Schedule 40S threaded piping was selected to provide a convenient means of assembly. The selected pipe size and class of fittings have been verified to meet the minimum thickness requirements at the maximum design operating pressure of 100 psig.
- The water tank is made from 304 stainless, is sourced from Mixer Direct, and has a capacity of 50 gallons. This capacity provides enough testing time to confidently identify a faulty nozzle even if every nozzle on the TRDC's largest spray bar needs to be tested. The tank is easily detachable from the spray rig and can be refilled or drained through provided camlock couplings.
- A pressure regulator and liquid strainer are used to provide smooth, clean, and safe flow to the spray nozzles. Pressure sensor fittings and ball valves are installed near the nozzles to measure the pressure supplied to each individual nozzle.

4.2. Air Delivery System

The air delivery system, one subsection of the test rig, intends on delivering a clean, dry and continuous supply of air to the air atomizing nozzle(s). Factors such as discharge temperature and pressure, as well as flow capacity were considered throughout the design process.

4.2.1. Detailed Design of Air Delivery System

In this sub section a detailed design summary of the air delivery system is provided. The selected air compressor and air preparation units are presented along with the various pipe fittings and adaptors used throughout the air delivery system.

The selected air compressor for the final design is Atlas Copco's oil-injected rotary-screw compressor model GA7VSD$^+$. The compression unit has a direct coupling to the Interior Permanent Magnet (IPM) motor, a 10-horse power drive train. The IPM delivers variable speed to the drive train, capable of continuous and variable power supply to meet the air compressor demand. The variable flow range is recommended to be between 20 to 100 % duty [13]. The oil environment is treated by the built-in oil-separator contained within the unit. Separated oil remains in the flow routing in the compressor setup and is brought back to lubricate the rotary screw element. The housing for the air compressor dampens noise produced while running to a maximum of 62 dB (A) [13], and features an integrated and programmable on-board electronic controller for system diagnostics and pressure band settings. A photo of the GA7VSD$^+$ unit is shown in Figure 9.

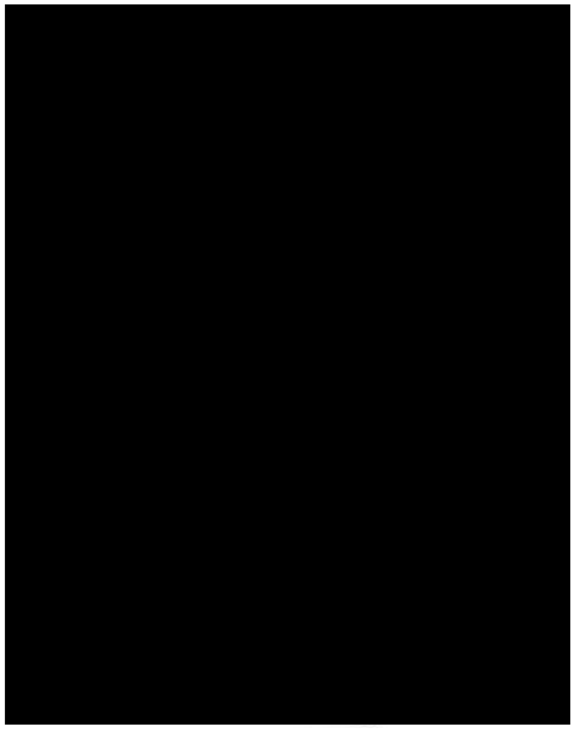

Figure 9. Atlas Copco GAVSD7+ rotary screw compressor [14]

The key points of this model are summarized in the following list:

- Has a working pressure range from 80 to 181 PSIG.
- Has an installed motor power of 10 HP.
- Has a working range of 15.2 to 46.4 cfm.
- Has decibel reading well below the exposure limit producing only 62 dB (A).
- Has an integrated, on-board electronic display for maintenance scheduling, online status visualization, and warning indication.
- Has an expansion pack which includes a built-in air dryer unit for removal of moisture from the compressed air.
- Has an NPT threaded outlet connection port that includes a shut-off valve.
- Has a built in electronic auto drain valve to manage condensate levels without loss of compressed air.

The onboard controller unit allows for active monitoring of the air compressor, displaying information on the status of various internal operating conditions, such as, pressure, temperature and the operating set point for the variable speed drive. Operating points can be set in the allowable working pressure range with the VSD capable of varying the discharge rate out from the compressor. This model has a built-in air dryer unit for the removal of moisture from the compressed air in order to meet the client's expectation on the delivery of dry air. The air dryer unit receives the separated oil-air mixture from the oil separator unit and removes the moisture by diverting the condensate away using by-pass valves.

This particular model was selected as it met several of the client's deliverables for the air delivery system. The self-containing feature, built-in components and layout allows for ease of mind as it is built with compatibility of components and accessories in mind. The self-containment unit acts as a noise barrier as well, preventing excess noise generation that can damage the hearing of the user(s). The coupled motor drive train allows for continuous and variable supply of compressed air, with the air dryer removing lingering moisture out from the oil-air mixture and on board electronic display to monitor system performance and critical parameters. As such, the $GA7VSD^+$ has desirable qualities that meet the client's needs and desirable operating conditions.

In order to meet clean air requirements an oil coalescing filter and oil vapor tower have been incorporated at the outlet from the compressor and are intended to remove the residual oil content from the oil-air mixture. These models are provided by Atlas Copco and are the UD25+ and the QDT20 models [15], receiving air purity Class 1 for total oil according to ISO 8573-1:2010 standards in compressed air application [16]. The maximum oil carrying over in the respective air treatment units is 0.0009 [15] and 0.003 mg/m^3 [16] of oil content with a corresponding pressure drop of 245 and 125 mbar [15]. This air preparation combination is used for treatment of the compressed air to achieve minimal oil carryover to the downstream equipment in the final design.

The treated air out from the air treatment package precedes the design's air receiver tank. The receiver tank is constructed from 304 stainless steel and selected for reasons that are presented in Section 4.1.3. The effective tank size required to accommodate the storage of compressed air from the compressor based on maximum airflow capacity is 50 gallons [17].

However, The Samuel Pressure Vessel Group offers limited tank sizes in stock. Due to this constraint, a 60 gallon tank was selected to serve as the final design air storage unit. The key points for the receiver tank are summarized as the following:

- Tank orientation is vertical with 4 legs.
- Has a storage capacity of 60 gallons.
- Has a height of 50 ¼", an internal diameter of 20", and 2 1/4" of clearance from the frame mounts to the base of the tank.
- The tank has six adapter ports of three different NPT thread sizes to provide multiple port entrants for pipe routing.
- Takes 8 minutes to fully charge the air receiver under the maximum flow output of the compressor.

Several devices are implemented on the final design's air receiver tank and are summarized in the following list:

- The bottom port hole is used for connection to an electronic auto drain valve, the eco drain ED3002N115-K ,offered by Parker Hannifin [18]

- Mounted to the side port is an adapter to house a vessel pressure gauge. The mount is a tee connection made of stainless steel, fitted with a plug and a pressure-snubber to suppress pressure fluctuations that can be harmful to the pressure gauge. The various components are sourced from Ackland's Grainger Canada

In the event pressures within the vessel reach a preset limit, the pressure relief valve located at the top adapter port of the vessel has been designed to open, preventing any chance of over pressurization. To ensure condensate levels in the tank are kept at a minimum, an electronic auto drain valve is included. Once the receiver tank reaches a desirable pressure, the ball valve is manually opened to release the compressed air within the vessel to the downstream equipment.

The compressed air released from the receiver tank is first drawn through the inline condensate separator, into a tee connection with a mounted pressure gauge, and then into the pressure regulator to regulate the pressure of the air supply to the nozzles. The placement of the condensate separator removes the remaining condensate from the compressed air stream before entering the tee connection and pressure regulator. The drain connection port is connected to an electronic auto drain valve that then delivers the removed condensate to a holding tank. Mounted on the tee connection is a pressure gauge to monitor pressure levels before regulation. Once treated, the air flows into the inline air regulator to meet the desirable pressure points set by the operator. A needle valve has been placed downstream from the inline filter and regulator in order to control the airflow rate.

To connect the air compressor line to the receiver tank, a ball valve, quick connect coupler, and flex hose are used. The fixed line from the receiver tank to the nozzles uses threaded adapters and pipe fittings as necessary. The part numbers of the various adapters and pipe fittings are provided in Appendix B.

4.2.2. Air Delivery System Design Summary

As part of the design process, primary components and accessories of the rig's air delivery system have been selected.

The chosen air compressor system consists of Atlas Copco GA7VSD^{+} oil injected rotary screw compressor, coupled directly to an Interior Permanent Magnet motor drive provided by Atlas Copco, with a built-in air dryer and oil separator unit. The airline routing in the air delivery system is made from 304 stainless steel and incorporates several airline accessories for the treatment of the compressed air, such as oil and oil vapor filters a condensate separator, pressure regulation and a needle valve for flow control. The receiver tank volume is recommended in the range of 40–50 gallons, but due to supplier limitations, a 60-gallon air receiver tank has been selected provided by Samuel Pressure Vessel Group. Specific part numbers of the various components are provided in the bill of materials in Appendix B.

4.3. Water Heating System

The water heating system is responsible for rising the deionized water temperature to the required operating temperature of 180°F (82.2°C) at a flow rate of 0.33 GPM for a single nozzle and 1 GPM for all three nozzles.

Two different manufacturers and several different concepts were considered for the water heater system. The down-selection process detailed in Appendix C resulted in the final recommendation of Wattco's 30KW industrial horizontal inline water heater with a built-in control module. The selection of an inline heater minimizes the amount of start-up time that the system requires before testing can commence, and ensures a constant flow of water at the required test point of 180°F.

The specifications sent to Wattco for the custom heater design are detailed in the following table:

TABLE IV. WATER HEATER SPECIFICATIONS AS SENT TO WATTCO

Description	Spec	Units
Inlet Temperature	32	°F
Outlet Temperature	180	°F
Min Flow	0.2	GPM
Max Flow	1.3	GPM
Fluid	deionized water	
Supply Voltage	240	V
Power Phase	1 or 3	

Comparing the above listed specifications to the actual design requirements, it is confirmed that the heater will be meet the intended application. Margin is provided on both flow rate values, and a minimum tank water temperature of 32°F can be accommodated. The quoted price from Wattco for the inline water heating system including the control module is $5975.50 USD. For reference, the full quote is provided in Appendix F.

The following figure (on the next page) is a CAD rendering of the heater from Wattco's online catalog.

[redacted]

Figure 10. Wattco inline water heater

The above model does not show the required control box, though the control box is included in the final design layout presented in section 3.

4.4. Insulation

Insulation requirements are included in the test rig design to maintain the elevated temperature of the working fluids throughout the rig's piping system and to reduce the risk of operator injury from exposed high temperature piping surfaces. Fibreglass was selected as the optimal insulation material, and a minimum insulation thickness of 9.07 mm was calculated for the external surface temperature to remain below a burn temperature threshold of 44°C. The concept selection process and analytical heat transfer calculations justifying this minimum thickness requirement are provided in Appendix C and D, respectively.

Insulation sourced from McMaster Carr is available in a minimum thickness of ½"(12.7 mm) for standard 3/8" NPT pipe sizes. The additional 3 mm thickness provides a 40% margin to ensure that the 44°C surface temperature is not exceeded and accommodates any quantitative errors from the empirical equations used in the calculations. The selected insulation's part number is 5556K26, has a cost of $8.67 per 3 ft lengths, and comes with a kraft paper service jacket. To install the insulation, ASJ tape is required. The McMaster-Carr part number for the ASJ tape is 76755A67 for a 3"x30' roll, at $8.73 per roll.

4.5. Air Heating System

The air heating system selected was also an inline system. The air heater selected was the O.E.M. Heaters HA-12 (P/N K310031) in line air heater, shown in Figure 11. Its lightweight design (7 lbs) make it easy to integrate into the design as it can be supported by the process connection alone.

[redacted]

Figure 11. O.E.M. Heaters HA-12 1500W Inline Air Heater [19]

To control the heat output, the group selected the O.E.M. Heaters K510021 Digital PID Controller. The controller takes 240V single phase power and uses PID control with feedback from a thermocouple to output a variable power to the heater. The target output temperature as well as the actual temperature are shown on a digital display built into the controller, as well as the option for manual PID tuning. The controller is shown in Figure 12.

[redacted]

Figure 12. O.E.M Engineering K520021 Digital PID Controller [20]

Feedback to the controller will be accomplished using a T-type thermocouple, which is the limiting factor in both the minimum and maximum temperature capabilities of the air heating system as the heater itself is rated for a much wider range of temperatures. Specifications for the air heating system are shown in TABLE V.

TABLE V. AIR HEATING SYSTEM SPECIFICATIONS

Description	Spec	Units
Min Inlet Temperature	-4	°F
Max Outlet Temperature	752	°F
Max Flow	50	CFM
Max Pressure	100	psig
Fluid	air	
Supply Voltage	240	V
Supply Current	6.25	A
Power Phase	single	

4.6. Measurement and Control System

The measurement and control system was further broken up into four sub-categories:

- Flow measurement
- Pressure measurement
- Temperature measurement
- Controller, data logging and user interface

Several concepts for each sub-category were considered and a final concept was selected for each of these categories, and devices were sourced to form a completed concept for the entire measurement and control system. The process is described in detail in APPENDIX C.

The group decided, where possible, to source sensors already being used on the TRDC to simplify sourcing, integration of the sensors into the design and sensor maintenance. Two sensors already being used on the TRDC are the Emerson Rosemount 2088 series pressure transmitters and the FTI ft-series flowmeters. Therefore, the group sourced sensors from these series to use on the test rig.

For this design, the group sourced QTY (1) of the FT4-8NEW-LEA-2 flowmeter to measure the water flowrate through all three nozzles. The selected flowmeter has the following specifications:

- ½” NPT external threads process connection and 0.37 ID
- 10 points normal calibration, 10:1 range, in water
- 316SS housing with a 430SS rotor
- 440CSS ball bearings
- Magnetic pickoff with MS connector
- Extended flow range of 0.1 gpm to 3 gpm

Key dimensions of the flowmeter are found by using values from TABLE VI, applied to Figure 13

TABLE VI. DIMENSIONS FOR VARIOUS FT SERIES FLOWMETERS WITH NPT FITTINGS [21]

[redacted]

The flowmeter selected by the group was from the FT-8 series, therefore the values for A and B in TABLE VI are 2.45 in and 1 in, respectively.

[redacted]

Figure 13. Dimensioned Drawing for FT series Flowmeter with NPT Fittings [21]

Overall cost of the flowmeter with taxes was quoted at $1,789.92CAD by CB Enginering Ltd. Details from the quote can be found in APPENDIX F.

The group sourced QTY (6) of the Rosemount 2088G 2 S 22 A 1 pressure transmitter to measure water and air pressure at each nozzle, and QTY (2) of the Rosemount 2088G 2 SS 22 A 1 M4 pressure transmitter to measure water and air pressure at their respective regulator outlets. These two pressure transmitters have a digital display to aid in setting the system pressures, whereas the other six do not. Otherwise, all eight pressure transmitters have the following specifications:

- Pressure readings are in gage
- Pressure readings rated from -14.7 psig to 150 psig
- 4-20 mA DC output
- 316L SST ½”-14 female NPT process connection
- ½”-14 NPT conduit entry

Figure 14 shows the Rosemount 2088 pressure transmitter with the digital display option included.

Figure 14. Rosemount 2088 Pressure Transmitter with Digital Display [22]

The group sourced QTY (3) of the Omega TJ26-CPSS-18G-6 thermocouple, two to measure the air and water temperatures near the nozzles and one to use as feedback for the air heater. The thermocouples have the following specifications:

- T-type thermocouple probe
- 1/8” diameter 316SS sheath, 6” in length
- Transition joint with strain relief spring
- Grounded tip

The cost of one thermocouple is $43.50 CAD. An example of a TJ36 series thermocouple can be seen in Figure 15.

[redacted]

To mount these thermocouples, the group also sourced compression fittings from Omega [24]. The specific fittings sourced were Qty (3) SSLK-18-14 stainless steel compression fittings for 1/8” sheath and ¼” NPT connection. Cost of these compression fittings are $27 CAD each. An example of an Omega compression fitting can be seen in Figure 16.

[redacted]

Figure 16. Omega Stainless Steel Compression Fitting [24]

The group selected the Automation Direct CLICK PLC system for controls and data acquisition. As part of this control system, the group sourced QTY (1) of the C0-02DD1-D PLC as the main controller, QTY (2) of the C0-04AD-1 analog input module, QTY (1) of the C0-04THM thermocouple input module and QTY (1) of the C0-01AC power supply. A programming cable D2-DSCBL is also required for PC communication. The total cost of the PLC, power supply, modules and cable is $533.40 CAD.

For data logging, the group sourced the FC-LOG Data Logger from InterConnecting Automation Inc. [25], which costs $163 and stores up to 4GB of data on a micro SD card.

Finally, the group sourced the LM2907 frequency to analog converter from Texas Instruments [26]. This converter will require wiring and to be mounted on a breadboard. The converter can be seen in

To cut the signal to the water heater during an emergency stop, the group sourced QTY (1) of the Omega SSRL240DC75 solid state relay [27], rated to 280 VAC at 75 A max load for 3-32 VDC input signal. To cut the signal to the air heater, air compressor and water pump during an emergency stop, the group sourced QTY (2) of the Omega SSRL240DC10 solid state relays [27], rated to 280 VAC at 10 A max load for 3-32 VDC input signal. To prevent these relays from overheating, the group also sourced QTY (3) of the Omega FHS-2 finned heat sink [27]. The cost of one SSRL240DC75 relay is $86 CAD. The cost of one SSRL240DC10 is $31.50 CAD. The cost of one FHS-2 heat sink is $29.50 CAD. An example of an Omega solid state relay mounted on a finned heat sink is show in Figure 17.

Figure 17. Example of an Omega Solid State Relay Mounted on a Finned Heat Sink [27]

TABLE VII summarizes all the components that make up the measurement and control system.

TABLE VII. SUMMARY OF MEASUREMENT AND CONTROL DEVICES

Description	Part Number	Supplier	Qty
PLC	C0-02DD1-D	Automation Direct	1
Power Supply	C0-01AC	Automation Direct	1
Analog Input Module	C0-04AD-1	Automation Direct	2
Thermocouple Input Module	C0-04THM	Automation Direct	1
Flowmeter	FT4-8NENW-LEA-2	CB Engineering Ltd	1
Pressure Transmitter	2088G 2 S 22 A 1	Emerson	6
Pressure Transmitter	2088G 2 S 22 A 1 M4	Emerson	2
T-Type Thermocouple	TJ36-CPSS-18G-6	Omega	3
Compression Fitting	SSLK-18-14	Omega	3
Data Logger	FC-Log	InterConnecting Automation Inc.	1
100A Solid State Relay	SSRL240DC100	Omega	1
Finned Heat Sink	FHS-2	Omega	3
Programming cable	D2-DSCBL	Automation Direct	1
10A Solid State Relay	SSRL240DC10	Omega	2

Final specifications for the entire measurement and control system is shown in TABLE VIII.

TABLE VIII. SPECIFICATIONS FOR MEASUREMENT AND CONTROL SYSTEM

Description	Spec	Units
Min Flow Rate	0.1	gpm
Max Flow Rate	3	gpm
Max Pressure	150	psig
Max Temperature	250	°F
Voltage Inputs	1 or 2	#
Current Inputs	8 or 9	#
Thermocouple Inputs	4	#
Digital Inputs	4	#
Digital Outputs	4	#
Supply Voltage	120	V
Power Phase	single	

As discussed in section 2.2, the software and wiring development are outside the scope of this project, and would need to be implemented by the TRDC instrumentation team before finalizing the design of this section

4.7. Spray Pattern Measurement System

Measurement of spray pattern geometry is accomplished using Oxford Laser's Envision Patternate spray analysis software. The software takes either a still image or a high-speed movie as input, and, after calibration, provides the user with the ability to measure coordinates, mark out spray angles, and qualitatively examine the spray density using colour maps. A sample output of the program from a fuel injector spray is shown in Figure 18, below.

Figure 18. Sample output of Envision Patternate spray analysis software [28]

For simple spray geometry measurements, only still images are needed, and a high-performance camera is not required. Therefore, to capture the spray angle, a simple waterproof GoPro 6 is recommended. This camera is easy to use and set-up, and can also upload files wirelessly to a laptop through an internet connection or over Bluetooth. The estimated cost of the spray analysis software is $2000 CAN, and the GoPro 6 is available from any local electronics department store for approximately $600 CAN.

In order to gather velocity data or insights into the spray formation from the software, a high-speed camera would be required. However, due to the high output velocities of the air atomizing nozzles used at the TRDC, even a professional high-speed camera is not guaranteed to have an adequate shutter speed to capture to track individual droplets [29].

As a result, laser imaging products are recommended should GE wish to gather velocity, droplet size, and spray formation data using the test rig. The recommended system is Oxford Imaging's VisiSize N60V package, which uses laser shadowgraph techniques to capture very small, fast moving droplets. The system handles droplets as small as 5 μm, and has a velocity range up to up to 700 m/s for droplets 50 μm in size. The system has been used successfully at another engine icing test facility (as shown in the specification package provided in Appendix F), and thus would confidently meet the spray conditions at the TRDC. The N60V camera head and laser light source are pictured in Figure 19, below.

[redacted]

Figure 14 also shows the rail system used for installation of the N60V. However, as part of the purchase, Oxford Imaging installs the system and provides training for up two staff members regarding the system usage. The quoted all-in cost for the system is $121k USD ($154K CAN).

4.8. Frame Assemblies

The frame subsystems provide structural platforms to mount and support the weight of the test rig's components. In addition, the frame assemblies address GE's needs for the test rig to be easily portable. First, a summary of the selected frame material and caster types are provided, followed by a weight breakdown of the test rig components, and a description of the final frame assemblies.

Through the conceptual design process detailed in Appendix C, grade A513, 2x2" square steel tubing was selected as the optimal material and geometry for the frame members. The selection of square tubing provides a convenient means of mounting flanges, plates and other components to the frame. The selected dimensions also eliminate the need for excessively long hardware and easily accommodate standard drill bit lengths. The selected A513 grade is also commonly available, is suitable for structural applications, and has good machining and welding characteristics [31].

To provide a safe and stable rolling platform, one locking caster is used on each corner of the frame. The selected casters are plate mounted 3x1-1/4" total locking casters with urethane on nylon wheels, and are each rated for load of 250 lbs. The casters have been sourced from Casterland for $23.79 each [32].

To ensure that the rig can be rolled manually, the Canadian Centre for Occupational Health and Safety (CCOHS) guidelines were consulted. In the guidelines, it states that that the maximum weight of a four-wheel handcart must not exceed 227 kg (500 lbs) for one person to move a cart over a distance of 33 m [11]. Therefore, due to the weight of all of the required components, the test rig has been designed as three separate assemblies.

As discussed in Section 4.1.4, the water storage tank weighs 415 lbs from the water alone, and is therefore required to be on a detachable independent platform. The tank itself weighs 70 lbs, and has been sourced to come with pre-installed casters.

Similarly, the air compressor sourced for the test rig weighs 732 lbs, and as a result, an independent frame has been designed to transport the compressor when required. After accounting for the weight of the frame, this secondary assembly weighs 790 lbs in total.

The remainder of the components for the test rig are installed on the primary frame, and a weight break-down of the important components is shown in TABLE IX

TABLE IX. LISTING OF COMPONENT WEIGHTS ON THE PRIMARY TEST RIG FRAME

Part	QTY	Unit Weight [lbs]	Total Weight [lbs]
Frame (per ft)	84	2.14	179.76
Water Heater and Controller Box	1	150	150
Air Tank	1	148	148
Fittings and accessories	50	1-2*	70
Pipes (per ft)	30	0.66-2.7	45
Water Pump Motor	1	30	30
Water Pump	1	10*	10
Air Heater	1	7	7
HDPE	N/A	7	7
Misc. (Hardware, contro	N/A	5*	5
Sum			651.76

* Estimated weights due to unavailability of exact data

As shown in TABLE IX, the sum of all major components making up the primary test rig frame exceeds the 500 lb limit suggested by the CCOHS guidelines for a single person to move. Therefore, when the rig is fully assembled, it is recommended that two people are used to transport it.

Based on the estimated sum of all the component weights on the test rig, simple analytical calculations were performed to select the require gauge of steel tubing. The calculations provided in Appendix D justify that 14-gauge steel is adequate for the frame members. To summarize the calculations, a single span of the longest frame member is able to support half of the frame's total distributed component load and a 200 lb maintenance worker/operator at the midspan with a safety factor of 1.7.

The primary frame measures 6' long, 4'4" wide, and has additional cross-members installed where support and mounting locations for components supports are required. The frame members are welded together, and components are mounted using medium strength, hex head bolts and hardware. Adequate clearances are provided between components for ease of maintenance or replacement, if required. Raised platforms are provided for ease of access to the control system and to the adjustable pressure regulators.

The air compressor frame is made from the same material, and incorporates the same assembly method as the primary frame. However, the air compressor frame's dimensions are matched to the mounting curb of the air compressor at approximately 40" by 28".

The primary test rig frame is shown in Figure 20 and the compressor frame is shown in Figure 21.

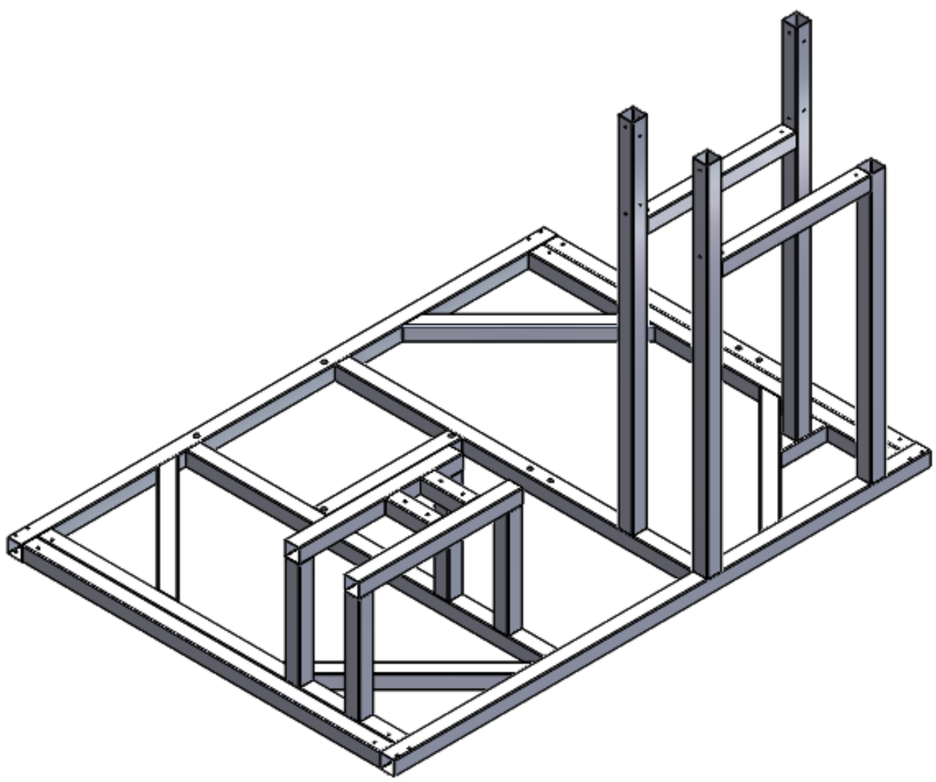

Figure 20. Primary test rig frame

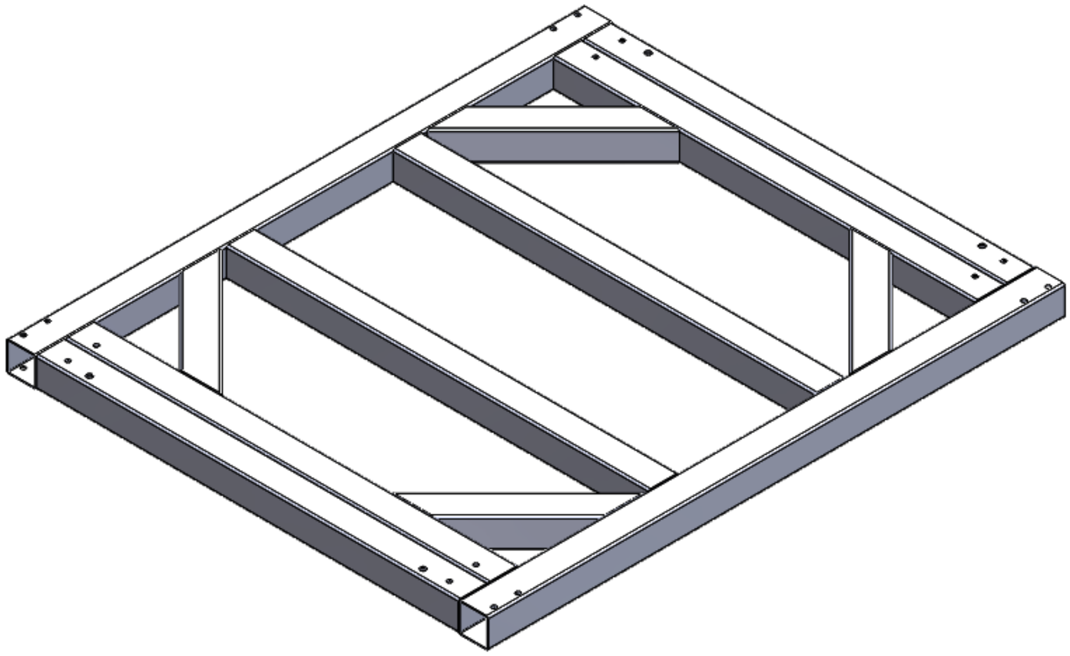

Figure 21. Air compressor frame

Figure 20 and Figure 21 show that similar geometries are used for both the primary and air compressor frames to simplify the manufacturing and assembly processes. Detailed drawings for both frame assemblies are provided in Appendix A.

5 Summary

This report describes activities undertaken as part of a design project submitted by GE to address their air atomizing nozzle troubleshooting needs at the Engine Test and Research Development Centre, Winnipeg MB. The current method of identifying malfunctioning nozzles through inspection is time consuming and ineffective. Additionally, the TRDC currently has no way of gathering spray pressure and flow rates curves or spray pattern data on-site. Therefore, an independent air atomizing nozzle test rig has been designed which controls the water and air flow to troubleshoot and collect data for either one, two, or three nozzles at a time. The water and air flows are provided at pressures of up to 100 pisg and temperatures of 180°F to simulate the conditions on the TRDC spray mast during engine icing certifications. The rig simultaneously collects and records data for the flow properties using pressure, temperature and flow rate sensors. The output spray patterns are characterized using a video camera and spray analysis software. Project deliverables included in this report's appendices are preliminary drawings of the test rig, a parts list with approved vendors, a cost report, and operating instructions.

As part of the design process, the test rig was first broken up into several subsections including the water and air delivery systems, the heating system, the measurements and control system, and the overall frame design. Within each subsection, several concepts were evaluated before selecting the final parts and equipment.

For the water delivery system, the selected pump and motor combination is a rotary gear pump coupled to a half-horsepower DC motor. The water and air lines are threaded, schedule 40S, 304 stainless steel, which provide more than adequate thickness to withstand the maximum design operating pressure of 100 pisg. Class 150 threaded fittings are used to provide a convenient means of assembly and disassembly for maintenance. The water tank has a capacity of 50 gallons, is installed on casters separately from the rest of the rig, and is configured with camlock couplings for easy refilling. A pressure regulator and a liquid filter are provided on the water supply system to ensure a smooth, safe flow free of contaminants to the spray nozzles. On both the water and air lines, ball valves are installed to test either one two or three nozzles at a time.

The selected air compressor and motor combination is Atlas Copco's oil-injected rotary-screw compressor with direct coupling to a 10 horsepower variable speed motor. Several air preparation units have been incorporated outside the compressor for the treatment of the compressed air mixture. Further downstream, a pressure regulator and needle valve are provided on the air supply system to ensure the desired pressure point and discharge rate of compressed air is delivered to the nozzle setup.

The heating system comprises of a 30 kW electric resistance inline water heater, an electric inline air heater, and fiberglass insulation. The heating system design ensures that a continual supply of air and water can be delivered to the spray nozzles at the required 180°F,

and that no external surface of the air or water pipes heats up to beyond 44°F for operator safety.
The group has selected, where possible, measurement devices already used at the TRDC such as the Flow Technology FT-8NENW-LEA-2 flowmeter and the Emerson Rosemount 2088 G-2-S -22-A-1 pressure transmitter. To measure temperature, the group sourced the Omega TJ36-CPSS-18G-6 T type thermocouple. Data will be read by the Automation Direct CLICK PLC (P/N C0-02DD1-D), which will also be able to execute an emergency stop procedure. Data is logged using the InterConnecting Automation FC-LOG data logger. Spray geometry characterization is provided by a GoPro Hero 6 which feeds images into a laptop running Oxford Laser's Envision Patternate spray analysis software. Optionally, a proposal to incorporate Oxford's VisiSize N60 system for droplet size and droplet velocity measurement has also been included at a significant additional cost of $130K CAN.

For the frame design, square steel tubing is used throughout, and the frame itself is supported on rolling casters for mobility. The primary frame measures 6' by 4'4" wide and is 4'8" tall at the highest point with all components installed. An additional air compressor frame has been designed to support the compressor separately from the primary rig.

The primary test rig weighs an estimated 650 lbs, and costs $49,900 CAN (without the optional droplet size and droplet velocity measurement system).

By verifying compliance to the client's needs and the identified metrics for the design as a whole and within each subsystem, the team has all ensured the production of a viable design solution. Implementation of the design would provide GE TRDC an effective way of troubleshooting their current supply of nozzles as well as the new capability to gather flow parameters and spray characteristics on individual nozzles.

6 Recommendations

The final design integrates components which meet the design needs to high degree. However, as with almost any design, there are opportunities to improve if time and resources permit. Below are two examples of recommendations for potential cost and weight savings at the TRDC's discretion.

6.1. Compressor

Through continued communication with GE TRDC, it has been brought to the design team's attention that diesel air compressors may be available on-site periodically for nozzle testing while they are not being used for engine testing purposes. Therefore, if a dedicated air compressor is not required for the rig, this part may be omitted along with the air/oil mixture treatment accessories, presenting cost savings of approximately $15,000 CAN. A simple change of the fittings to the air receiver tank should allow for compatibility with the diesel air compressors. However, long flex hoses may be required and the placement of the rig may be restricted with this option since the diesel air compressor must be run outdoors, and the test rig is rated for indoor operation inside of one of the TRDC's maintenance sheds.

6.2. Frame Optimization

The frame components of the design are comprised of durable, standard materials, which can be easily assembled. In order to simplify the frame assemblies, uniform cross-sections were utilized that meet the highest load conditions over the longest span. However, designing all members for the highest stressed component means that the majority of the frame members are oversized relative to their actual applied loads. Examples of clearly oversized members are in the support structures for the PLC mounts or the raised mounting platform for the pump. Therefore, it is reasonable to assume that the weight of the frame could be substantially reduced by optimizing the oversized components to smaller cross-sectional areas. To determine the amount of possible weight reduction, performing numerical finite element analysis on the frame components is recommended.

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APPENDIX A

Drawing Package for the Construction of the Test Rig

Table of Contents

A-1 Introduction

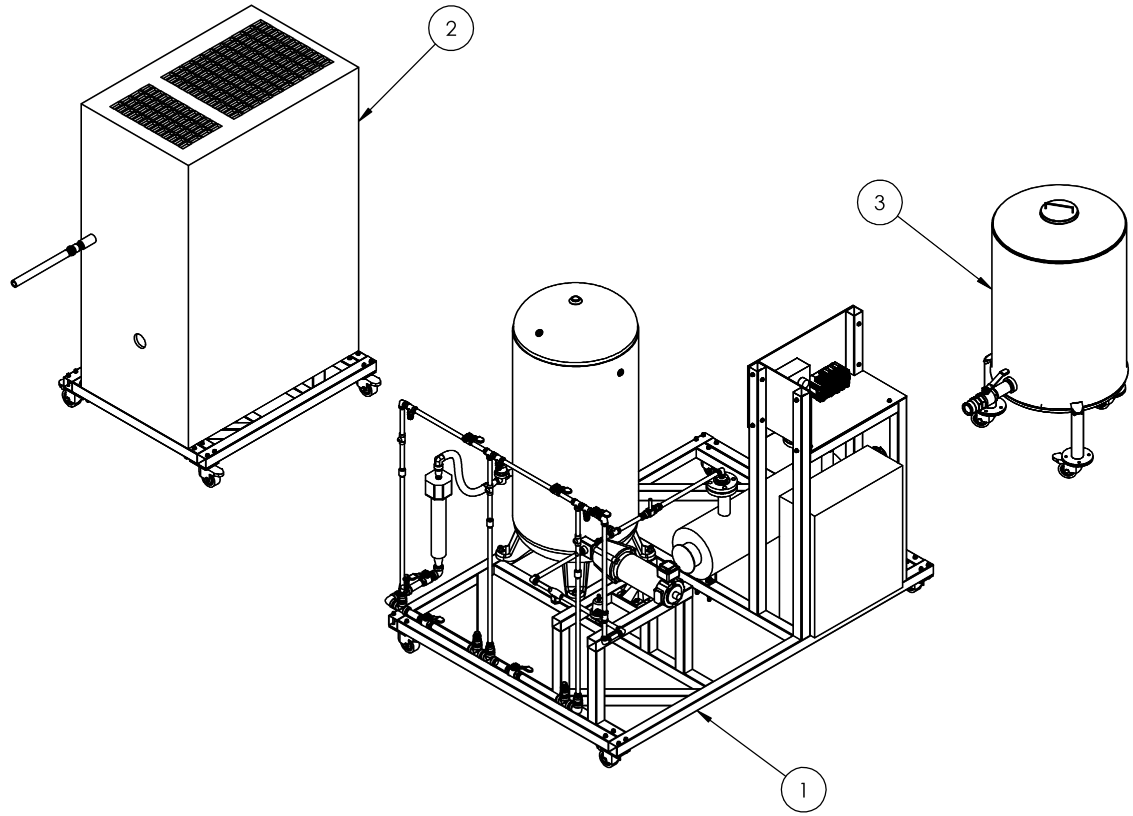
This appendix presents the complete drawing package. Drawings have been prepared from the specifications outlined in the body of the report, to outline construction and orientation of components. The drawing package includes: a master assembly, subassemblies and fabricated parts. In all assemblies, a build of materials (BOM) has been included, along with part identification callouts. Details on specified parts and quotes from various suppliers can be found in Appendix F.

Furthermore, frame assemblies include member location dimensions and welding details.

A-2 Drawing Package

The following series of drawings is the drawing package:

Item#		Description	QTY
	A01	Test Rig - Top Level	
1	A02	Control Platform	1
2	A03	Compressor Sub Asm	1
3	A04	Water Tank	1



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GD&T PER ASME Y14.5-2009
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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER
N/A = NOT APPLICABLE

GENERAL TOLERANCE
CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

MATERIAL

Next Assembly

DO NOT SCALE DRAWING

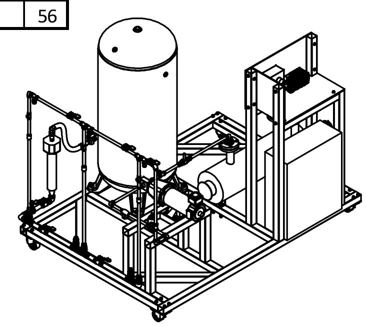
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

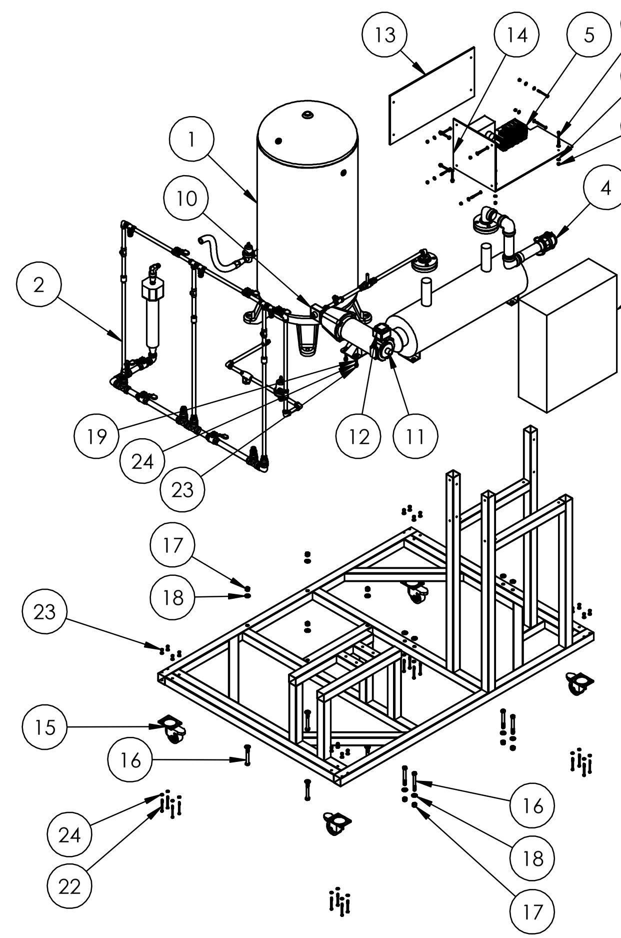
TITLE:
TEST RIG
MAIN ASSEMBLY

SIZE: B | DWG. NO. A01 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

Item#	Part#	Description	Supplier	QTY
	A02	Control Platform		
1	A06	Air Tank Subassembly		1
2	A07	Spray Boom Subassembly		1
3	A08	Hot Pipe Subassembly		1
4	A09	Cold Pipe Subassembly		1
5	A10	PLC Subassembly		1
6	A11	Control Platform Frame		1
7	FLS930X2825-T	Water Heater	Wattco	1
8	MFLS930X2825-T	Water Heater Circulation Vessel	Wattco	1
9	NEMA 4 BOX TYPE	Water Heater Control Box	Wattco	1
10	R10316CA-C1	Water Pump	Motion Canada	1
11	CDP3326	Water Pump Motor	Baldor	1
12	7793K51	Water Pump Speed Controller	McMaster Carr	1
13	8619K462	HDP Panel 12x24x1/4"	McMaster Carr	2
14	8619K461	HDP Panel 12x12x1/4"	McMaster Carr	1
15	CCEP3125UNSPBTB	Complete Total Caster 3"	Casterland	4
16	91247A728	Bolt 1/2-13x4"	McMaster Carr	8
17	97135A250	Nut Nylon Lock 1/2-13"	McMaster Carr	8
18	98023A033	Washer 1/2"	McMaster Carr	16
19	91247A594	Bolt 5/16-18x2-3/4"	McMaster Carr	4
20	97135A220	Nut Nylon Lock 5/16-18"	McMaster Carr	4
21	98023A030	Washer 5/16"	McMaster Carr	8
22	91247A553	Bolt 1/4-20x2-3/4"	McMaster Carr	28
23	97135A210	Nut Nylon Lock 1/4-20"	McMaster Carr	28
24	98023A029	Washer 1/4"	McMaster Carr	56





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NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

MATERIAL

Next Assembly
A01

DO NOT SCALE DRAWING

UNIVERSITY of MANITOBA — MECH 4860 - TEAM 15

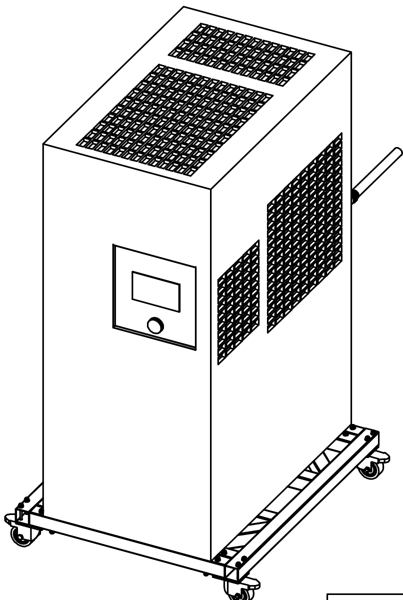
TITLE:
TEST RIG
CONTROL PLATFORM

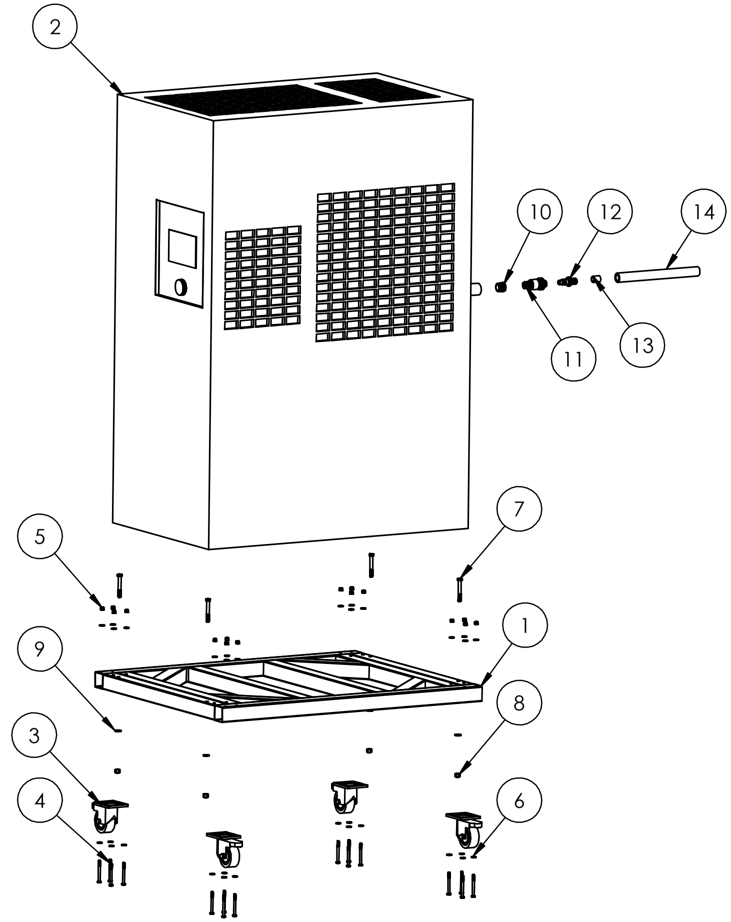
SIZE B — DWG. NO. A02 — REV 0

WEIGHT: N/A — SHEET 1 OF 1

DWG. NO. A02 REV 0

Item#	Part#	Description	Supplier	QTY
	A03	Compressor Subassembly		
1	A05	Compressor Frame Subassembly		1
2	8153-0383-21	GA7VSD ROTARY SCREW COMPRESSOR	Atlas Copco	1
3	CCEP3125UNSPBTB	Complete Total Lock Caster 3"	Casterland	4
4	91247A553	Bolt 1/4-20x2-3/4"	McMaster-Carr	16
5	97135A210	Nut Nylon Lock 1/4-20"	McMaster-Carr	16
6	98023A029	Washer 1/4"	McMaster-Carr	32
7	91247A635	Bolt 3/8-16x2-3/4"	McMaster-Carr	4
8	97135A230	Nut Nylon Lock 3/8-16"	McMaster-Carr	4
9	98023A031	Washer 3/8"	McMaster-Carr	8
10	4464K384	Bushing Reducer 3/4x1/2" NPT	McMaster-Carr	1
11	9582K22	Hose Coupling Socket Industrial 1/2" NPT 1/2" C	McMaster-Carr	1
12	6534K64	Hose Coupling Plug Industrial 3/4" H 1/2" C	McMaster-Carr	1
13	9256T35	Crimp Ferrules 3/4"	McMaster-Carr	1
14	5405K12	Air hose 3/4" ID 50'	McMaster-Carr	1





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NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

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			DWN / CKD
			DWN / CKD
			DWN / CKD

MATERIAL

Next Assembly A01

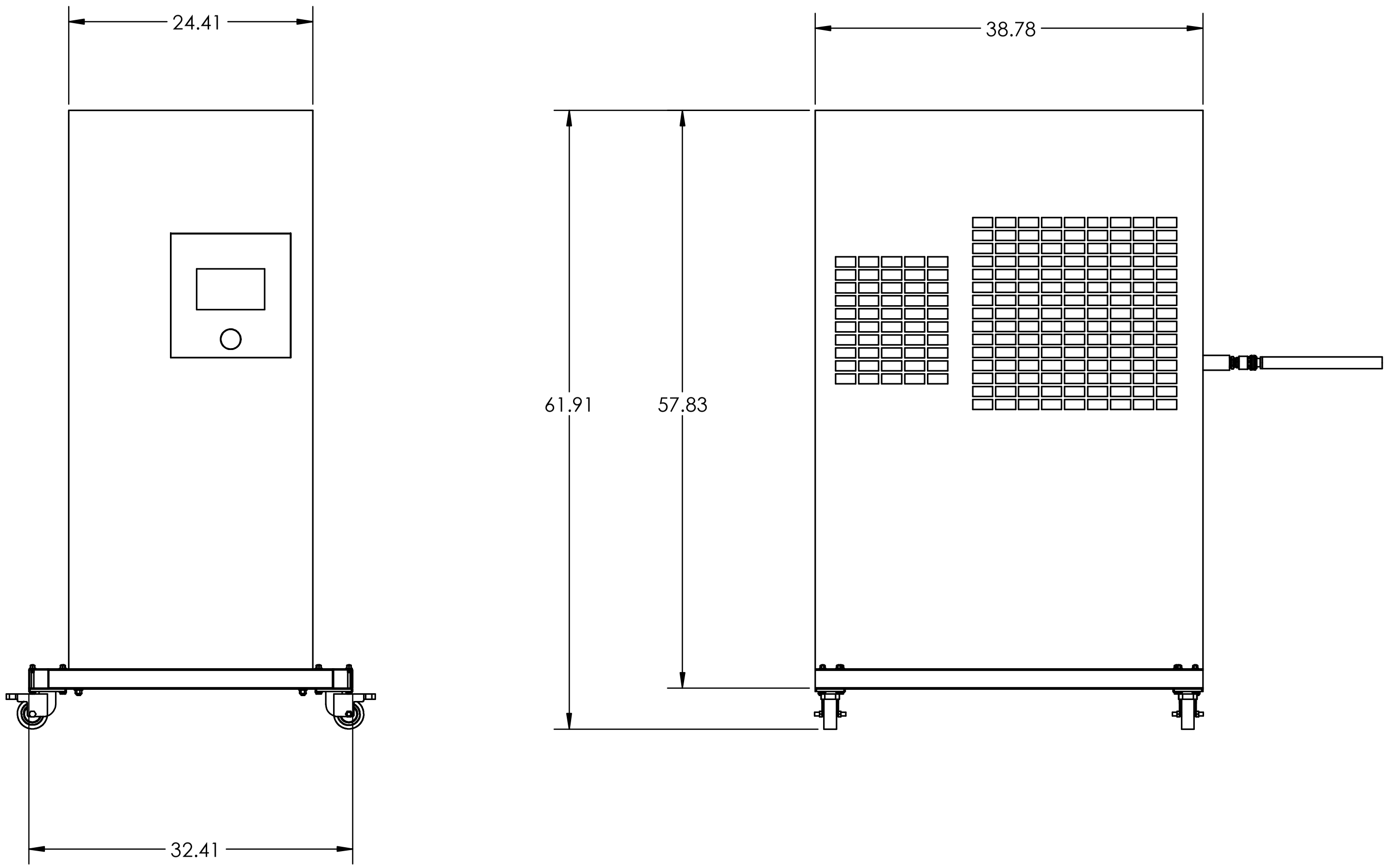
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
COMPRESSOR SUBASSEMBLY

SIZE **B** | DWG. NO. A03 | REV 0

WEIGHT: N/A | SHEET 1 OF 2



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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

MATERIAL

Next Assembly
A01

DO NOT SCALE DRAWING

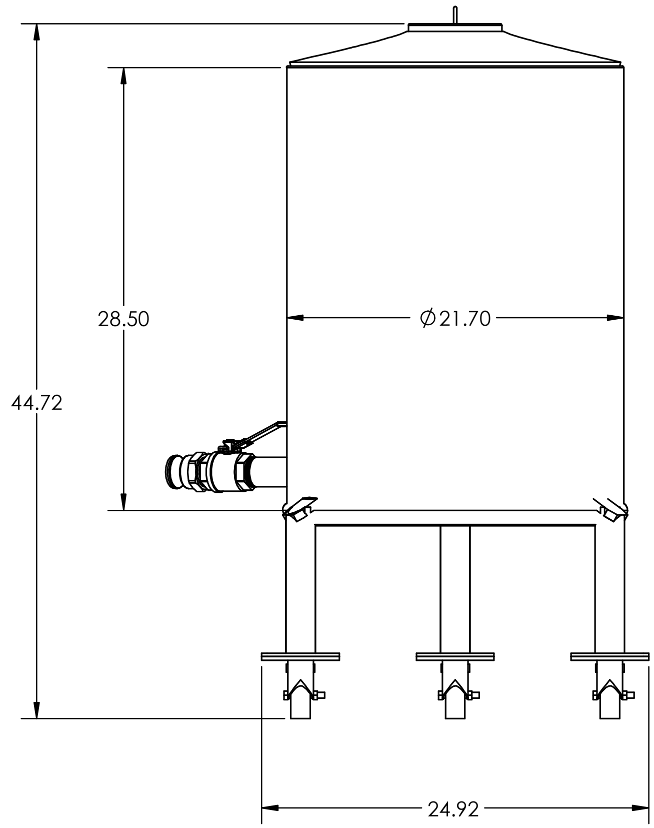
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

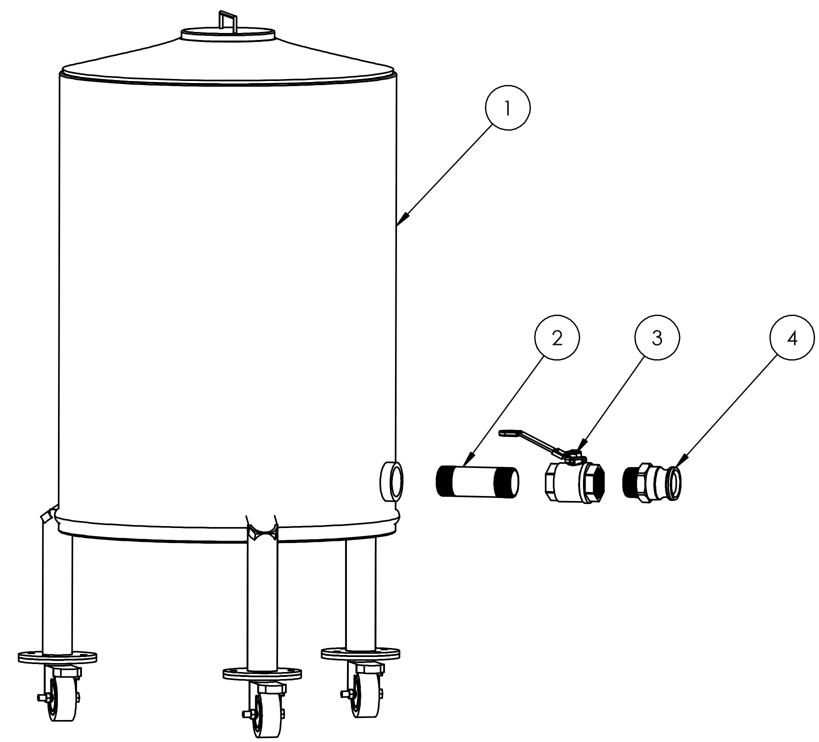
TITLE:
TEST RIG
COMPRESSOR SUBASSEMBLY

SIZE **B** | DWG. NO. A03 | REV 0

WEIGHT: N/A | SHEET 2 OF 2

Item#	Part#	Description	Supplier	QTY
	A04	Water Tank		
1	S4TSC0050-0969	Water Tank 50 Gal	Mixer Direct	1
2	4830K267	Nipple 1-1/2" NPT 5"	McMaster Carr	1
3	46325K330	Ball Valve 1-1/2" NPT	McMaster Carr	1
4	53015K440	Cam and Groove Hose Coupling 1-1/2"	McMaster Carr	1





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DIMENSIONAL UNIT: MILLIMETER

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GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

MATERIAL
ENTER SPEC

Next Assembly
A01

DO NOT SCALE DRAWING

UNIVERSITY of MANITOBA
MECH 4860 - TEAM 15

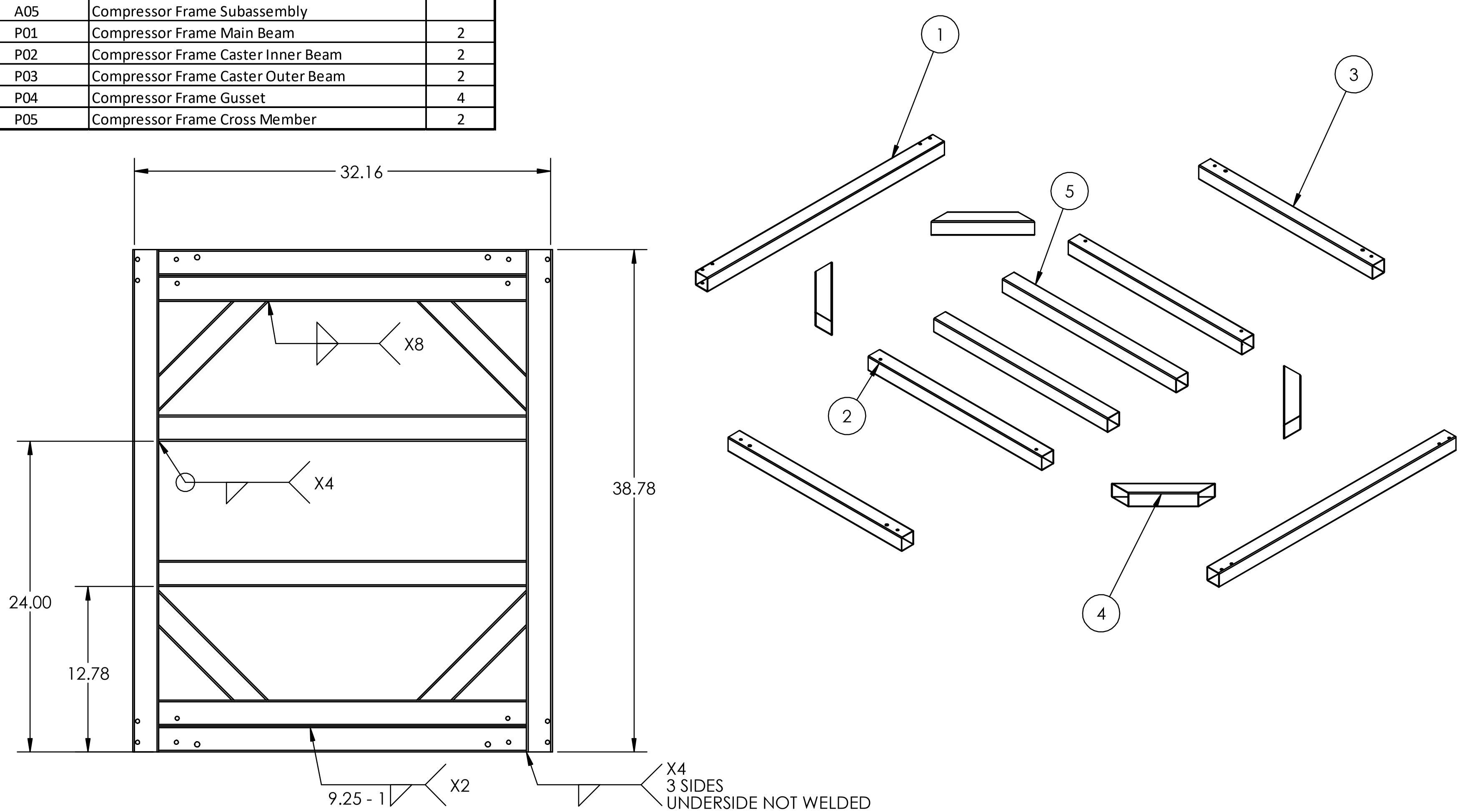
TITLE:
TEST RIG
WATER TANK SUBASSEMBLY

SIZE B | DWG. NO. A04 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. A04 REV 0

Item#	Part#	Description	QTY
	A05	Compressor Frame Subassembly	
1	P01	Compressor Frame Main Beam	2
2	P02	Compressor Frame Caster Inner Beam	2
3	P03	Compressor Frame Caster Outer Beam	2
4	P04	Compressor Frame Gusset	4
5	P05	Compressor Frame Cross Member	2



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NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

CHAMFERS
FILLETS
BREAK SHARP
SHARP

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

REV | DATE Y/M/D | DESCRIPTION | DWN | CKD

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Next Assembly A03

DO NOT SCALE DRAWING

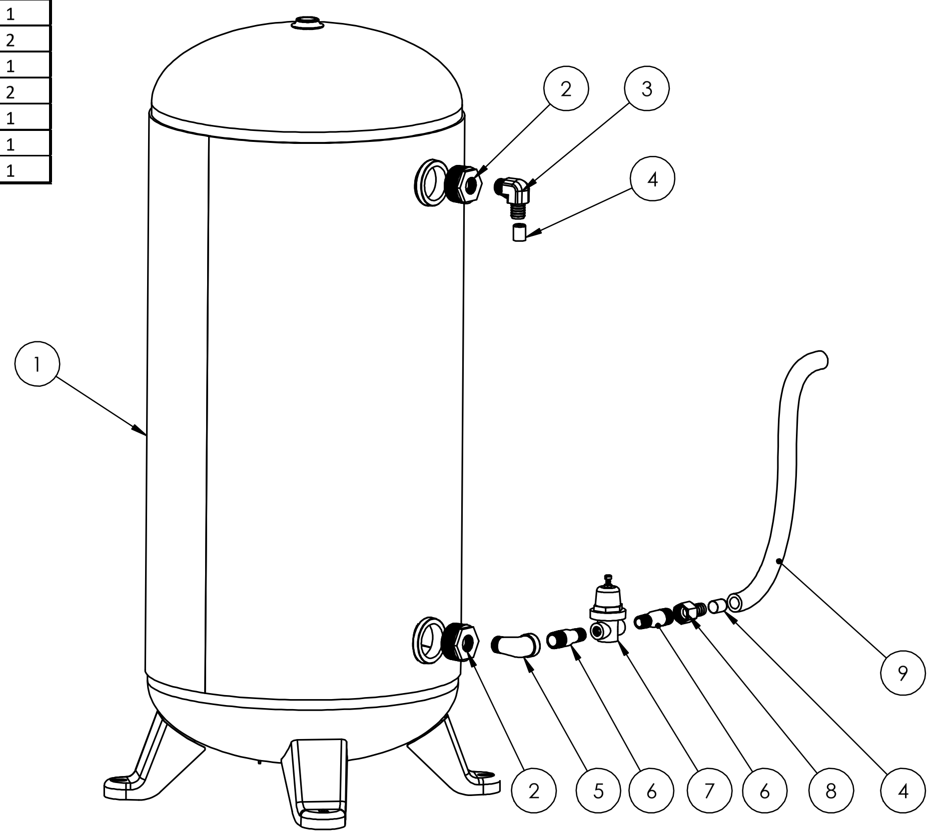
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
COMPRESSOR SUBASSEMBLY
COMPRESSOR FRAME SUBASSEMBLY

SIZE B | DWG. NO. A05 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

Item#	Part#	Description	Supplier	QTY
		Air Tank Assembly		
1	A10043	Air Tank	Samuel Pressure Vessel Group	1
2	6850K33	Bushing Reducer 2" NPT 3/4 NPTF	McMaster Carr	2
3	5361K45	Male Barbed 3/4" 90 Deg Elbow	McMaster Carr	1
4	9256T35	Crimp Ferrule 3/4"	McMaster Carr	2
5	4464K39	Male to Female 3/4" 90 Deg Elbow	McMaster Carr	1
6	2161K14	Male Reducer 3/4 x 1/2" NPT	McMaster Carr	2
7	5022K25	Air Pressure Regulating Valve 1/2 NPTF	McMaster Carr	1
8	5346K58	Female Barbed 3/4" Straight NPTF	McMaster Carr	1
9	5405K13	Air Hose 3/4" ID	McMaster Carr	1



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NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

REV | DATE Y/M/D | DESCRIPTION | DWN | CKD

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MATERIAL

Next Assembly A02

DO NOT SCALE DRAWING

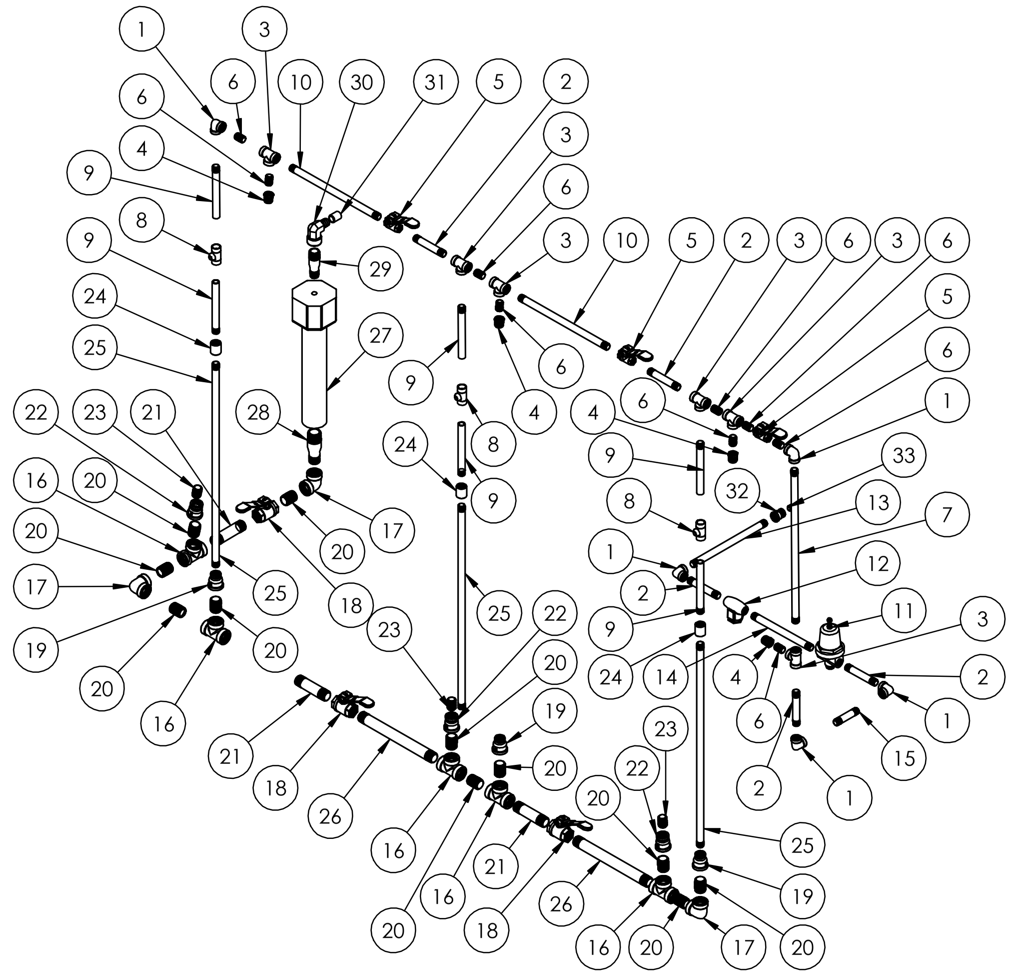
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM
AIR TANK SUBASSEMBLY

SIZE B | DWG. NO. A06 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

Item#	Part#	Description	Supplier	QTY
		Spray Boom Assembly		
1	4464K13	Female Elbow 3/8" 90 Deg	McMaster Carr	5
2	4830K156	Nipple 3/8" NPT 4"	McMaster Carr	5
3	4464K49	Tee 3/8" NPT	McMaster Carr	6
4	4464K266	Bushing Adapter 3/8 MNPT X 1/2" FNPT	McMaster Carr	4
5	46325K27	Ball Valve 3/8" NPT	McMaster Carr	3
6	4830K151	Nipple 3/8" CL	McMaster Carr	9
7	4813K123	Nipple 3/8" NPT 18"	McMaster Carr	1
8	S.S CO. 37596	Nozzle 3/8"	Spray Systems Co.	3
9	9157K93	Nipple 3/8" NPT 6"	McMaster Carr	6
10	4830K162	Nipple 3/8" NPT 12"	McMaster Carr	2
11	5022K334	Pressure Regulating Valve 3/8" FNPT	McMaster Carr	1
12	9998K33	Liquid Strainer 3/8" NPT	McMaster Carr	1
13	4830K161	Nipple 3/8" NPT 10"	McMaster Carr	1
14	4830K159	Nipple 3/8" NPT 8"	McMaster Carr	1
15	4830K155	Nipple 3/8" NPT 3"	McMaster Carr	1
16	4464K52	Tee 3/4" NPT	McMaster Carr	5
17	4464K15	Female Elbow 3/4" 90 Deg	McMaster Carr	3
18	46325K29	Ball Valve 3/4" NPT	McMaster Carr	3
19	4464K528	Reducer 3/4 X 3/8" FNPT Straight	McMaster Carr	3
20	4830K191	Nipple 3/4" CL	McMaster Carr	11
21	4830K196	Nipple 3/4" NPT 4"	McMaster Carr	3
22	4464K529	Reducer 3/4 X 1/2" FNPT Straight	McMaster Carr	3
23	4830K171	Nipple 1/2" CL	McMaster Carr	3
24	4464K353	Connector 3/8" NPT Straight	McMaster Carr	3
25	4813K21	Nipple 3/8" NPT 24"	McMaster Carr	3
26	4830K211	Nipple 3/4" NPT 10"	McMaster Carr	2
27	HA2-12 (K310031)	Air Heater 1500 W	OEM Heating	1
28	2161K16	Male Reducer 1 X 3/4" NPT	McMaster Carr	1
29	2161K14	Male Reducer 3/4 X 1/2" NPT	McMaster Carr	1
30	5346K128	Female Barb 3/4" Elbow 3/4" FNPT 90 Deg	McMaster Carr	1
31	9256T35	Crimp Ferrules 3/4"	McMaster Carr	1
32	4464K522	Reducer 3/8 X 1/4" FNPT Straight	McMaster Carr	1
33	4830K131	Nipple 1/4" CL	McMaster Carr	1



UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

CHAMFERS
FILLETS
BREAK SHARP
SHARP

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

MATERIAL

Next Assembly: A02

DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM
SPRAY BOOM ASSEMBLY

SIZE: B | DWG. NO.: A07 | REV: 0

WEIGHT: N/A | SHEET 1 OF 2

REV	DATE Y/M/D	DESCRIPTION	
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			DWN / CKD
			DWN / CKD
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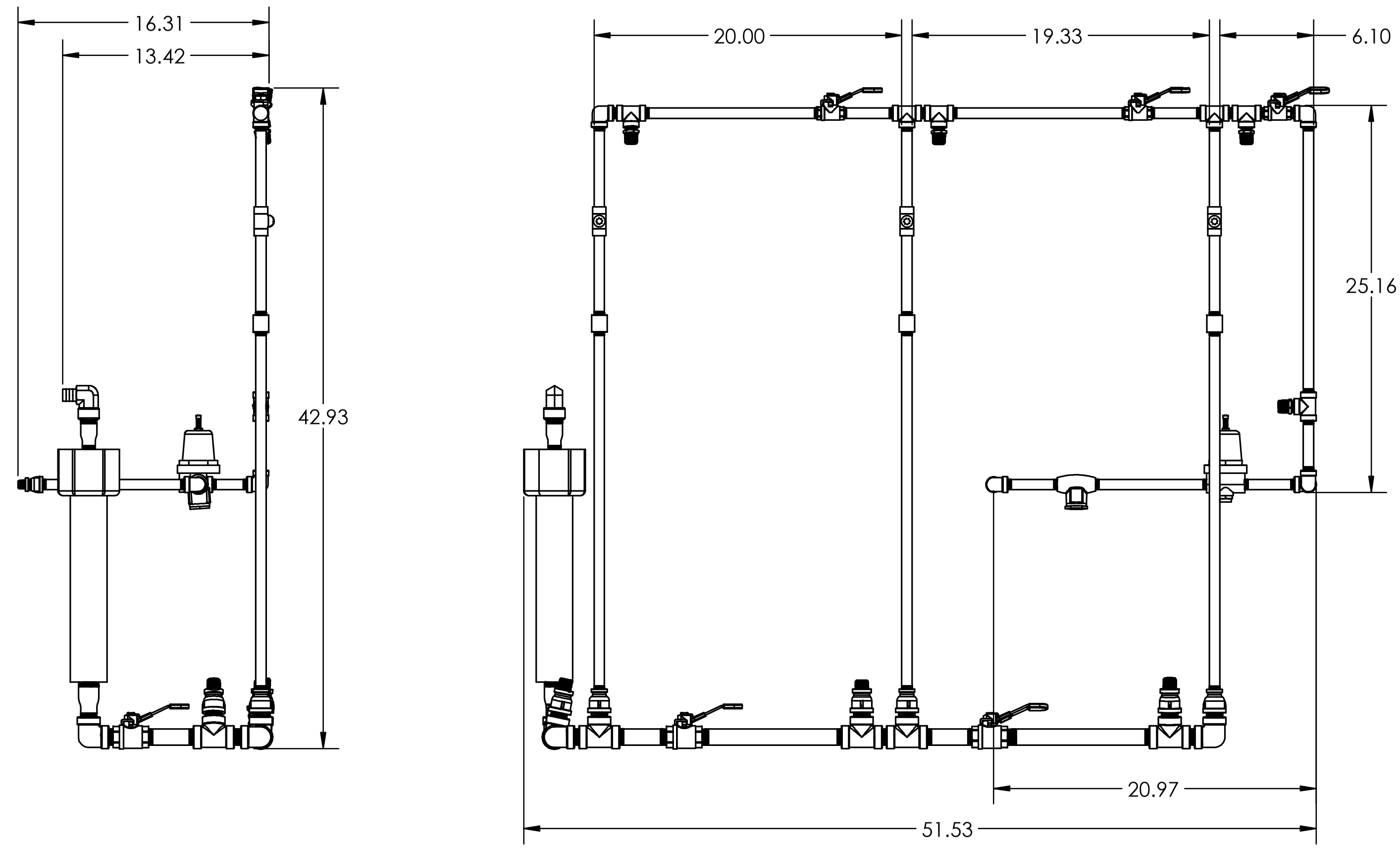
			DWN / CKD



REV	DATE Y/M/D	DESCRIPTION	
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			DWN # NAME / CKD # NAME

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GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

MATERIAL

Next Assembly
A02

DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA
MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM
SPRAY BOOM ASSEMBLY

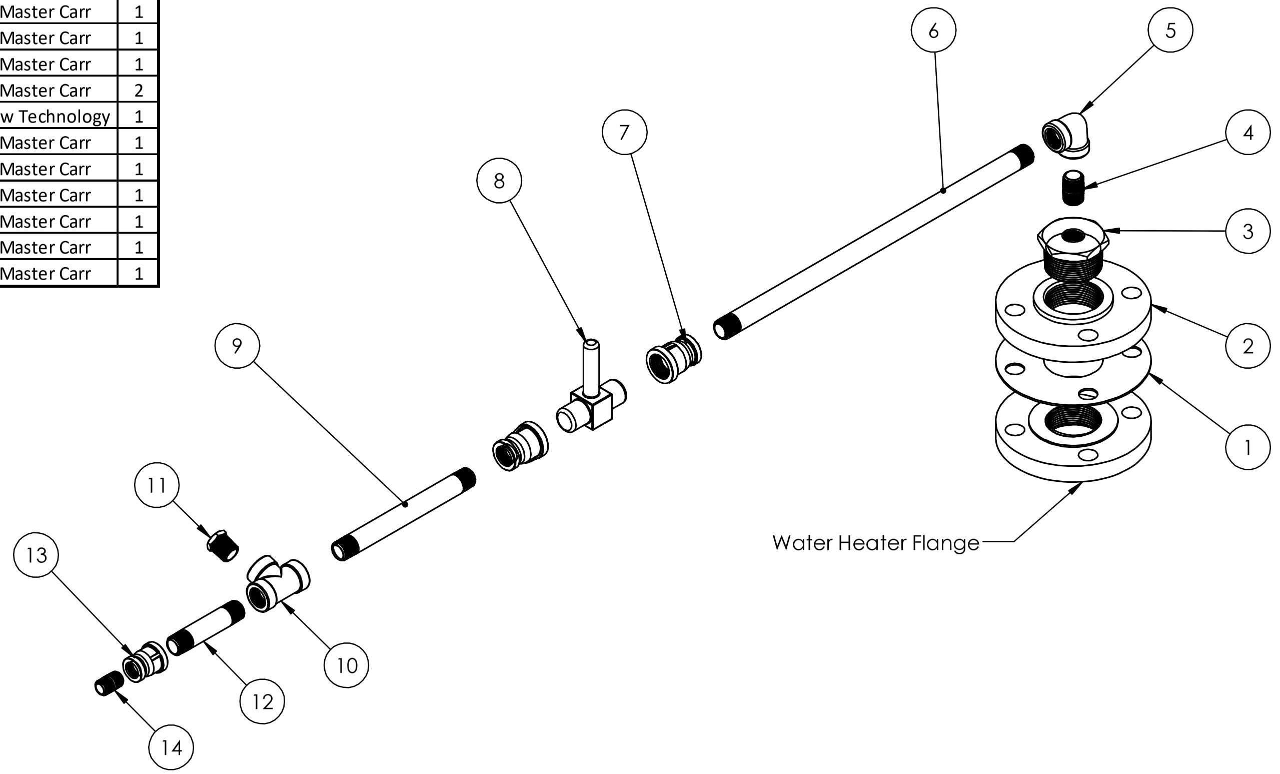
SIZE **B** | DWG. NO. A07 | REV 0

WEIGHT: N/A

SHEET 2 OF 2

DWG. NO. A07 REV 0

Item#	Part#	Description	Supplier	QTY
		Hot Pipe Assembly		
1	4459K74	Flange Gasket	McMaster Carr	1
2	44685K15	Flange Adapter 1-1/2" NPT	McMaster Carr	1
3	4464K154	Bushing Adapter 1-1/2" MNPT x 3/8" FNPT	McMaster Carr	1
4	4830K151	Nipple 3/8" NPT	McMaster Carr	1
5	4464K13	Female Elbow 3/8" FNPT 90 Deg	McMaster Carr	1
6	4813K171	Nipple 3/8" NPT 14"	McMaster Carr	1
7	4464K525	Reducer 1/2 x 3/8" NPT Straight	McMaster Carr	2
8	FT-8NEW-LEA-2	Flowmeter (placeholder)	Flow Technology	1
9	4830K158	Nipple 3/8" NPT 6"	McMaster Carr	1
10	4464K49	Tee 3/8" NPT	McMaster Carr	1
11	4464K263	Bushing Adapter 3/8" MNPT x 1/4" FNPT	McMaster Carr	1
12	4830K155	Nipple 3/8" NPT 3"	McMaster Carr	1
13	4464K522	Reducer 3/8 x 1/4" NPT Straight	McMaster Carr	1
14	4830K131	Nipple 1/4" NPT	McMaster Carr	1



UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR, INTERNAL THREADS AT ØMINOR

CHAMFERS
FILLETS
BREAK SHARP
SHARP

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

MATERIAL

Next Assembly: A02

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

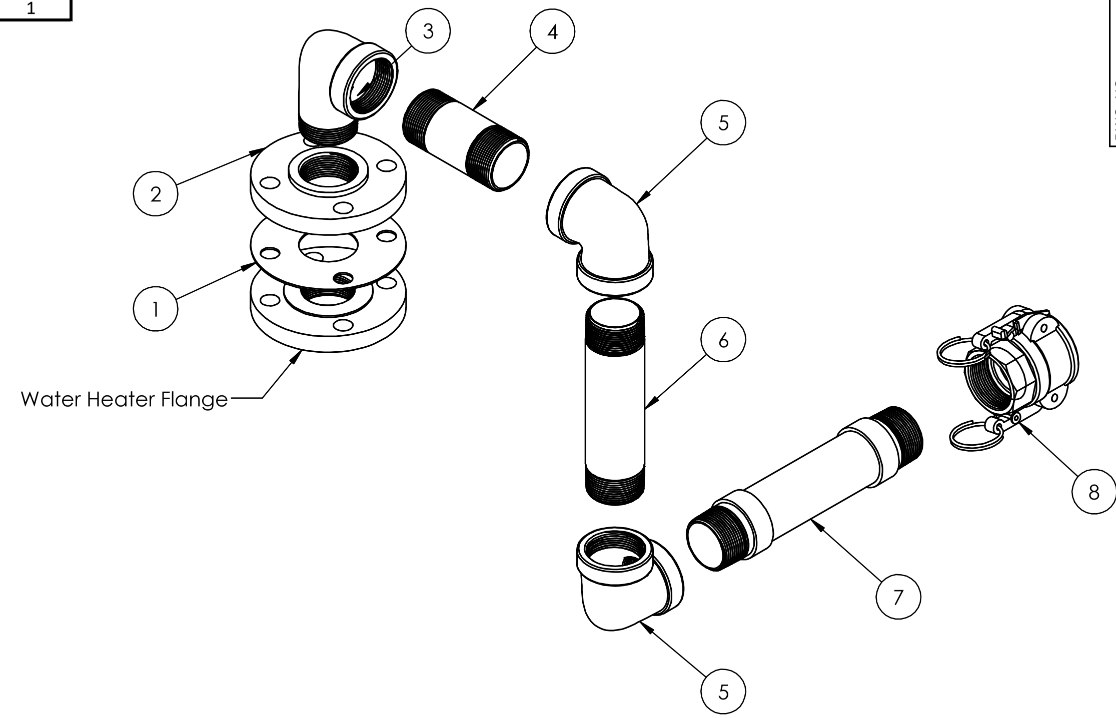
TITLE: TEST RIG CONTROL PLATFORM HOT PIPE ASSEMBLY

SIZE	DWG. NO.	REV
B	A08	0

DO NOT SCALE DRAWING | WEIGHT: N/A | SHEET 1 OF 1

REV	DATE Y/M/D	DESCRIPTION	
			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD

Item#	Part#	Description	Supplier	QTY
		Cold Pipe Assembly		
1	4459K74	Flange Gasket 1-1/2"	McMaster Carr	1
2	44685K15	Flange Adapter 1-1/2"	McMaster Carr	1
3	4464K43	Male to Female Elbow 1-1/2" 90 Deg	McMaster Carr	1
4	4830K266	Nipple 1-1/2" NPT 4"	McMaster Carr	1
5	4464K180	Female Elbow 1-1/2" FNPT 90 Deg	McMaster Carr	2
6	4830K201	Nipple 1-1/2" NPT 7"	McMaster Carr	1
7	5468K950	Braided hose 1-1/2" NPT 9"	McMaster Carr	1
8	53015K174	Female Camlock Coupling D 1-1/2"	McMaster Carr	1



DWG. NO. A09 REV 0

REV	DATE Y/M/D	DESCRIPTION	
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			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD

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GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

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MATERIAL

Next Assembly
A02

DO NOT SCALE DRAWING

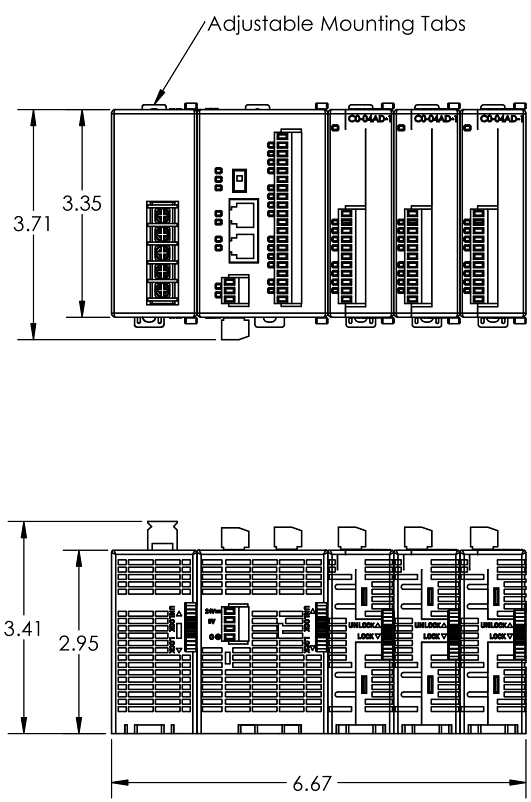
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

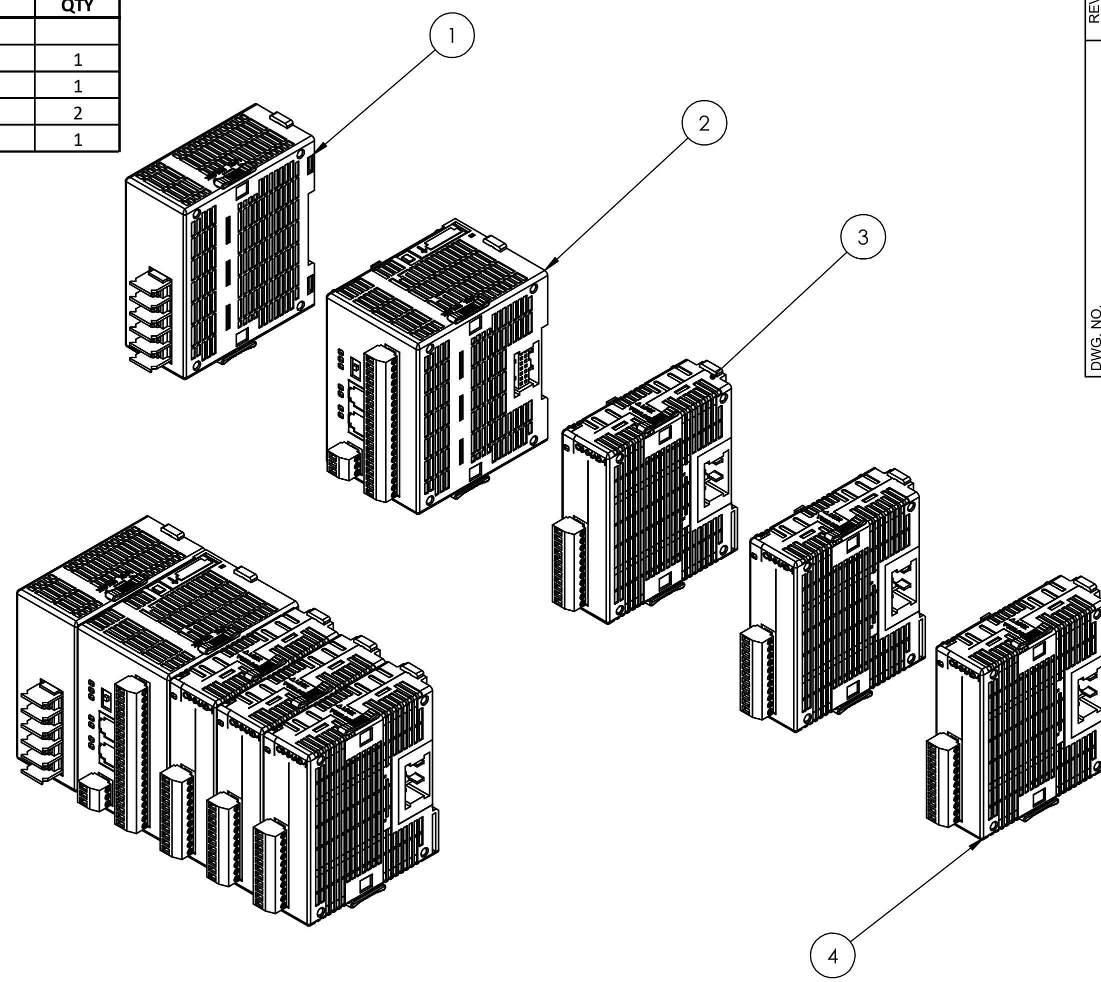
TITLE:
TEST RIG
CONTROL PLATFORM
COLD PIPE ASSEMBLY

SIZE **B** | DWG. NO. A09 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

Item#	Part#	Description	Supplier	QTY
	A10	PLC Subassembly		
1	C0-01AC	PLC Subassembly Power Supply	Automation Direct	1
2	C0-02DD1-D	PLC Subassembly Controller Module	Automation Direct	1
3	C0-04AD-1	PLC Subassembly Analog Input Module	Automation Direct	2
4	C0-04THM	PLC Subassembly Thermocouple Input Module	Automation Direct	1





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REV	DATE Y/M/D	DESCRIPTION		

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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

MATERIAL

Next Assembly
A02

DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA

MECH 4860 - TEAM 15

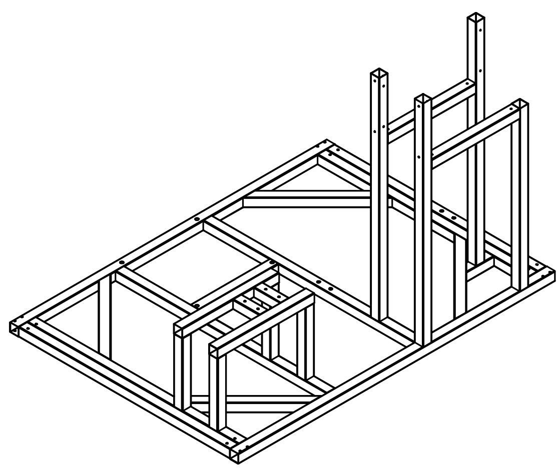
TITLE:
TEST RIG
CONTROL PLATFORM SUBASSEMBLY
PLC SUBASSEMBLY

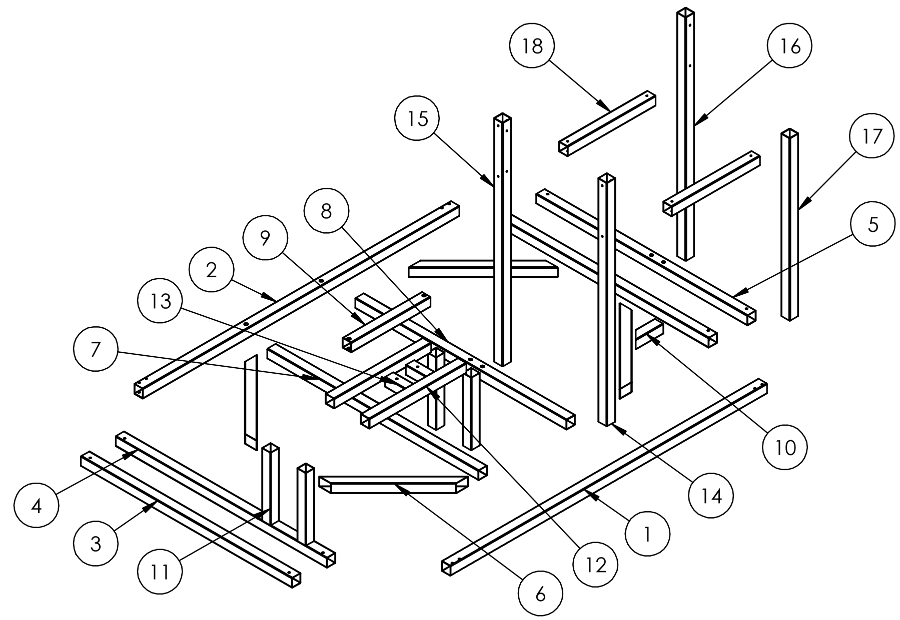
SIZE B | DWG. NO. A10 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. A10 REV 0

Item#	Part#	Description	QTY
	A11	Control Platform Frame	
1	P06	Control Platform Frame Main Beam	1
2	P07	Control Platform Frame Main Beam Air Tank Side	1
3	P08	Control Platform Frame Caster Outer Beam	1
4	P09	Control Platform Frame Caster Inner Beam	2
5	P10	Control Platform Frame Caster Beam Water Heater Side	1
6	P11	Control Platform Frame Gusset	4
7	P12	Control Platform Frame Cross Member	1
8	P13	Control Platform Frame Cross Member Water Heater Mount	1
9	P14	Control Platform Frame Air Tank Mount	1
10	P15	Control Platform Frame Controller Mount Gusset	1
11	P16	Control Platform Frame Pump Up Right	4
12	P17	Control Platform Frame Pump Upper	2
13	P18	Control Platform Frame Pump Mount	2
14	P19	Control Platform Frame Controller Up Right A	1
15	P20	Control Platform Frame Controller Up Right B	1
16	P21	Control Platform Frame Controller Up Right C	1
17	P22	Control Platform Frame Controller Up Right D	1
18	P23	Control Platform Frame Controller Upper	2





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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

REV	DATE Y/M/D	DESCRIPTION	DWN/CKD

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MATERIAL

Next Assembly
A02

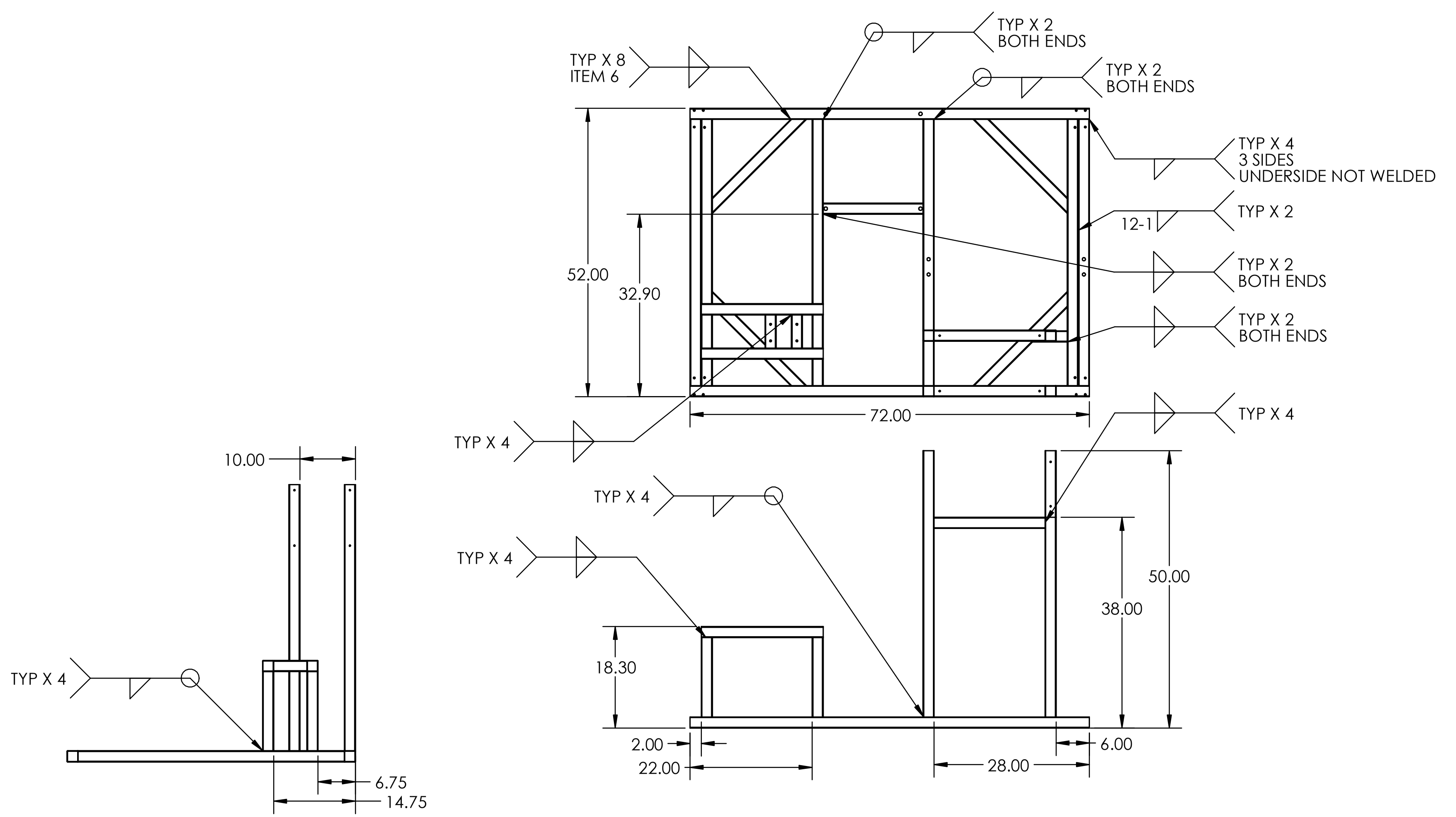
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM
CONTROL PLATFORM FRAME SUBASSEMBLY

SIZE B | DWG. NO. A11 | REV 0

WEIGHT: N/A | SHEET 1 OF 2



REV	DATE Y/M/D	DESCRIPTION		
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GD&T PER ASME Y14.5-2009
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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

MATERIAL

Next Assembly
A02

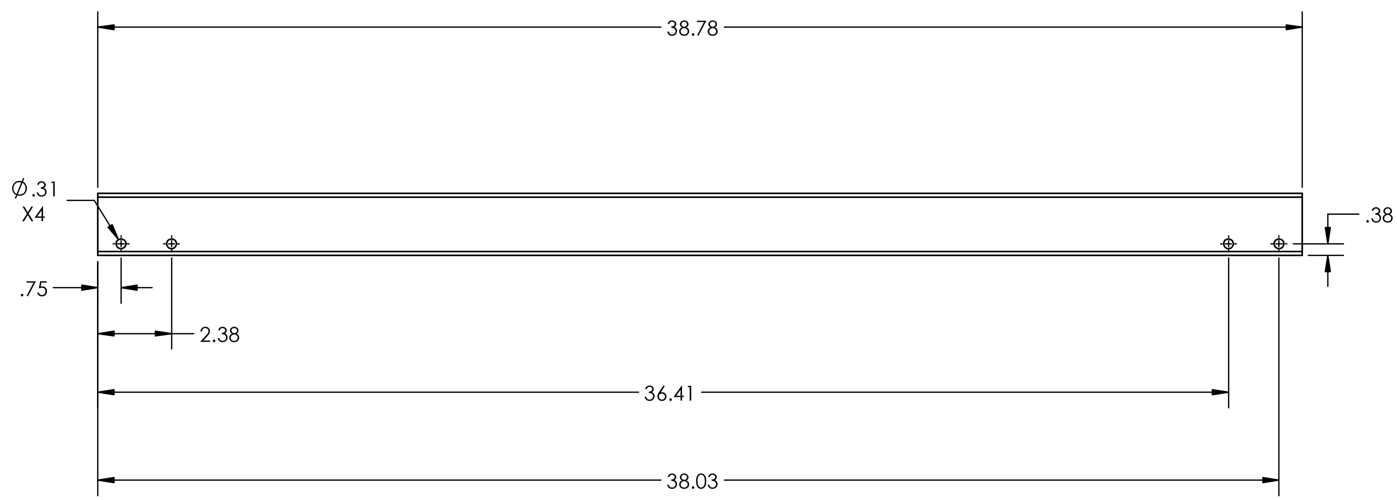
DO NOT SCALE DRAWING

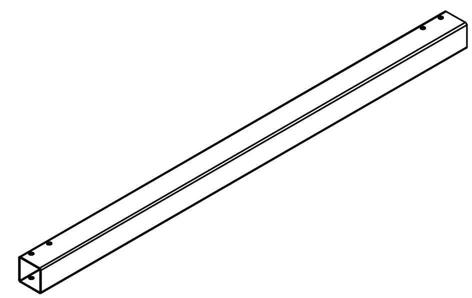
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM
CONTROL PLATFORM FRAME SUBASSEMBLY

SIZE	DWG. NO.	REV
B	A11	0

WEIGHT: N/A — SHEET 2 OF 2





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GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A05

DO NOT SCALE DRAWING

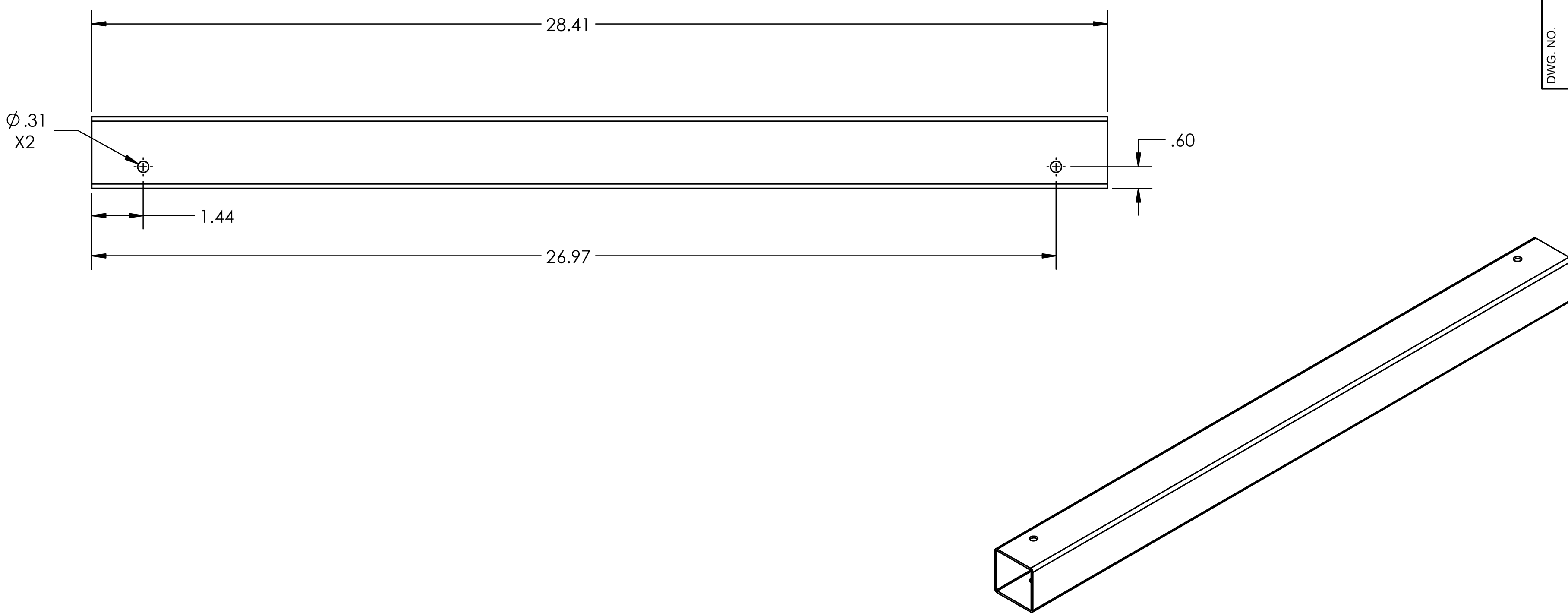
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
COMPRESSOR SUBASSEMBLY
COMPRESSOR FRAME SUBASSEMBLY
COMPRESSOR FRAME MAIN BEAM

SIZE: **B** | DWG. NO. P01 | REV 0

SCALE: 1:20 | WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P01 REV 0



UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE: CHAMFERS / FILLETS / BREAK SHARP / SHARP

THREADED FEATURES: EXTERNAL THREADS AT ØMAJOR, INTERNAL THREADS AT ØMINOR

REV	DATE Y/M/D	DESCRIPTION		
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			CKD	
			DWN	
			CKD	

MATERIAL: 2x2" 14GA A513 12' STEEL

Next Assembly: A05

DO NOT SCALE DRAWING

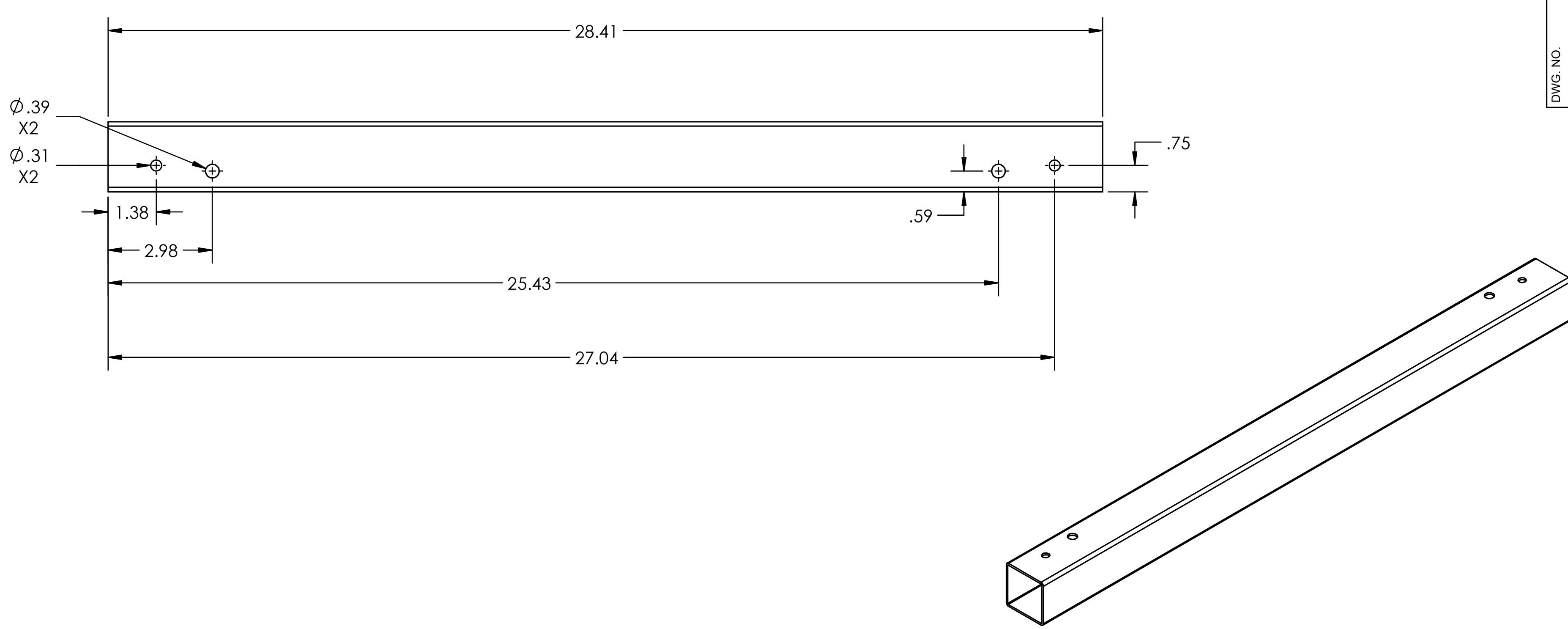
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
COMPRESSOR SUBASSEMBLY
COMPRESSOR FRAME SUBASSEMBLY
COMPRESSOR FRAME CASTER INNER BEAM

SIZE: B | DWG. NO.: P02 | REV: 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P02 REV 0



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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A05

DO NOT SCALE DRAWING

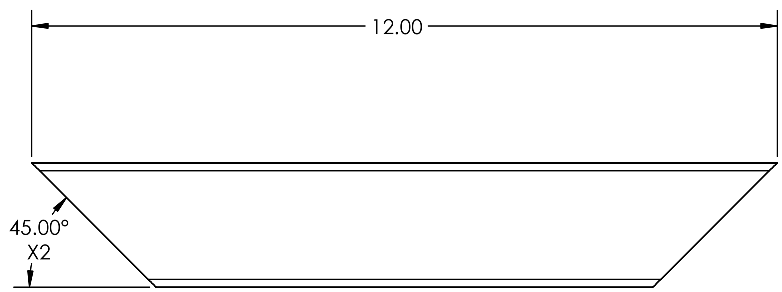
UNIVERSITY OF MANITOBA MECH 4860 - TEAM 15

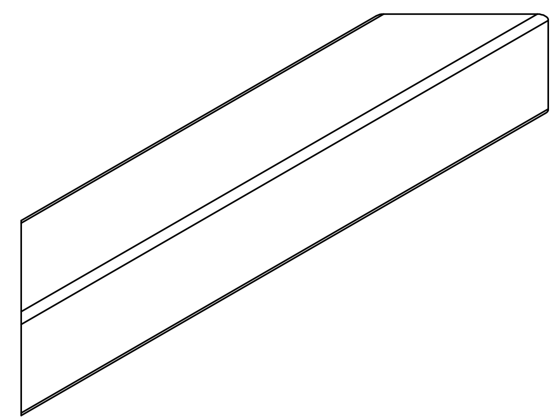
TITLE: TEST RIG
COMPRESSOR SUBASSEMBLY
COMPRESSOR FRAME SUBASSEMBLY
COMPRESSOR FRAME CASTER OUTER BEAM

SIZE **B**
DWG. NO. P03
REV 0

WEIGHT: N/A
SHEET 1 OF 1

DWG. NO. P03 REV 0





REV	DATE Y/M/D	DESCRIPTION	
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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS

FILLETS

BREAK SHARP

SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A05

DO NOT SCALE DRAWING

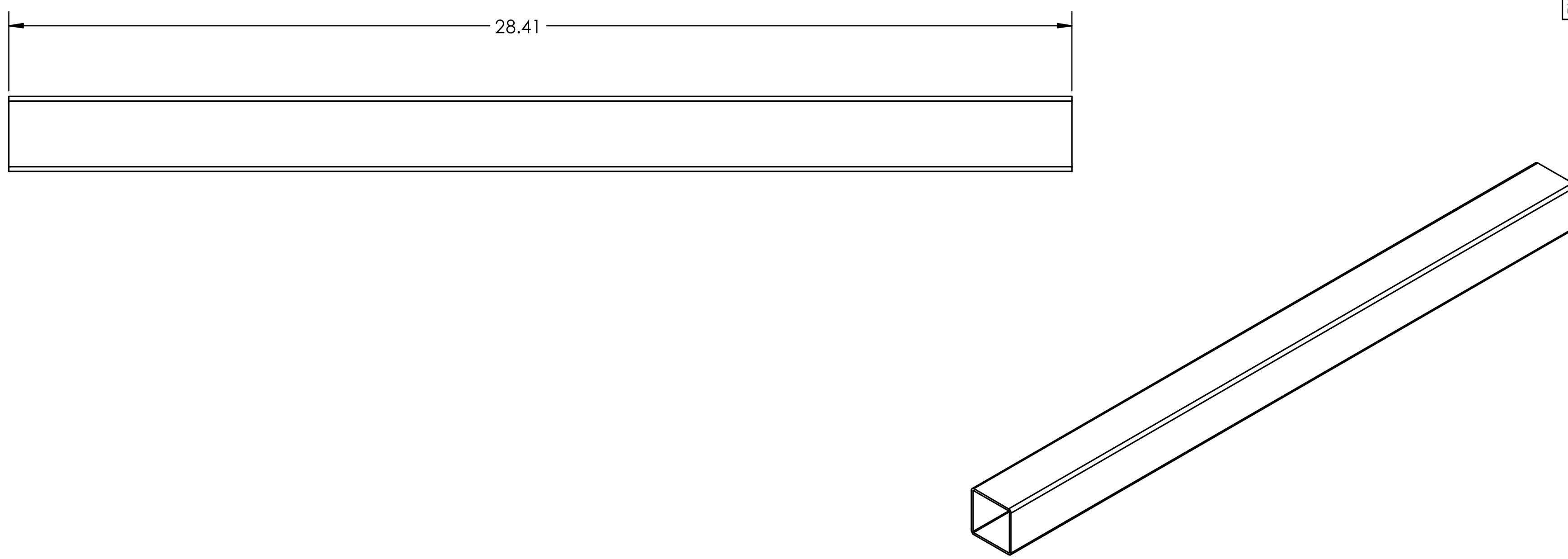
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
COMPRESSOR SUBASSEMBLY
COMPRESSOR FRAME SUBASSEMBLY
COMPRESSOR FRAME GUSSET

SIZE: **B** | DWG. NO. P04 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P04 | REV 0



DWG. NO. P05 REV 0

REV	DATE Y/M/D	DESCRIPTION		
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UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
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CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS

FILLETS

BREAK SHARP

SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A05

DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA

MECH 4860 - TEAM 15

TITLE: TEST RIG
COMPRESSOR SUBASSEMBLY
COMPRESSOR FRAME SUBASSEMBLY
COMPRESSOR FRAME CROSS MEMBER

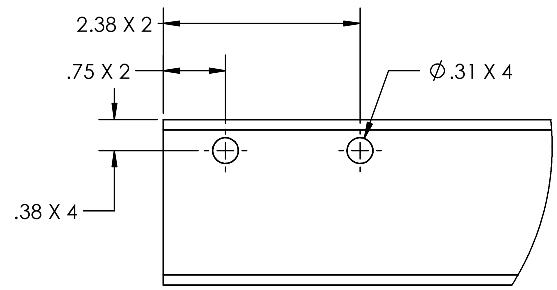
SIZE B

DWG. NO. P05

REV 0

WEIGHT: N/A

SHEET 1 OF 1



DETAIL A
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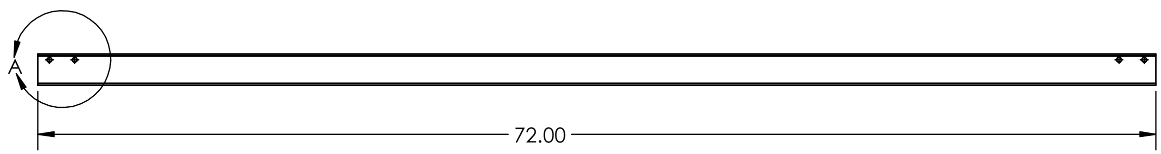

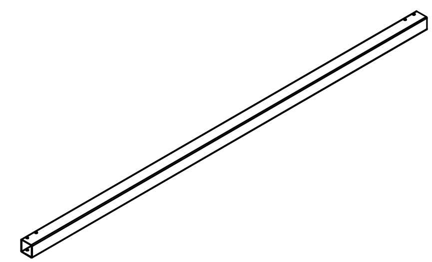

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			CKD	
			DWN	
			CKD	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ∅MAJOR
INTERNAL THREADS AT ∅MINOR

MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A05

DO NOT SCALE DRAWING

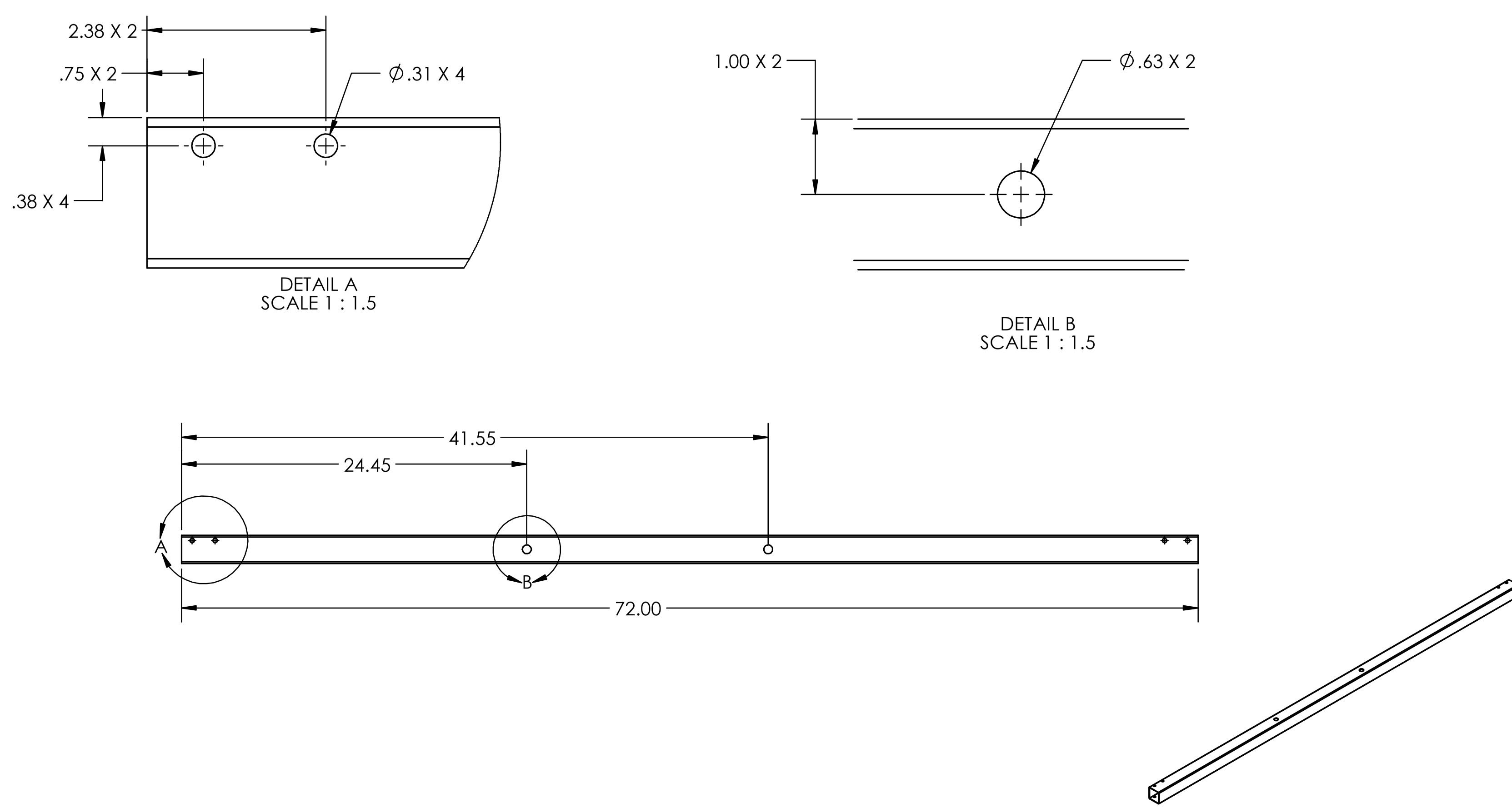
UNIVERSITY OF MANITOBA
MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
MAIN BEAM

SIZE **B**
DWG. NO. P06
REV 0

WEIGHT: N/A
SHEET 1 OF 1

DWG. NO. P06 REV 0



REV	DATE Y/M/D	DESCRIPTION	
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			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ∅MAJOR
INTERNAL THREADS AT ∅MINOR

MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

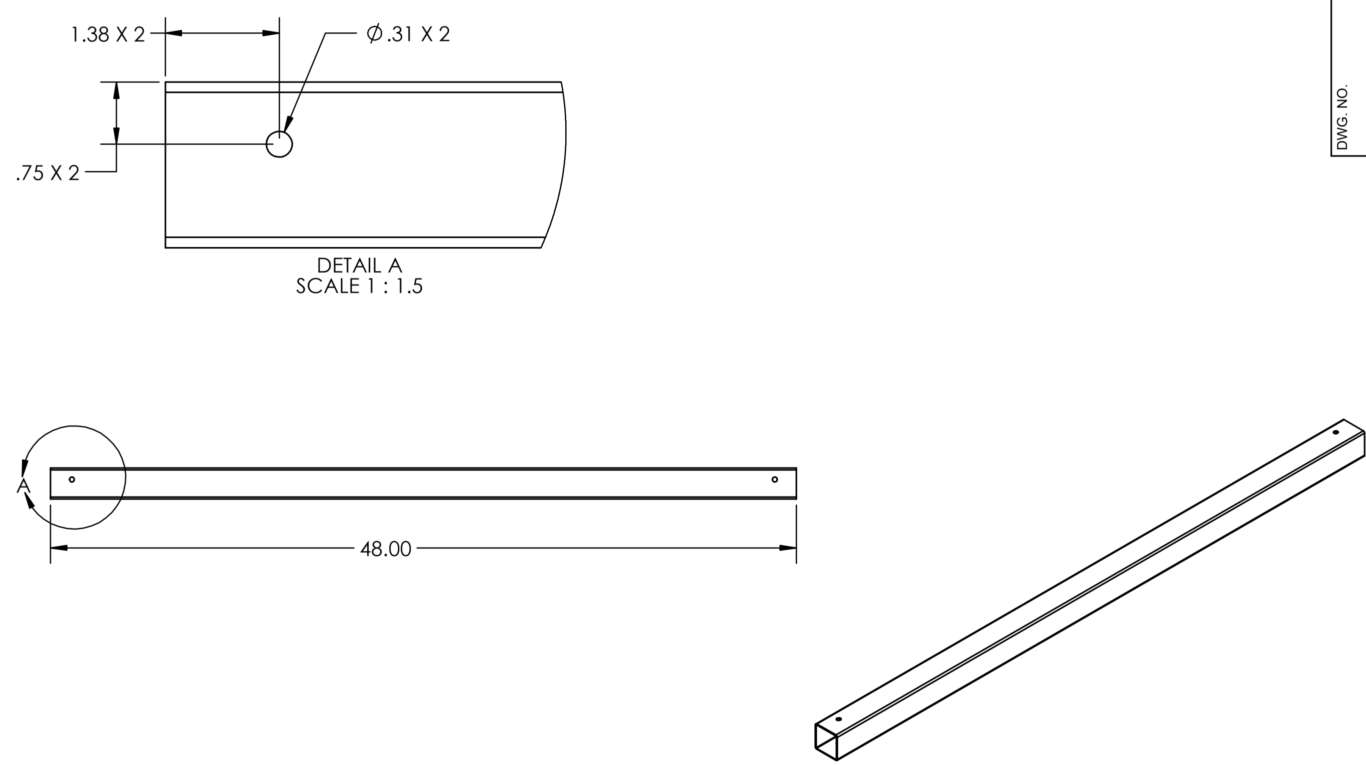
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
MAIN BEAM AIR TANK SIDE

SIZE: **B**
DWG. NO. P07
REV 0

WEIGHT: N/A
SHEET 1 OF 1

DWG. NO. P07 REV 0



REV	DATE Y/M/D	DESCRIPTION		
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			CKD NAME #	
			DWN NAME #	
			CKD NAME #	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ∅MAJOR, INTERNAL THREADS AT ∅MINOR

EDUCATIONAL AND PROPRIETARY
THE INFORMATION CONTAINED IN THIS DRAWING IS FOR EDUCATIONAL USE ONLY, AND **NOT FOR FABRICATION**. CONTENT IS PROPRIETARY AND MAY NOT BE USED WITHOUT THE WRITTEN CONSENT OF THE COURSE INSTRUCTOR.

MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

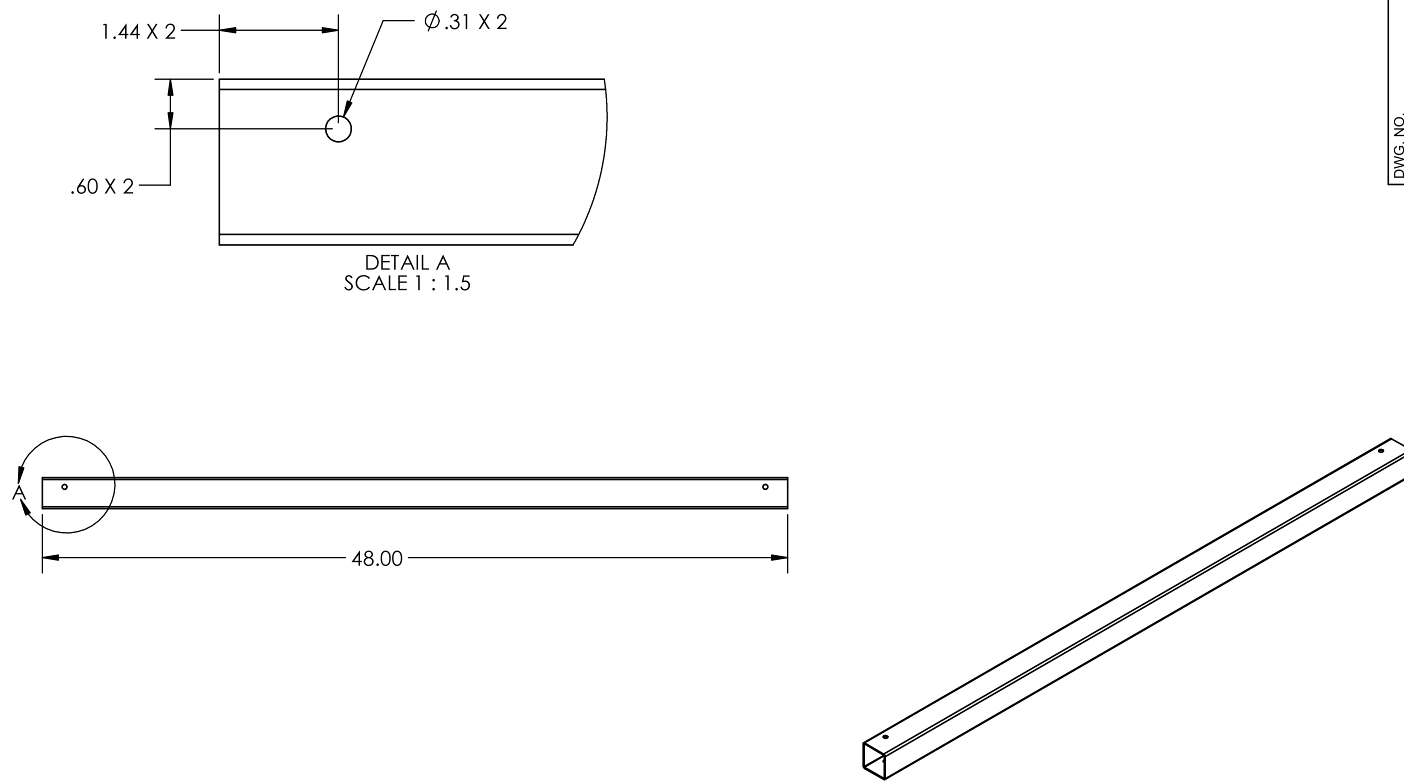
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CASTER OUTER BEAM

SIZE **B** | DWG. NO. P08 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P08 REV 0



REV	DATE Y/M/D	DESCRIPTION		
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			CKD NAME #	
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			CKD NAME #	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

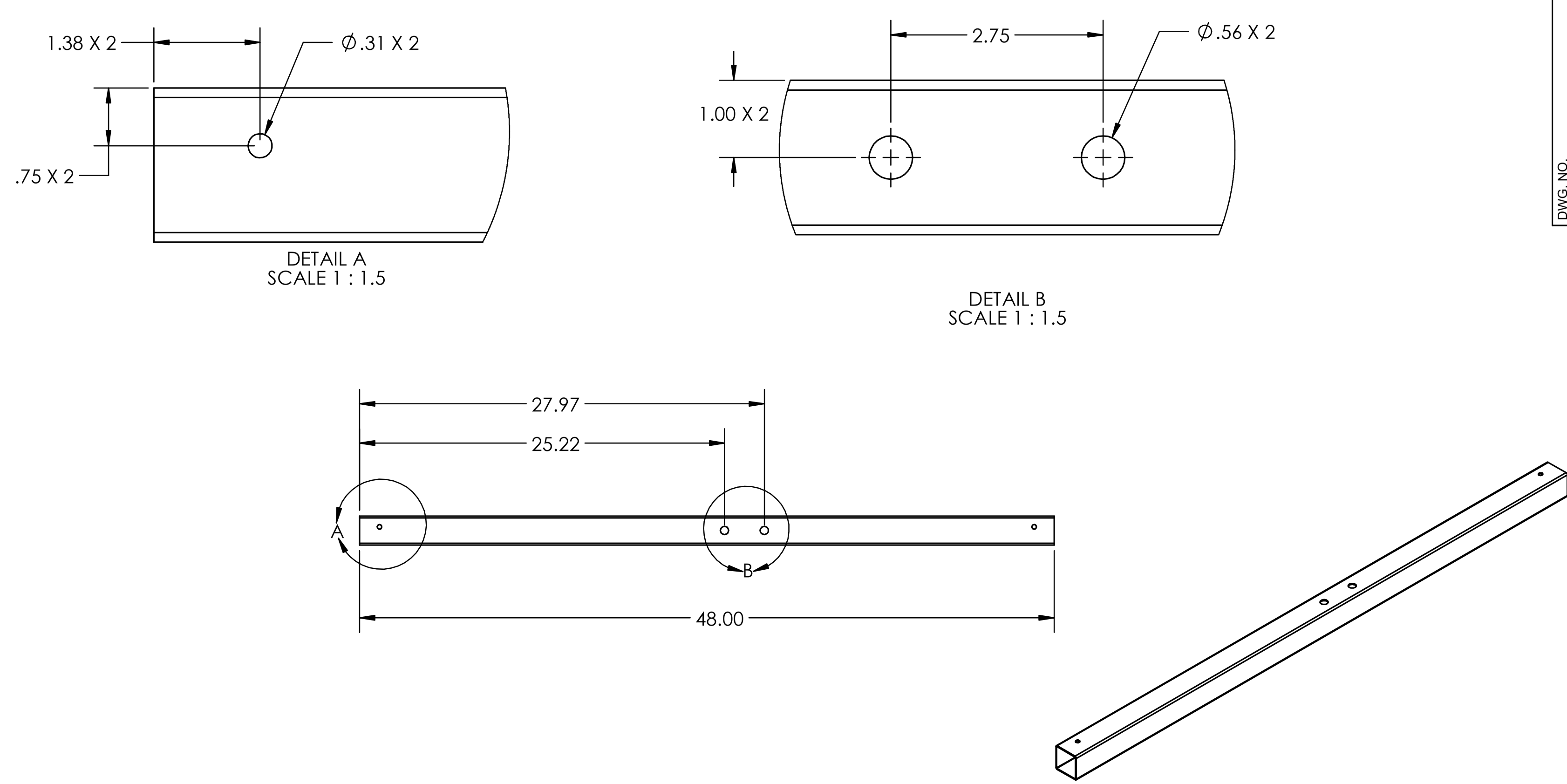
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CASTER INNER BEAM

SIZE: **B** | DWG. NO. P09 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P09 | REV 0



REV	DATE Y/M/D	DESCRIPTION		
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			DWN / CKD	
			DWN / CKD	
			DWN / CKD	
			DWN / CKD	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR; INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
THE INFORMATION CONTAINED IN THIS DRAWING IS FOR EDUCATIONAL USE ONLY, AND **NOT FOR FABRICATION**. CONTENT IS PROPRIETARY AND MAY NOT BE USED WITHOUT THE WRITTEN CONSENT OF THE COURSE INSTRUCTOR.

MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

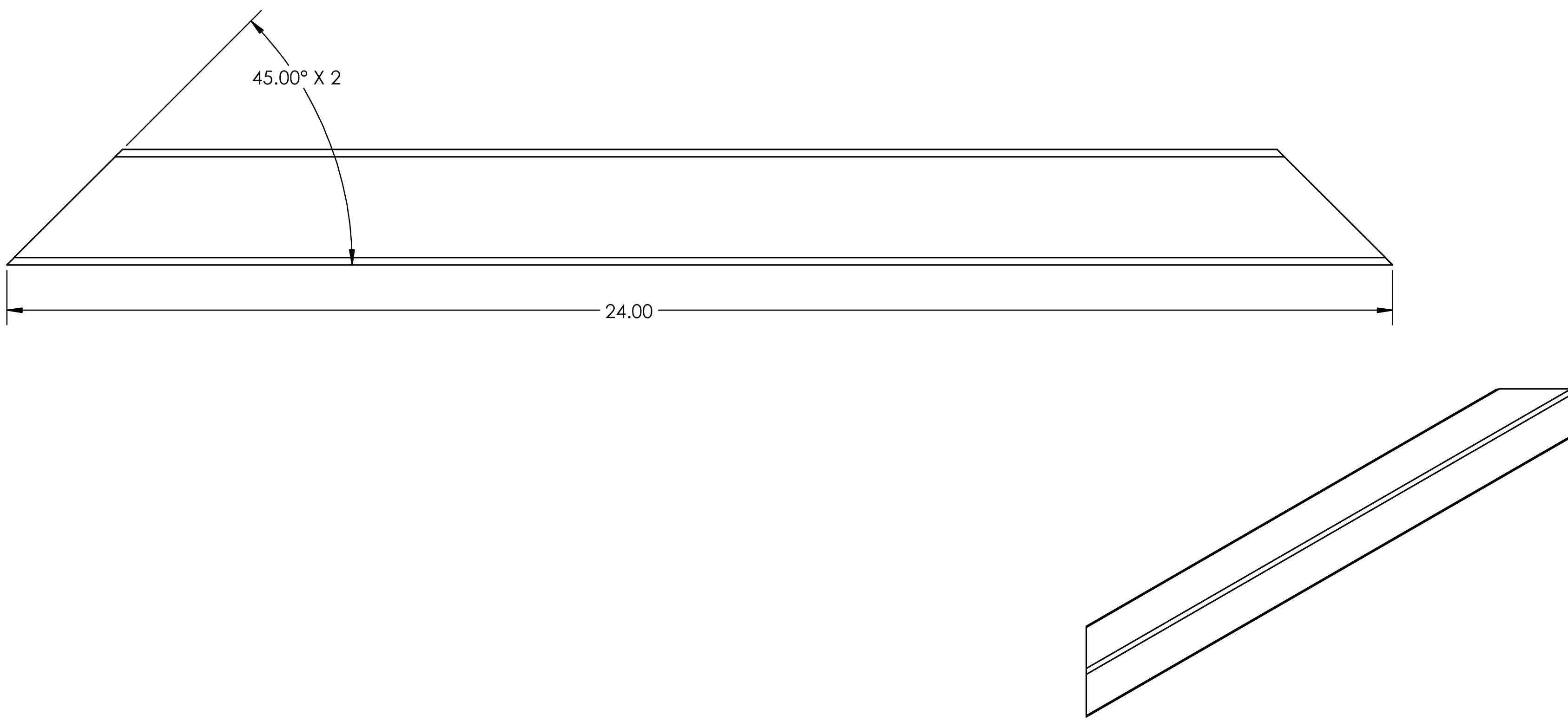
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CASTER OUTER WATER HEATER SIDE

SIZE: **B** — DWG. NO. P10 — REV 0

WEIGHT: N/A — SHEET 1 OF 1

DWG. NO. P10 — REV 0



UNLESS OTHERWISE SPECIFIED GD&T PER ASME Y14.5-2009 NONTOLERANCED DIMENSIONS ARE BASIC CAD MODEL IS BASIC NONDIMENSIONED GEOMETRIES PER CAD MODEL	DIMENSIONAL UNIT: MILLIMETER N/A = NOT APPLICABLE	**EDUCATIONAL AND PROPRIETARY** THE INFORMATION CONTAINED IN THIS DRAWING IS FOR EDUCATIONAL USE ONLY, AND **NOT FOR FABRICATION**. CONTENT IS PROPRIETARY AND MAY NOT BE USED WITHOUT THE WRITTEN CONSENT OF THE COURSE INSTRUCTOR.
GENERAL TOLERANCE	CHAMFERS FILLETS BREAK SHARP SHARP	MATERIAL 2x2" 14GA A513 12' STEEL
THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR		Next Assembly A11
		DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
GUSSET

SIZE	DWG. NO.	REV
B	P11	0

WEIGHT: N/A SHEET 1 OF 1

REV	DATE Y/M/D	DESCRIPTION		
			DWN NAME #	
			CKD NAME #	
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			CKD NAME #	
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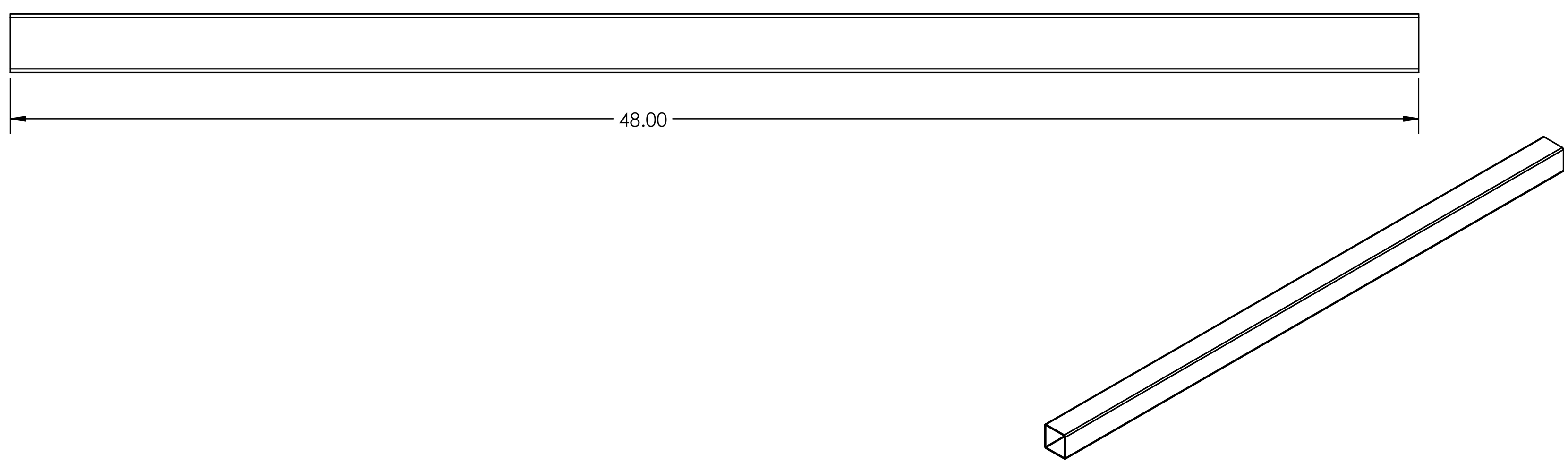
			CKD NAME #	

DWG. NO.	REV
P11	0



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REV	DATE Y/M/D	DESCRIPTION		
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			DWN	
			CKD	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
THE INFORMATION CONTAINED IN THIS DRAWING IS FOR EDUCATIONAL USE ONLY, AND **NOT FOR FABRICATION**. CONTENT IS PROPRIETARY AND MAY NOT BE USED WITHOUT THE WRITTEN CONSENT OF THE COURSE INSTRUCTOR.

MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

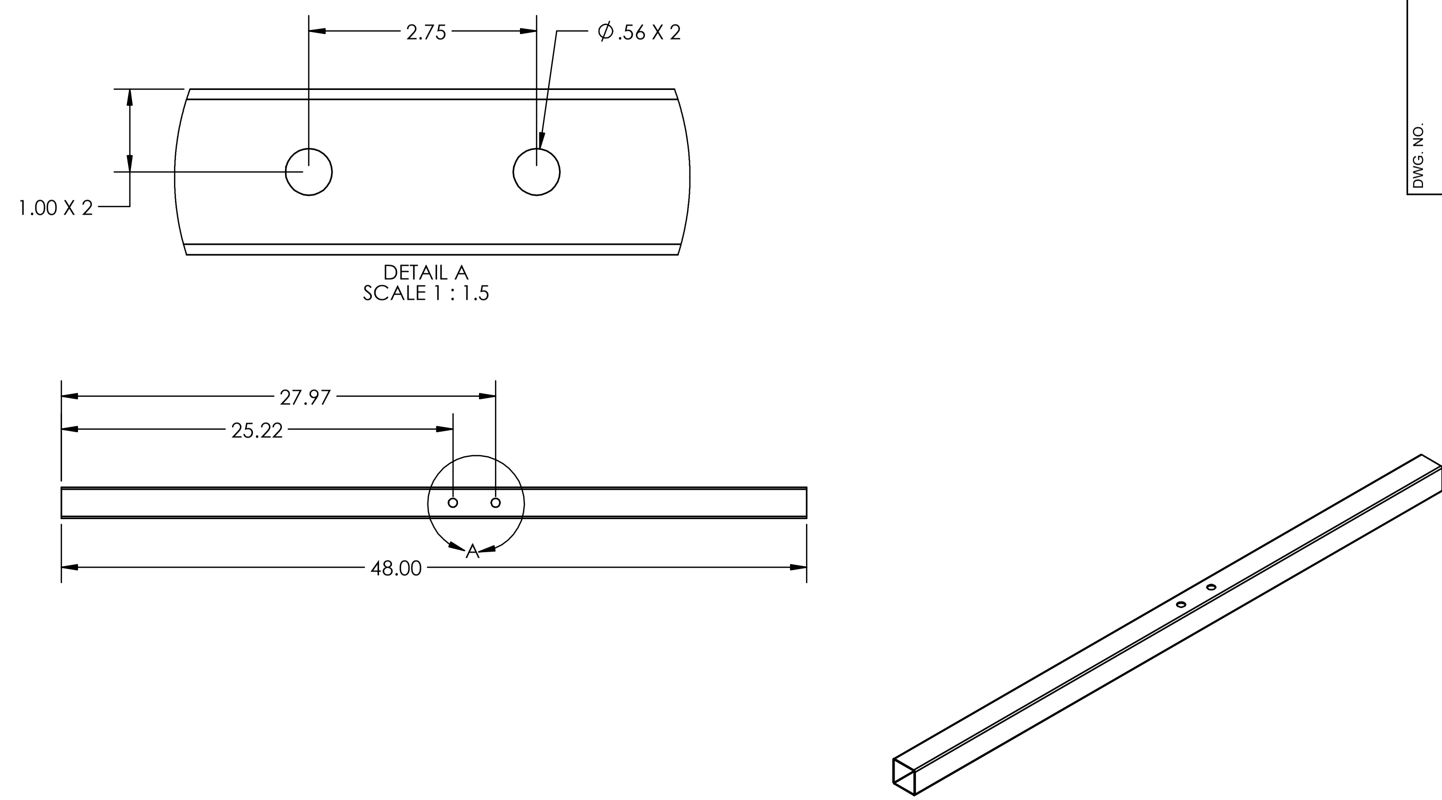
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CROSS MEMBER

SIZE **B** | DWG. NO. P12 | REV 0

WEIGHT: N/A | SHEET 1 OF 1



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			CKD NAME #	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ∅MAJOR
INTERNAL THREADS AT ∅MINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

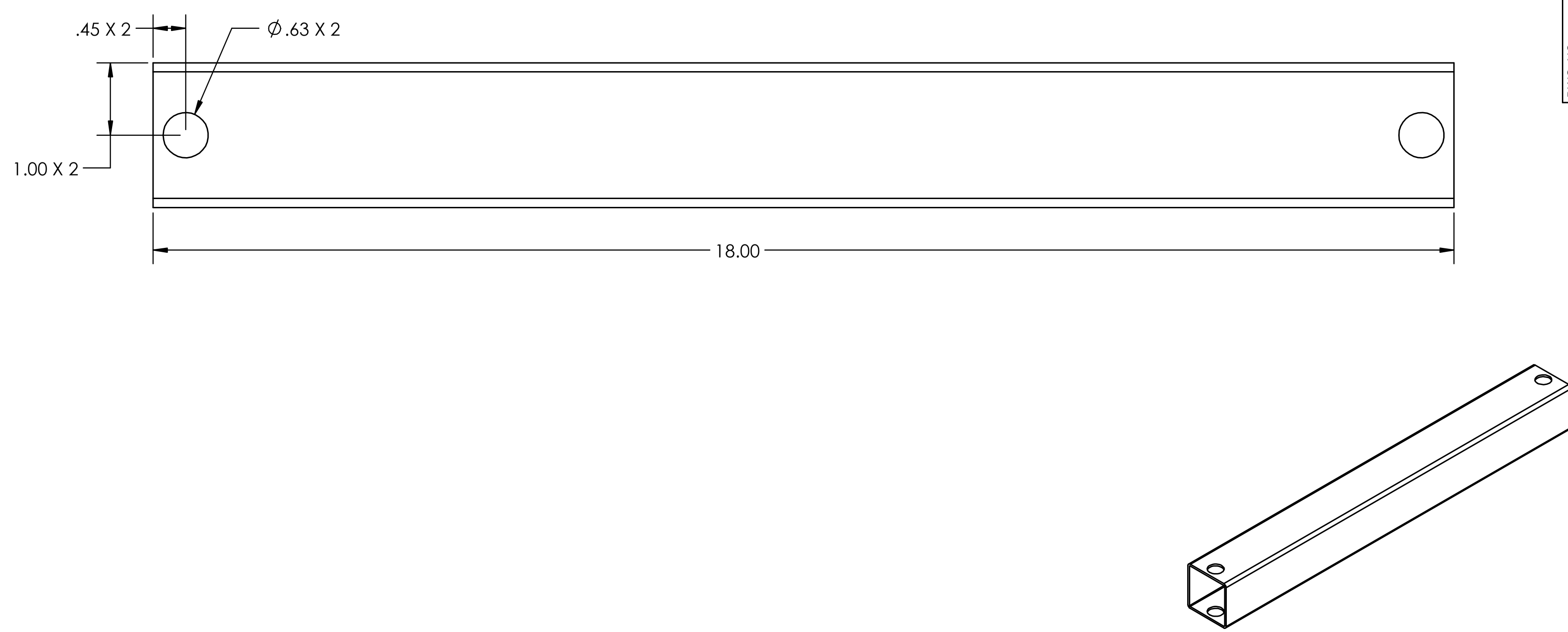
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CROSS MEMBER WATER HEATER MOUNT

SIZE **B** | DWG. NO. P13 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P13 REV 0



DWG. NO. P14 REV 0

REV	DATE Y/M/D	DESCRIPTION	
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			DWN / CKD
			DWN / CKD
			DWN / CKD

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ∅MAJOR INTERNAL THREADS AT ∅MINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

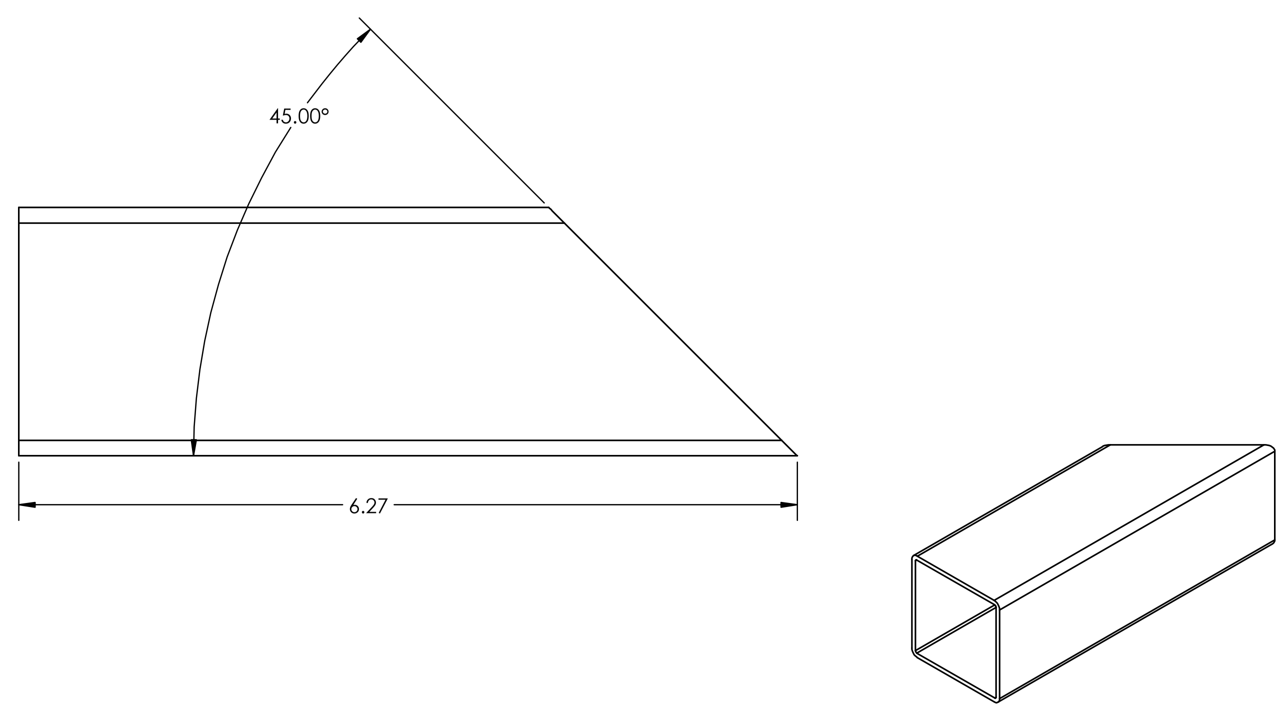
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
AIR TANK MOUNT

SIZE: **B** | DWG. NO. P14 | REV 0

WEIGHT: N/A | SHEET 1 OF 1



REV	DATE Y/M/D	DESCRIPTION	
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			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

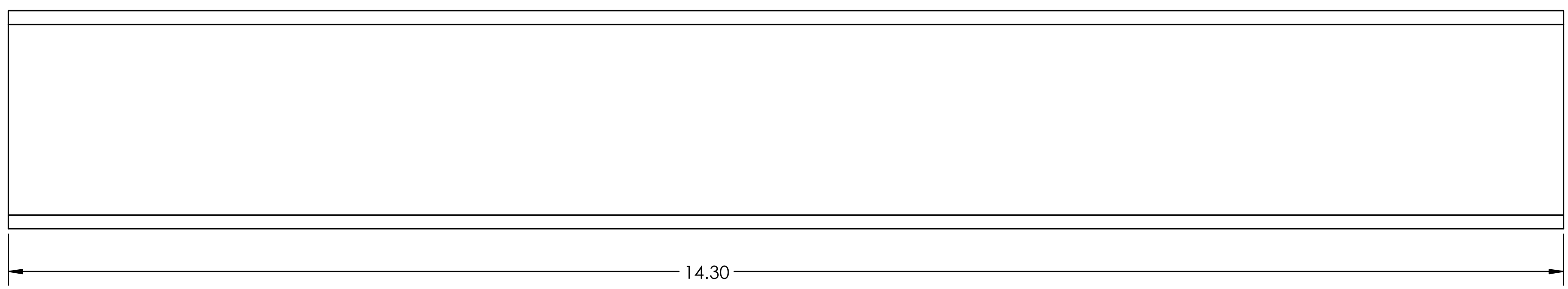
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

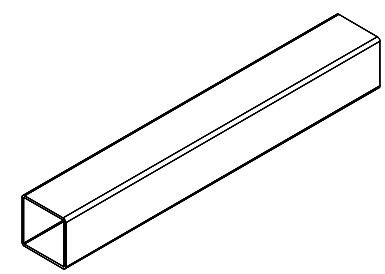
TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CONTROLLER MOUNT GUESSET

SIZE: **B** | DWG. NO. P15 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P15 REV 0





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			CKD NAME #	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS

FILLETS

BREAK SHARP

SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

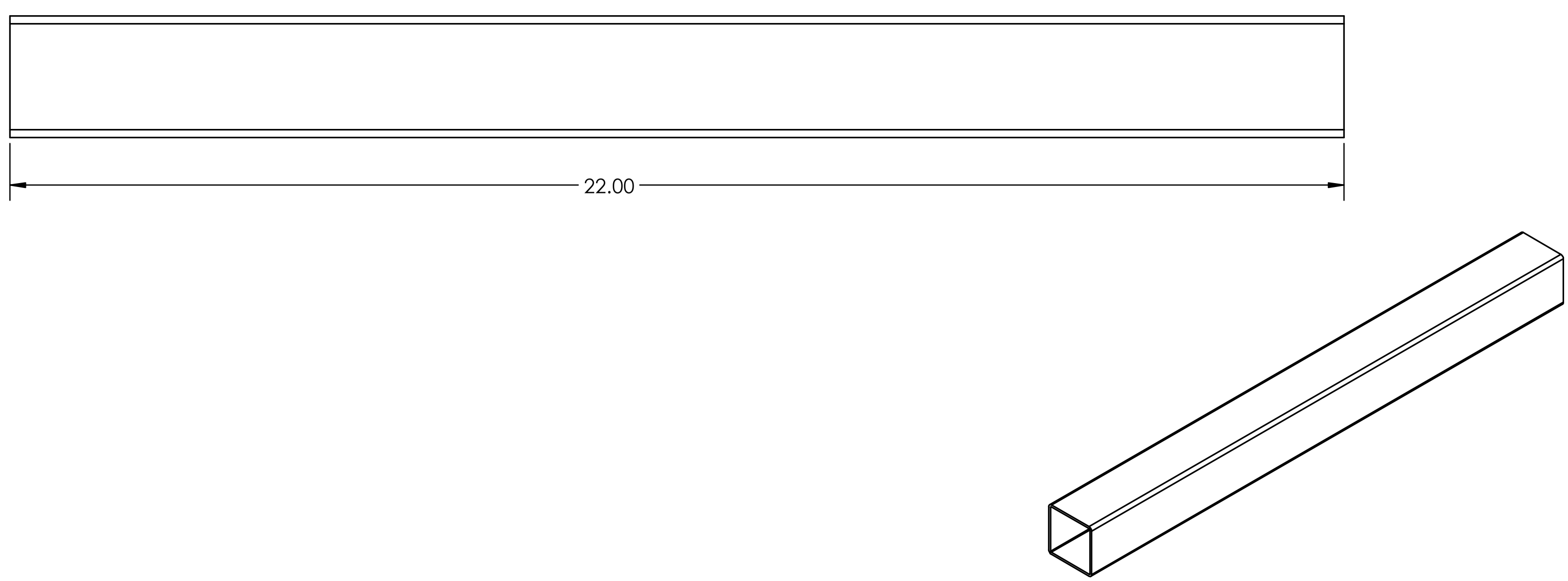
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
PUMP UP RIGHT

SIZE: **B** | DWG. NO. P16 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P16 | REV 0



DWG. NO. P17 REV 0

REV	DATE Y/M/D	DESCRIPTION		
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			CKD NAME #	
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			CKD NAME #	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

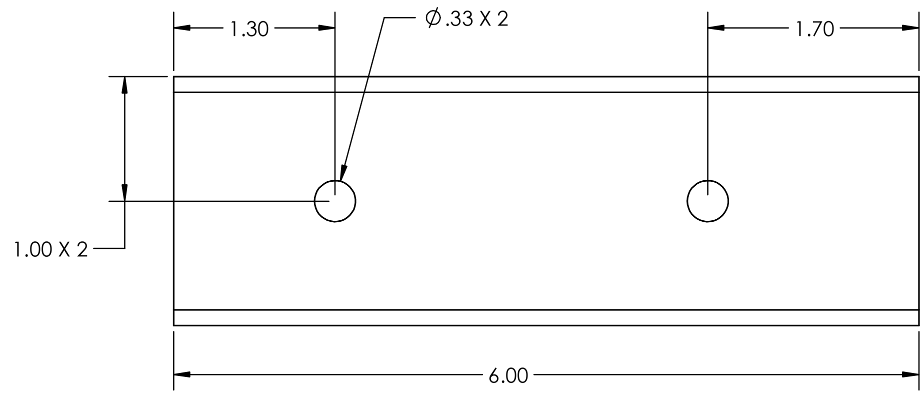
DO NOT SCALE DRAWING

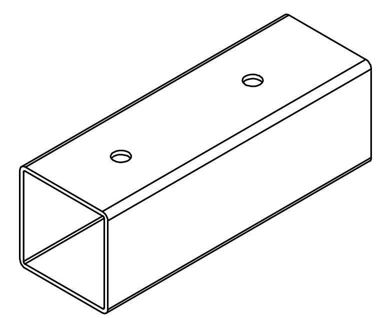
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
PUMP UPPER

SIZE **B** | DWG. NO. P17 | REV 0

WEIGHT: N/A | SHEET 1 OF 1





DWG. NO. P18 REV 0

REV	DATE Y/M/D	DESCRIPTION		
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			DWN	
			CKD	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

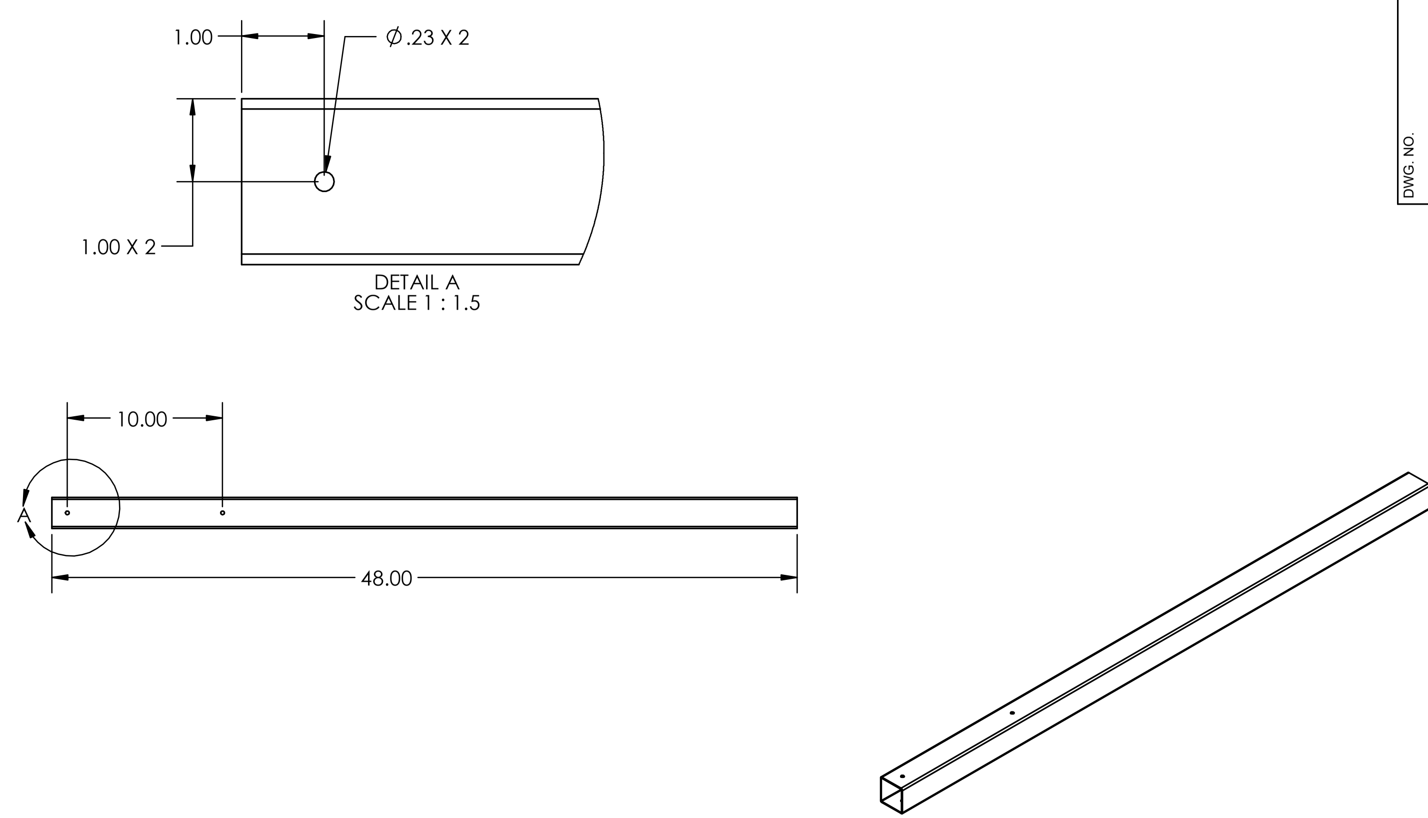
UNIVERSITY OF MANITOBA MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
PUMP MOUNT

SIZE	DWG. NO.	REV
B	P18	0

WEIGHT: N/A

SHEET 1 OF 1



REV	DATE Y/M/D	DESCRIPTION	
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			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

GENERAL TOLERANCE

THREADED FEATURES EXTERNAL THREADS AT ⌀MAJOR, INTERNAL THREADS AT ⌀MINOR

CHAMFERS
FILLETS
BREAK SHARP
SHARP

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

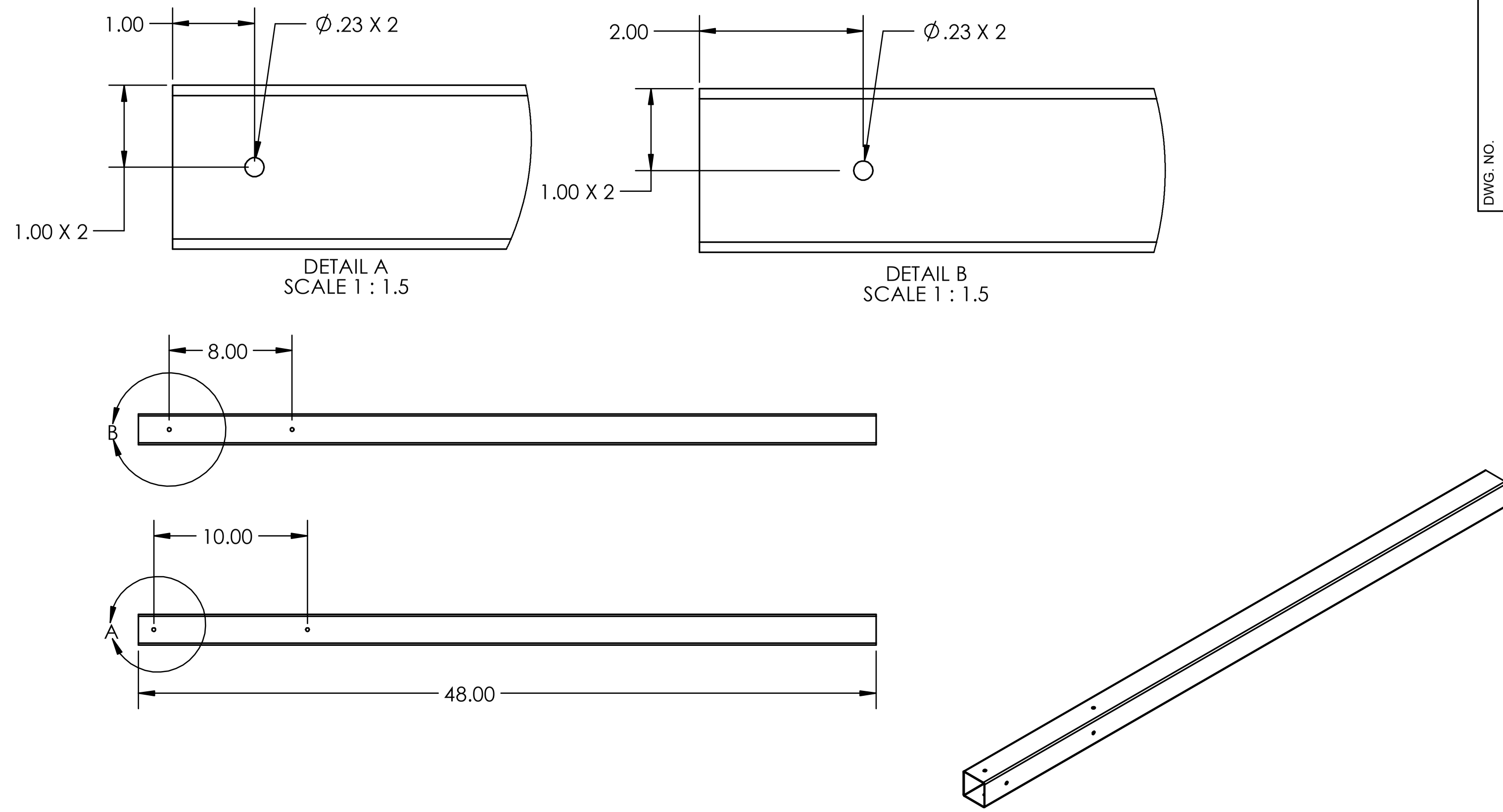
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CONTROLLER UP RIGHT A

SIZE: **B** — DWG. NO. P19 — REV 0

WEIGHT: N/A — SHEET 1 OF 1

DWG. NO. P19 — REV 0



REV	DATE Y/M/D	DESCRIPTION		
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			CKD # NAME	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR, INTERNAL THREADS AT ØMINOR

MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

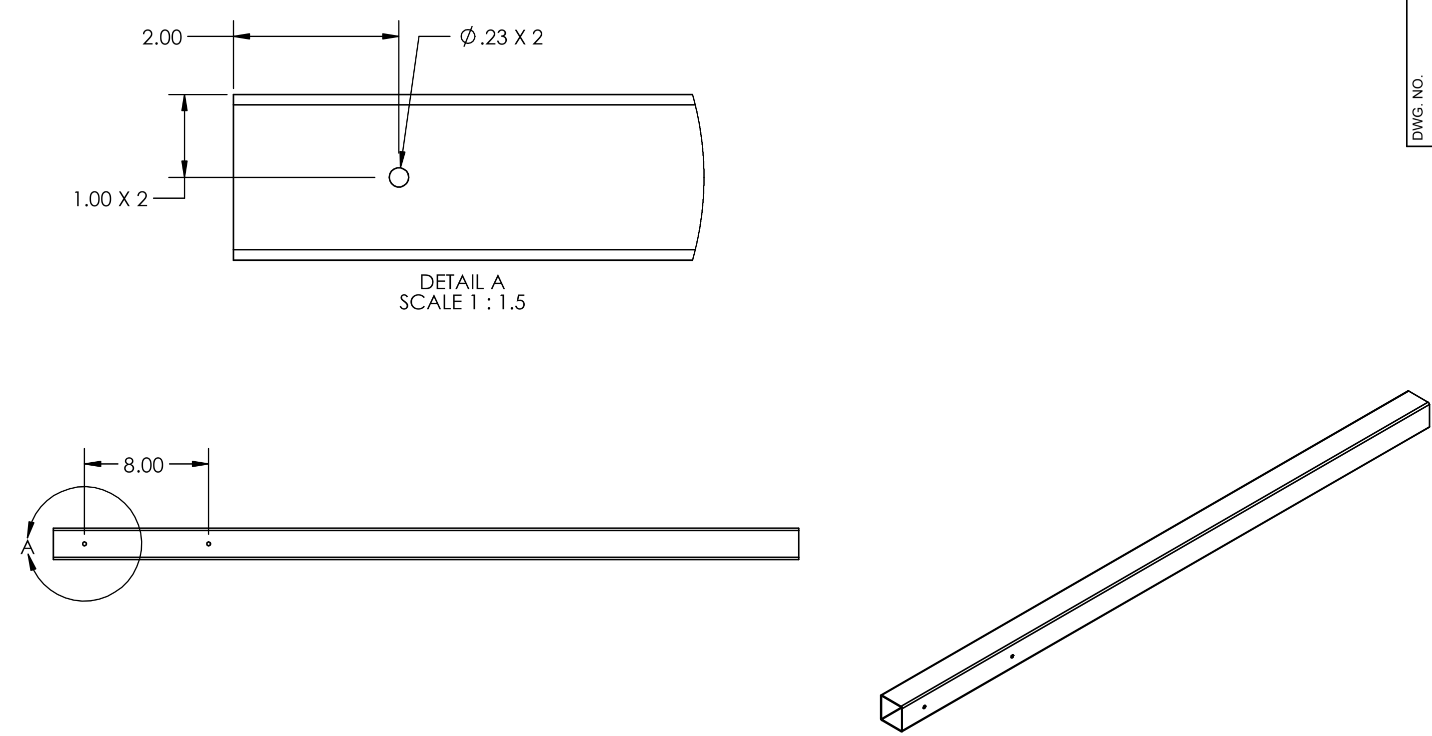
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CONTROLLER UP RIGHT B

SIZE: **B** | DWG. NO. P20 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P20 | REV 0



UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER
N/A = NOT APPLICABLE

GENERAL TOLERANCE
CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

REV	DATE Y/M/D	DESCRIPTION		
			DWN # NAME	
			CKD # NAME	
			DWN # NAME	
			CKD # NAME	
			DWN # NAME	
			CKD # NAME	
			DWN # NAME	
			CKD # NAME	
			DWN # NAME	
			CKD # NAME	

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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

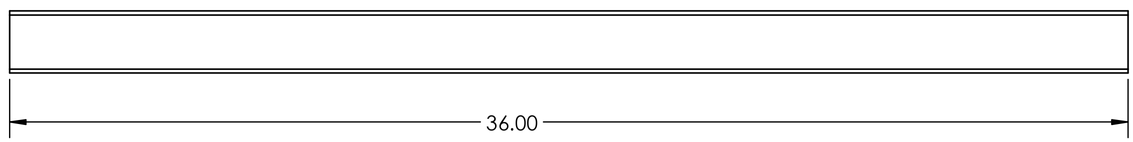
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

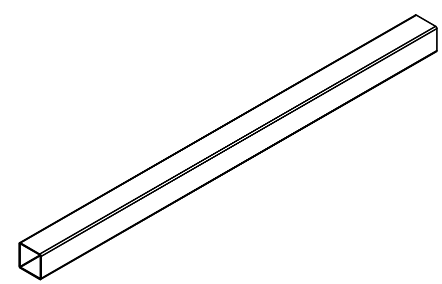
TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CONTROLLER UP RIGHT C

SIZE: **B**
DWG. NO. P21
REV 0

WEIGHT: N/A
SHEET 1 OF 1

DWG. NO. P21 REV 0





DWG. NO. P22 REV 0

REV	DATE Y/M/D	DESCRIPTION		
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			CKD NAME #	
			DWN NAME #	
			CKD NAME #	
			DWN NAME #	
			CKD NAME #	
			DWN NAME #	
			CKD NAME #	
			DWN NAME #	
			CKD NAME #	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR INTERNAL THREADS AT ØMINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

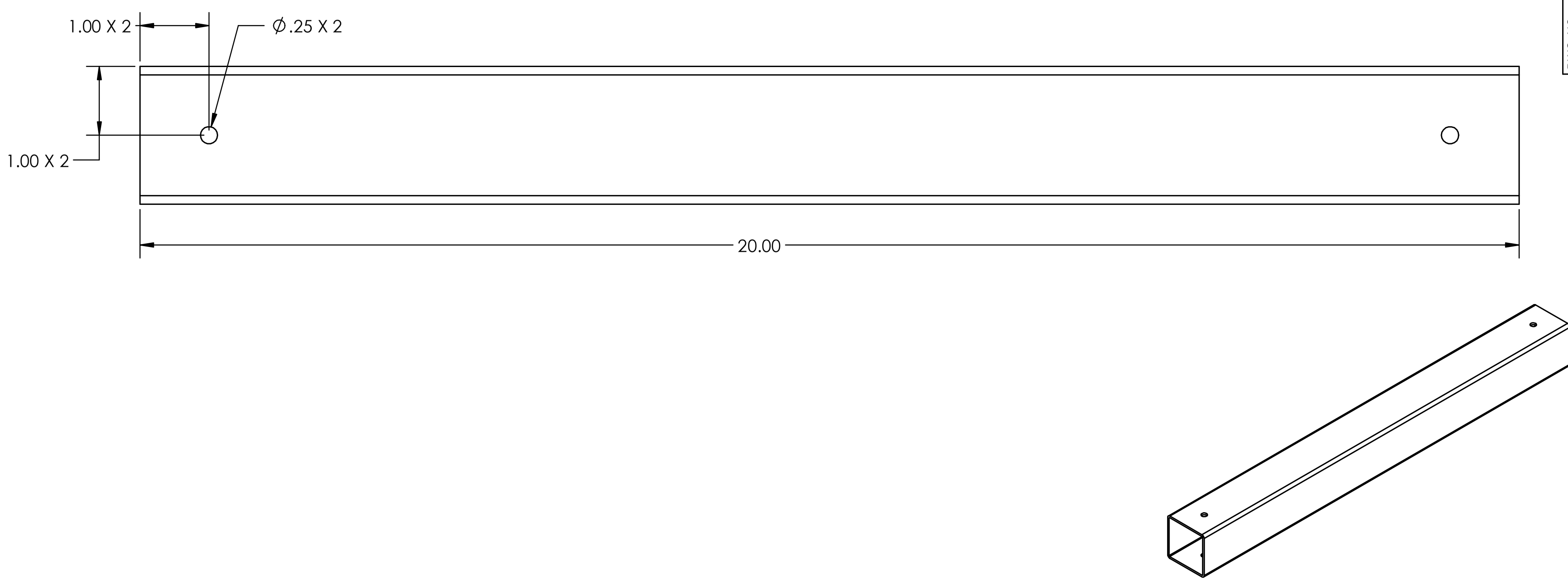
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CONTROLLER UP RIGHT D

SIZE **B** | DWG. NO. P22 | REV 0

WEIGHT: N/A | SHEET 1 OF 1



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UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ∅MAJOR INTERNAL THREADS AT ∅MINOR

REV	DATE Y/M/D	DESCRIPTION	
			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD
			DWN / CKD

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MATERIAL
2x2" 14GA A513 12' STEEL

Next Assembly
A11

DO NOT SCALE DRAWING

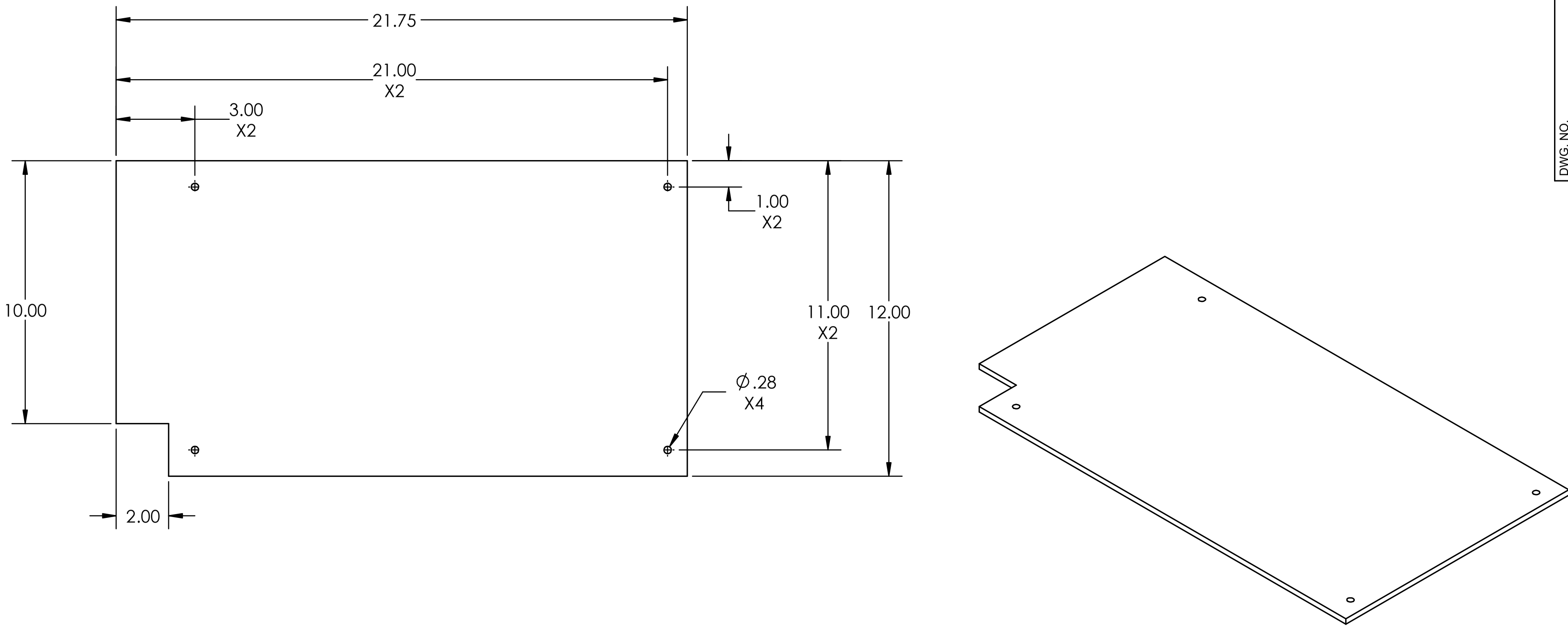
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE: TEST RIG
CONTROLER PLATFORM SUBASSEMBLY
CONTROLER PLATFORM FRAME
CONTROLLER UPPER

SIZE	DWG. NO.	REV
B	P23	0

WEIGHT: N/A

SHEET 1 OF 1



REV	DATE Y/M/D	DESCRIPTION

DWN / CKD (NAME #)

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR, INTERNAL THREADS AT ØMINOR

MATERIAL
HDPE sheet 12'x24'x0.25"

Next Assembly
A02

DO NOT SCALE DRAWING

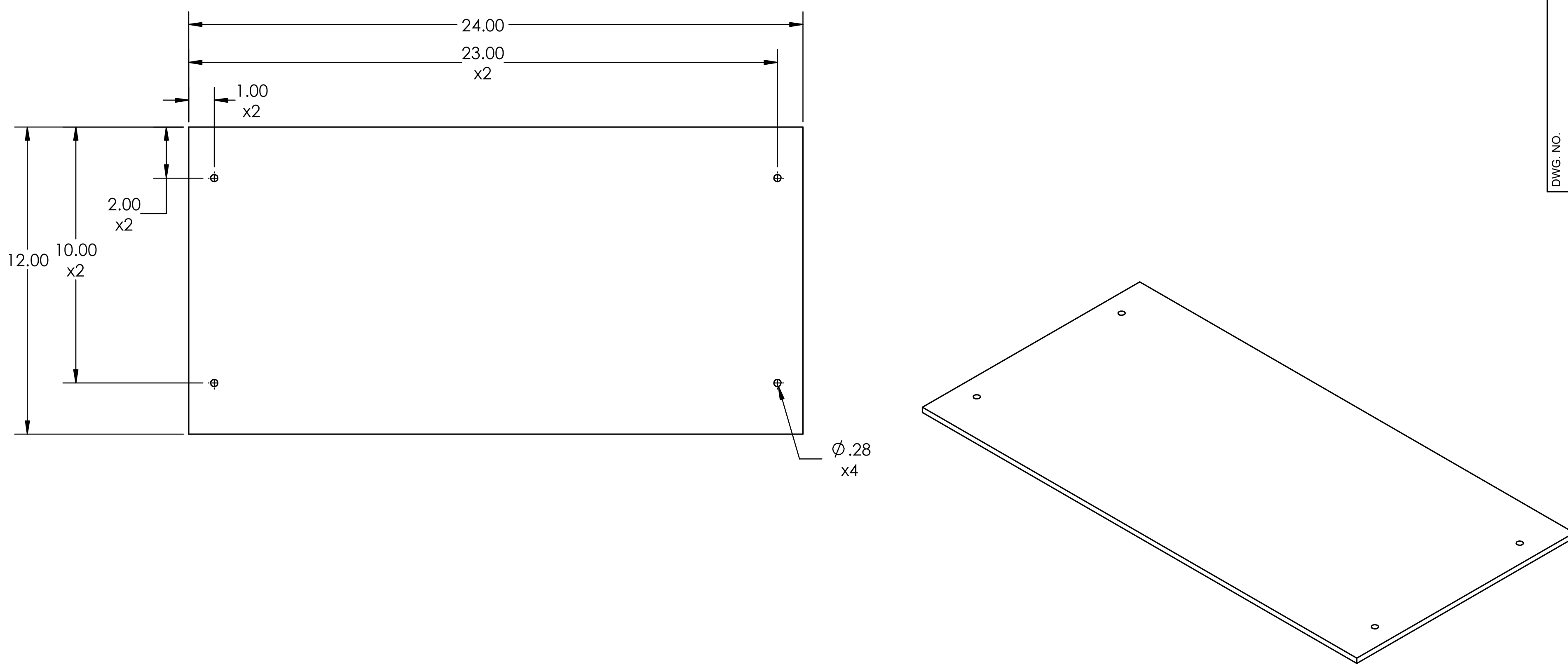
UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM SUBASSEMBLY
HDPE PANEL TOP

SIZE: **B** | DWG. NO. P24 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P24 | REV 0



DWG. NO. P25 REV 0

REV	DATE Y/M/D	DESCRIPTION		
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			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS
FILLETS
BREAK SHARP
SHARP

THREADED FEATURES EXTERNAL THREADS AT ∅MAJOR
INTERNAL THREADS AT ∅MINOR

EDUCATIONAL AND PROPRIETARY
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MATERIAL
HDPE sheet 12'x24'x0.25"

Next Assembly
A02

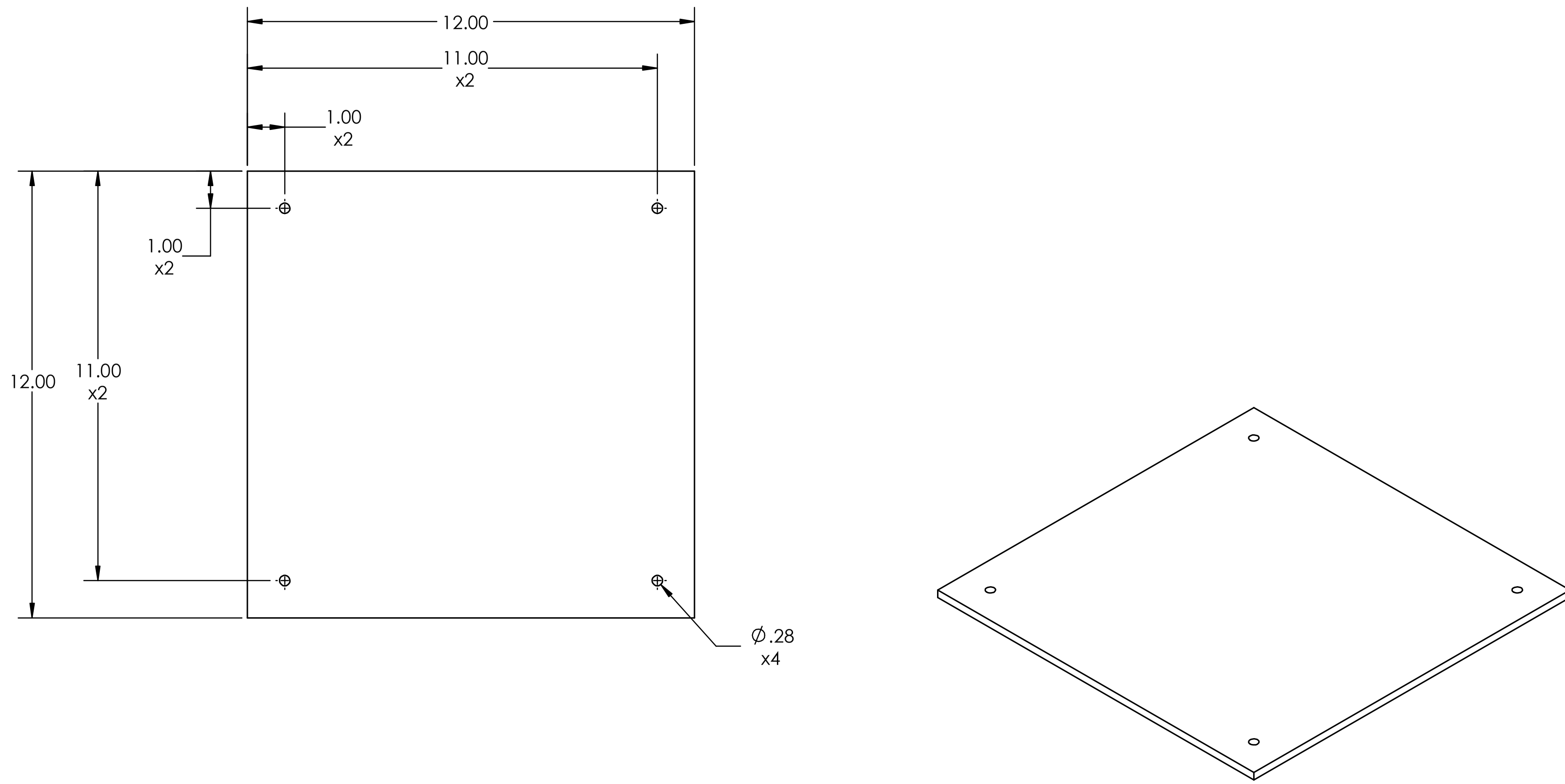
DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM SUBASSEMBLY
HDPE PANEL BACK SHIELD

SIZE **B** DWG. NO. P25 REV 0

WEIGHT: N/A SHEET 1 OF 1



REV	DATE Y/M/D	DESCRIPTION		
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	
			DWN	
			CKD	

UNLESS OTHERWISE SPECIFIED
GD&T PER ASME Y14.5-2009
NONTOLERANCED DIMENSIONS ARE BASIC
CAD MODEL IS BASIC
NONDIMENSIONED GEOMETRIES PER CAD MODEL

DIMENSIONAL UNIT: MILLIMETER

N/A = NOT APPLICABLE

GENERAL TOLERANCE

CHAMFERS

FILLETS

BREAK SHARP

SHARP

THREADED FEATURES EXTERNAL THREADS AT ØMAJOR
INTERNAL THREADS AT ØMINOR

MATERIAL
HDPE sheet 12'x12'x0.25"

Next Assembly
A02

DO NOT SCALE DRAWING

UNIVERSITY OF MANITOBA — MECH 4860 - TEAM 15

TITLE:
TEST RIG
CONTROL PLATFORM SUBASSEMBLY
HPDE PANEL LEFT SHIELD

SIZE: **B** | DWG. NO. P26 | REV 0

WEIGHT: N/A | SHEET 1 OF 1

DWG. NO. P26 REV 0

APPENDIX B

Detailed Bill of Materials Required for the Construction of the Test Rig

Table of Contents

List of Tables

No table of figures entries found.

B-1 Introduction

This appendix presents the complete list of materials and parts required to construct the test rig; quantities required; and recommended suppliers, their part numbers and their quoted prices, where applicable.

B-2 Bill of Materials

The following tables present the overall bill of materials for the construction of the test rig. Items are grouped by design sub-section in the following five categories:

- Water delivery components
- Air delivery components
- Heating and insulating components
- Measurement and control devices (including auxiliary electrical components)
- Frame and mounting components

Controllers and electrical components specific to pumps, motors and heaters are found in their respective categories and not in the measurement and control devices category.

From left to right, the first column of the bill of materials lists the item number, which is a letter specific to the component category followed by a number specific to each component within that category. For example, the first item in the water delivery category has W1 for its item number: W for water delivery and 1 for the first item in the category. The second column explicitly lists the category to which the item belongs. The third column lists a brief description of the item, and is unique to each item. The fourth column lists the item's part number from the recommended supplier for that component and the fifth column lists the name of the recommended supplier. The sixth column lists, where applicable, the item's quoted unit cost in $CAD from the supplier and the seventh column lists the item quantity required in the construction of the test rig. Finally, the eighth column lists the total estimated cost of that item, equal to the quoted unit cost multiplied by the item quantity.

For the unit cost, items quoted in $USD were converted to $CAD using the conversion rate of $1.27 CAD to $1.00 USD available on December 03, 2017 (rounded to the nearest cent) [1].

Details on quotes from various suppliers can be referenced in Appendix F.

Table I. Bill of Materials – Part I (Water Delivery Components)

Item #	Section	Description	Part Number	Supplier	Unit Cost [CAD]	# Units	Total Cost [CAD]
W1	Water	Pump	R10316CA-C1	MOTION CANADA	$ 4,385.99	1	$ 4,385.99
W2	Water	Motor	CDP3326	BALDOR	$ 1,397.00	1	$ 1,397.00
W3	Water	Enclosed AC to DC Motor Speed Controller	7793K51	McMaster Carr	$ 375.16	1	$ 375.16
W4	Water	304SS Water Tank 50 Gal	S4TSC0050-0969	Mixer Direct	$ 5,120.64	1	$ 5,120.64
W5	Water	90 Degree Adapter 1-1/2 FNPT X MNPT	4464K43	McMaster Carr	$ 51.47	1	$ 51.47
W6	Water	ASTM A312 304SS 1-1/2" SCH40S 4"Lg	4830K266	McMaster Carr	$ 13.79	1	$ 13.79
W7	Water	ASTM A312 304SS 1-1/2" SCH40S 5"Lg	4830K267	McMaster Carr	$ 14.57	1	$ 14.57
W8	Water	ASTM A312 304SS 1-1/2" SCH40S 7"Lg	4830K201	McMaster Carr	$ 20.12	1	$ 20.12
W9	Water	ASTM A312 304SS 3/8" SCH40S 12"Lg	4830K162	McMaster Carr	$ 13.84	2	$ 27.69
W10	Water	ASTM A312 304SS 3/8" SCH40S 18"Lg	4813K123	McMaster Carr	$ 18.81	1	$ 18.81
W11	Water	ASTM A312 304SS 3/8" SCH40S 14"Lg	4813K171	McMaster Carr	$ 14.64	1	$ 14.64
W12	Water	ASTM A312 304SS 3/8" SCH40S 4"Lg	4830K156	McMaster Carr	$ 5.49	5	$ 27.43
W13	Water	ASTM A312 304SS 3/8" SCH40S 6"Lg, One End	9157K93	McMaster Carr	$ 6.86	3	$ 20.57
W14	Water	ASTM A312 304SS 3/8" SCH40S 6"Lg	4830K158	McMaster Carr	$ 7.71	1	$ 7.71
W15	Water	Ball Valve, 316SS 1-1/2" NPT	46325K33	McMaster Carr	$ 99.02	1	$ 99.02
W16	Water	Ball Valve, 316SS 3/8" NPT	46325K27	McMaster Carr	$ 27.08	3	$ 81.23
W17	Water	Braided Hose, 304SS, 1 1/2" NPT, 9" Lg	5468K950	McMaster Carr	$ 107.06	1	$ 107.06
W18	Water	Bushing Adapter 1-1/2" MNPT X 3/8" FNPT	4464K154	McMaster Carr	$ 20.92	1	$ 20.92
W19	Water	Bushing Adapter 3/8" MNPT X 1/2" FNPT	4464K266	McMaster Carr	$ 6.08	1	$ 6.08
W20	Water	Female Elbow 304SS 1-1/2" NPT	4464K180	McMaster Carr	$ 39.18	2	$ 78.36
W21	Water	Female Elbow 304SS 3/8" NPT	4464K130	McMaster Carr	$ 7.62	6	$ 45.72
W22	Water	Female Threaded Camlock Coupling, D, 1-1/2"	53015K174	McMaster Carr	$ 112.64	1	$ 112.64
W23	Water	Flange Adapter, 304SS, 1 /1/2" NPT	44685K15	McMaster Carr	$ 53.45	2	$ 106.91
W24	Water	Flange Gasket, ANSI Class 150, 1 1/2"	4459K74	McMaster Carr	$ 4.85	2	$ 9.70
W25	Water	Liquid Strainer 3/8"	9998K33	Spray Systems Co.	$ 371.42	1	$ 371.42
W26	Water	Male Cam-and-Groove Hose Coupling, 1-1/2"	53015K440	McMaster Carr	$ 59.11	1	$ 59.11
W27	Water	Nickel Anti-Seize 550°F PTFE Tape	1/2" x 600"	Fastenal	$ 32.83	1	$ 32.83
W28	Water	Nipple 304SS 1/4XCL	4830K131	McMaster Carr	$ 1.91	2	$ 3.81
W29	Water	Nipple 304SS 3/8XCL	4830K151	McMaster Carr	$ 2.27	10	$ 22.73
W30	Water	Straight Reducer 304SS 1/4 X 3/8 FNPT	4464K522	McMaster Carr	$ 6.13	2	$ 12.27
W31	Water	Straight Reducer 304SS 3/8 X 1/2 FNPT	4464K525	McMaster Carr	$ 6.59	2	$ 13.18
W32	Water	Tee 304SS 3/8" NPT	4464K49	McMaster Carr	$ 11.21	7	$ 78.50
W33	Water	Water Pressure Regulator 3/8"	11438-251S	Spray Systems Co.	$ 131.43	1	$ 131.43
W34	Water	Pressure Regulating Valve 3/8" FNPT	5022K334	McMaster-Carr	$ 306.21	1	$ 306.21
W35	Water	ASTM A312 304SS 3/8" SCH40S 3"Lg	4830K155	McMaster-Carr	$ 4.27	2	$ 8.53
W36	Water	ASTM A312 304SS 3/8" SCH40S 8"Lg	4830K159	McMaster-Carr	$ 10.25	1	$ 10.25
W37	Water	ASTM A312 304SS 3/8" SCH40S 10"Lg	4830K161	McMaster-Carr	$ 12.61	1	$ 12.61
SUBTOTAL	**Water**						**$ 13,226.12**

Table II. Bill of Materials – Part II (Air Delivery, Heating and Insulating Components)

Item #	Section	Description	Part Number	Supplier	Unit Cost [CAD]	# Units	Total Cost [CAD]
A1	Air	GA7VSD ROTARY SCREW COMPRESSOR	8153-0383-21	Atlas Copco	$ 18,415.00	1	$ 18,415.00
A2	Air	Air Receiver	A10043	Samuel Pressure Vessel Group	$ 2,540.00	1	$ 2,540.00
A3	Air	ASTM A312 304SS 3/4" SCH40S 10"Lg	4830K211	McMaster Carr	$ 14.96	2	$ 29.92
A4	Air	ASTM A312 304SS 3/4" SCH40S 4"Lg	4830K196	McMaster Carr	$ 7.48	3	$ 22.44
A5	Air	ASTM A312 304SS 3/8" SCH40S 24"Lg	4813K210	McMaster Carr	$ 25.08	3	$ 75.25
A6	Air	ASTM A312 304SS 3/8" SCH40S 6"Lg, One End	9157K930	McMaster Carr	$ 6.86	3	$ 20.57
A7	Air	Ball Valve, 316SS 3/4" NPT	46325K29	McMaster Carr	$ 39.45	3	$ 118.34
A8	Air	Female Elbow 304SS 3/4" NPT	4464K15	McMaster Carr	$ 11.70	3	$ 35.09
A9	Air	Nipple 304SS 1/2XCL	4830K171	McMaster Carr	$ 2.77	3	$ 8.31
A10	Air	Nipple 304SS 3/4XCL	4830K191	McMaster Carr	$ 3.44	11	$ 37.86
A11	Air	Straight Connector, 3/8" NPT	4464K353	McMaster Carr	$ 4.99	3	$ 14.97
A12	Air	Straight Reducer 304SS 3/4 X 1/2 FNPT	4464K384	McMaster Carr	$ 9.53	3	$ 28.58
A13	Air	Straight Reducer 304SS 3/4 X 3/8 FNPT	4464K384	McMaster Carr	$ 9.16	3	$ 27.47
A14	Air	Tee 304SS 3/4" NPT	4464K52	McMaster Carr	$ 18.62	5	$ 93.09
A15	Air	Male Reducer 304SS 1 X 3/4 NPT	2161K16	McMaster Carr	$ 48.11	1	$ 48.11
A16	Air	Male Reducer 304SS 3/4 X 1/2 NPT	2161K14	McMaster Carr	$ 37.85	3	$ 113.54
A17	Air	Female Barbed 3/4 Elbow Brass 3/4 NPTF	5346K128	McMaster Carr	$ 32.93	1	$ 32.93
A18	Air	Crimp Ferrules 304SS 3/4	9256T35	McMaster Carr	$ 1.49	4	$ 5.95
A19	Air	Male Barbed 3/4 Elbow 304SS 3/4 NPT	5361K45	McMaster Carr	$ 20.62	1	$ 20.62
A20	Air	Female Barbed 3/4 Straight Brass NPTF	5346K58	McMaster Carr	$ 10.01	1	$ 10.01
A21	Air	Elbow male to female 3/4 NPT 304SS	4464K39	McMaster Carr	$ 18.71	1	$ 18.71
A22	Air	Air Pressure Regulating Valve 1/2 NPTF	5022K25	McMaster Carr	$ 320.12	1	$ 320.12
A23	Air	Bushing Steel 2 NPT 3/4 NPTF	6850K33	McMaster Carr	$ 52.21	2	$ 104.42
A24	Air	Hose Coupling Plug Industrial 3/4 H 1/2 C	6534K64	McMaster Carr	$ 6.20	1	$ 6.20
A25	Air	Hose Coupling Socket Industrial 3/4 NPT 1/2 C	9582K22	McMaster Carr	$ 29.83	1	$ 29.83
A26	Air	Bushing 304SS 3/4 NPT 1/2 NPTF	4464K384	McMaster Carr	$ 11.13	1	$ 11.13
A27	Air	Air hose 3/4 ID 1-3/16 OD 300 PSI Red (priced by foot)	5405K12	McMaster Carr	$ 2.57	51	$ 130.84
A28	Air	Complete total lock caster 3" urethane on nylon 250lb	CCEP3125UNSPBTB	Casterland	$ 30.21	4	$ 120.85
A29	Air	Reducer 3/4 X 1/2" NPT	4464K529	McMaster Carr	$ 9.53	3	$ 28.58
A30	Air	Bushing Adapter 3/8" MNPT X 1/2" FNPT	4464K266	McMaster Carr	$ 6.08	3	$ 18.25
A31	Air	Electronic Condensate Drain 3/8" NPT	ED3002N115-K	Parker Hannifin	$ -	1	$ -
SUBTOTAL	**Air**						**$ 22,486.96**
H1	Heating	In line air heater, 1500W	HA2-12 (K310031)	O.E.M. Heaters	$ 967.46	1	$ 967.46
H2	Heating	Tempearture controller	K520021	O.E.M. Heaters	$ 101.60	1	$ 101.60
H3	Heating	Solid State Relay	K500065	O.E.M. Heaters	$ 85.95	0	$ -
H4	Heating	inline water heater 30KW, 240V, 3P	FLS930X2825-T	Wattco	$ 4,565.65	1	$ 4,565.65
H5	Heating	Ciculation vessel, 1.5" inlet/outlet	MFLS930X2825-T	Wattco	$ -	1	$ -
H6	Heating	Water heater control panel terimnal	NEMA 4 BOX TYPE	Wattco	$ 2,660.65	1	$ 2,660.65
H7	Heating	Fiberglass with service jacket 3/8 pipe 5/8IDx1/2" Wall R2.2, 3ft	5556D26	McMaster-Carr	$ 11.01	9	$ 99.10
H8	Heating	Insulation - Service Jacket Tape 3"x30'	76755A67	McMaster-Carr	$ 11.09	1	$ 11.09
SUBTOTAL	**Heating**						**$ 8,405.55**

Table III. Bill of Materials – Part III (Measurement, Controls, Frame and Mounting Components)

Item #	Section	Description	Part Number	Supplier	Unit Cost [CAD]	# Units	Total Cost [CAD]
M1	Measurement	PLC	C0-02DD1-D	Automation Direct	$ 163.83	1	$ 163.83
M2	Measurement	Power Supply	C0-01AC	Automation Direct	$ 49.53	1	$ 49.53
M3	Measurement	Analog Input Module	C0-04AD-1	Automation Direct	$ 113.03	2	$ 226.06
M4	Measurement	Thermocouple Input Module	C0-04THM	Automation Direct	$ 189.23	1	$ 189.23
M5	Measurement	Flowmeter	FT-8NEW-LEA-2	CB Engineering Ltd	$ 1,789.00	1	$ 1,789.00
M6	Measurement	Pressure Transmitter	2088G 2 S 22 A 1	Emerson	$ -	6	$ -
M7	Measurement	Pressure Transmitter	2088G 2 S 22 A 1 M4	Emerson	$ -	2	$ -
M8	Measurement	T-Type Thermocouple	TJ36-CPSS-18G-6	Omega	$ 43.50	3	$ 130.50
M9	Measurement	Compression Fitting 1/8" sheath 1/4" NPT	SSLK-18-14	Omega	$ 27.00	3	$ 81.00
M10	Measurement	Data Logger	FC-Log	InterConnecting Automation Inc.	$ 163.83	1	$ 163.83
M11	Measurement	75A Solid State Relay (3-32VDC input, 24-280VAC output)	SSRL240DC75	Omega	$ 86.00	1	$ 86.00
M12	Measurement	Finned Heat Sink 1.2C/W	FHS-2	Omega	$ 29.50	3	$ 88.50
M13	Measurement	Programming cable	D2-DSCBL	Automation Direct	$ 17.78	1	$ 17.78
M14	Measurement	10A Solid State Relay (3-32VDC input, 24-280VAC output)	SSRL240DC10	Omega	$ 31.50	2	$ 63.00
M15	Measurement	Envision Spray Analysis Software License	N/A	Oxford Imaging	$ 1,300.00	1	$ 1,300.00
M16	Measurement	GoPro Hero6	N/A	GoPro	$ 600.00	1	$ 600.00
SUBTOTAL	**Measurement**						**$ 4,948.26**
F1	Frame	Complete total lock caster 3" urethane on nylon 250lb	CCEP3125UNSPBTB	Casterland	$ 30.21	4	$ 120.85
F2	Frame	1/4-20x2-3/4" bolt GR 5 Zinc Plated Partially Threaded	91247A553	McMaster-Carr	$ 0.24	44	$ 10.56
F3	Frame	1/4-20" Nut Nylon Lock GR 8 Zinc Yellow Plated	97135A210	McMaster-Carr	$ 0.17	44	$ 7.67
F4	Frame	1/4" Washer Zinc Yellow Plated OD 0.625"	98023A029	McMaster-Carr	$ 0.08	88	$ 7.43
F5	Frame	Frame 2x2 Square tube 14 gauge (0.083" wall) 12 Ft	T12214	Metal Depot	$ 5.14	112	$ 576.07
F6	Frame	HDPE Sheet 12"x24"x.25"	8619K462	McMaster-Carr	$ 16.43	2	$ 32.87
F7	Frame	HDPE Sheet 12"x12"x.25"	8619K461	McMaster-Carr	$ 9.47	1	$ 9.47
F8	Frame	1/2-13x4" bolt GR 5 Zinc Plated Partially Threaded	91247A728	McMaster-Carr	$ 1.25	8	$ 10.03
F9	Frame	1/2-13" Nut Nylon Lock GR 8 Zinc Yellow Plated	97135A250	McMaster-Carr	$ 0.55	8	$ 4.38
F10	Frame	1/2" Washer Zinc Yellow Plated OD 0.625"	98023A033	McMaster-Carr	$ 0.32	8	$ 2.55
F11	Frame	3/8-16x2-3/4" bolt GR 5 Zinc Plated Partially Threaded	91247A635	McMaster-Carr	$ 0.49	4	$ 1.97
F12	Frame	3/8-16" Nut Nylon Lock GR 8 Zinc Yellow Plated	97135A230	McMaster-Carr	$ 0.26	4	$ 1.02
F13	Frame	3/8" Washer Zinc Yellow Plated OD 0.625"	98023A031	McMaster-Carr	$ 0.15	8	$ 1.21
F14	Frame	5/16-18x2-3/4" bolt GR 5 Zinc Plated Partially Threaded	91247A594	McMaster-Carr	$ 0.50	4	$ 2.02
F15	Frame	5/16-18" Nut Nylon Lock GR 8 Zinc Yellow Plated	97135A220	McMaster-Carr	$ 0.23	4	$ 0.93
F16	Frame	5/16" Washer Zinc Yellow Plated OD 0.625"	98023A030	McMaster-Carr	$ 0.13	8	$ 1.03
SUBTOTAL	**Frame**						**$ 790.06**
						TOTAL	**$ 49,856.95**

B-3 References

[1] XE, "XE - The World's Trusted Authority: Money Transfers and Free Exchange Rate Tools," XE, 03 December 2017. [Online]. Available: http://www.xe.com/. [Accessed 03 December 2017].

APPENDIX C

Design Methodology and Down-Selection of Conceptual Designs

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C-1 Introduction

This appendix presents the concept generation, screening and scoring processes that were performed for the selection of parts in each subsection of the final test rig design.

The appendix is organized as follows. First, the overall design methodology is presented below, along with the screening and scoring tools used at the down-selection phases. Following that, the test rig design conceptual design is broken up into several main subsystems. Within each subsystem, the concept generation, screening and scoring process is performed on important design components. At the end of the down-selection process specific to each components, parts for the final design that are detailed in the body of the report are presented.

C-2 Design Methodology

The chosen methodology was broken up into seven steps:

1. Dividing components of the design up into separate categories
2. Formulating general concepts of solutions for each category through individual and team brainstorming sessions
3. Screening the general concepts and selecting one or two general concepts from each category to develop further
4. Performing further research on the selected general concepts to identify examples of specific components and their estimated metrics
5. Scoring the specific components against one another and selecting one or two to develop as part of the final design
6. Integrating specific components from separate categories together and establishing the final design concept
7. Refining, validating, and presenting the final design solution

The considerations taken at each of these steps and a description of the tools used throughout the down-selection process are provided in the remainder of this section.

For step 1, the project components were split up into several main systems including:

- Water delivery system
- Air delivery system
- Heating system
- Measurements and control system
- Spray pattern characterization system
- Frame and mobility systems

For step two, general concepts of solutions were generated for each main design component. These concepts were intended to be used for the broad comparison of generic configurations or for families of parts and materials. Once a wide range of general concepts were identified, a quick screening process was used to eliminate infeasible or inferior designs. The screening criteria used was based off the client's primary requirements and the results from preliminary research. A sample matrix used for screening general concepts in each design sub-category is shown in Table A-1.

TABLE C-1. SAMPLE SCREENING MATRIX

Test Rig Subsection				
Criteria	**Concept #**	**Concept #**	**Concept #**	**Concept # Baseline**
Size	+	+	-	0
Cost	-	+	-	0
Toubleshooting Time	-	-	-	0
Safety	-	0	+	0
Reliability	0	0	0	0
Performance	+	-	+	0
Ease of use	-	+	0	0
"+"	2	3	2	0
"-"	4	2	3	0
"0"	1	2	2	7
Sum	-2	1	-1	0
Rank	**4**	**1**	**3**	**2**

Within Table III, a concept baseline is selected out of the possible alternatives and assigned a score of zero for all criteria. Every other concept is then graded as being better, equal to, or worse than the baseline by way of plus signs, zeros, or minus signs, respectively. Where applicable, the plus and minus signs are also used to indicate pass or fail status when binary criteria are being considered. The sum of pluses and minuses for each concept is first calculated, and then the concepts are ranked accordingly. Due to the simple method used here, some concepts with similar scores were selected for further development and subjected to a more rigorous evaluation in step five.

For steps four and five, further research was performed to identify examples of specific procurable components and compare their estimated metrics. A sample scoring matrix for the specific components is shown in Table A-2.

TABLE C-2. SAMPLE SCORING MATRIX

Test Rig Subsection							
		Concept #		Concept #		Concept #	
Criteria	Weighting	Score	Weighted Score	Score	Weighted Score	Score	Weighted Score
Size							
Cost							
Toubleshooting Time							
Safety							
Reliability							
Performance							
Ease of use							
Additional Subsection Specific Metrics							
	Sum						
	Rank						

Key differences between the scoring matrix shown above and the screening method shown earlier are that the scores can range for greater resolution, and additional criteria relevant to the subsection of interest may be incorporated at the scoring stage. Additionally, the evaluation criteria in the scoring matrix are prescribed weights based on their relative importance, whereas the screening matrices weight all criteria equally.

From the final scores output from the scoring matrices, the concepts are assigned rankings from highest to lowest. High ranking alternatives are then reviewed for compatibility with the high scoring concepts from other sub-categories for incorporation into the final design.

For steps six and seven, component selections are validated through engineering calculations where possible, and a 3D CAD model is constructed to locate each component onto the frame and to provide a means of presenting the final, integrated design. Engineering calculations have been compiled into Appendix D, and the presentation of the final, integrated design is provided in the body of the report.

C-3 Conceptual Design Screening

The following subsections present the results of the generation and down-selection of conceptual designs for each subsystem (design methodology steps two through five). In order, the subsystems discussed are the:

- Water delivery system
- Air delivery system
- Heating system
- Measurements and control system
- Frame and mobility systems

C-3.1 Water Delivery System

The water delivery system addresses the client's needs to have a supply of pressurized water to the nozzles under test. For the conceptual design process, the system was broken down into four separate subcategories: the water pump, the pump motor, the piping system, and the water storage tank.

Several concepts in all main subcategories were generated and then screened based on size, cost, safety, reliability, performance, and ease of use or ease of installation. Additional factors considered within each specific subcategory at either the screening or scoring phases are discussed where applicable.

The final component selections are presented following the scoring processes in each subsection. Component selections are justified using technical data provided by the respective manufacturer or through engineering calculations performed by the design team.

C-3.1.1 Water Pump

Key factors specific to selecting the water pump were the amount of water flow rate and output pressure from the pump as well as the capability for varying these quantities for one, two, or three nozzle configurations. Concept generation ideas included the type of pump, such as reciprocating, gear, screw, vane, and centrifugal.

Table C-3 shows the concept screening matrix for the pump types, and is followed by a discussion on the assigned scores.

TABLE C-3.WATER PUMP SCREENING MATRIX

Test Rig Subsection: Water Pump					
Criteria	**Gear**	**Screw**	**Vane**	**Centrifugal**	**Reciprocating**
Size	+	0	0	+	0
Cost	0	-	-	+	0
Safety	0	0	0	+	0
Reliability	0	-	-	0	0
Ease of maintenance	+	-	-	0	0
Performance: Pressure	+	0	+	+	0
Performance: Flow Rate	+	-	+	-	0
"+"	4	0	2	4	0
"-"	0	-4	3	1	0
"0"	3	3	2	2	7
Sum	4	-4	-1	3	0
Rank	**1**	**5**	**4**	**2**	**3**

Starting with size criteria from TABLE C-3, the gear and centrifugal pumps are generally available in smaller sizes which are more suitable to our design space [1]. Centrifugal pumps are generally the least expensive type available, while screw and vane type pumps are the most expensive due to the complexity of operation and the amount of moving parts involved. For the same reasons, the screw and vane type pumps scored worst on reliability and ease of maintenance.

All the positive displacement pump types scored evenly in safety, while the centrifugal pump got a plus because it can continue to run with a fully blocked line without building up excess pressure. When it comes to pressure performance, most pumps were ranked higher than the reciprocating baseline because of the pulsating effects that are generally created by a reciprocating type pump. The reciprocating and screw type pumps are also commonly used in higher pressure applications than what is envisioned for the spray rig. Similarly, gear, screw, and vane type pumps can provide a more consistent flow rate over a wide range of differential pressures.

Regarding flow rate performance, screw types are generally not manufactured for flow rates less than 5 gpm and thus scored lower than the reciprocating baseline in this category. The centrifugal type also only scored less than the baseline in this category due to the large variations in flow rate that occur with a changing pump head, and the fact that they are typically not used in high pressure, low flow applications [1].

Because of the final rankings from the screening process, both gear and centrifugal pumps were considered for further design analyses and part sourcing research. The first specific concept considered was the pump type currently used for the TRDC spray mast. The spray mast pumps are stainless steel SM207 gear pumps manufactured by Oberdorfer. To stay consistent with the sourcing that GE has performed in the past, Oberdorfer was selected as the primary pump supplier for the test rig. They provide a wide range of pumps for various applications, and therefore, selecting them as the primary supplier does not limit the creative freedom of the conceptual designs.

Examples of both gear and centrifugal pumps were selected from Oberdorfer’s pump lines and are scored in TABLE C-4. Following the table are pictures of the selected pumps, and justifications for the assigned scores and the final pump selection.

TABLE C-4. WATER PUMP SCORING MATRIX

Test Rig Subsection: Water Pump									
		S207 (Current Gear)		R103M (Smaller Gear)		144 (Small Centrifugal)		101 M (Large Centrifugal)	
Criteria	**Weighting**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Size	2	2	4	3	6	5	10	2	4
Cost	2	2	4	3	6	5	10	4	8
Safety	5	3	15	3	15	4	20	4	20
Reliability	3	5	15	5	15	1	3	3	9
Ease of maintenance	2	3	6	3	6	2	4	2	4
Pressure performance	5	2	10	4	20	3	15	2	10
Flow rate performance	5	2	10	4	20	3	15	2	10
Variability for 1-3 nozzles	3	1	3	4	12	4	12	4	12
	Sum		**67**		**100**		**89**		**77**
	Rank	**4**		**1**		**2**		**3**	

Figure C-1. Oberdorfer pumps selected for evaluation; (a) S207 gear pump; (b) R103M gear pump; (c) 144 centrifugal pump; (d) 101M centrifugal pump [2]

Starting with the analysis of the current pump model that GE is using for the wind tunnel spray bar, the S207 gear pump scored lowest in cost and variability, highest in reliability, and in the middle for pressure and flow rate performance. The pump is made of stainless steel and is therefore robust and durable, but is also the most expensive pump considered. For example, BHP Pump & Equipment, Inc lists a variant of the S207 at $1,875 USD, while the bulk of the bronze-body centrifugal pumps are listed in the range of $300-500 USD. Another major drawback of the S207 is its unsuitability for the current design in terms of scaling down the output flow rates and pressures to the one or three nozzle configurations. For the actual spray mast application, the S207 is used for supplying pressurized water to five or-eight nozzles, or roughly a water flow of 2-3 gpm. The flow curves for this pump demonstrate that while it is suitable for those operating points using conventional motors, the pump would need to be run at a slow 400 rpm to reach the required 1 gpm turn-down point for the three-nozzle configuration. Additionally, no data is available from the manufacturer below the 400-rpm speed, and thus reaching the ~0.3 gpm flow rate required for a single nozzle configuration appears infeasible.

The two centrifugal pumps scored closely overall, though the designs do contain some key differences when compared to the gear pumps and to each other. The small centrifugal pump (model number 144) can provide enough flow rate at a marginally acceptable pressure, while the larger model actually provides a smaller pressure at too large a flow rate. In other words, the smaller pump would be running near the middle of its operating curve, while the larger one would be at its minimal turn-down point and both would be supplying marginally acceptable system pressure values.

Attractive features for these pumps when compared to the gear pump alternatives are the lower overall costs and improved safety regarding pressure build-up in the case of a blocked line. However, some concerns are present regarding the construction and material selection of these two pumps. The smaller pump's body and adapters are made of glass-reinforced nylon, which is rated for a maximum fluid temperature of 180°F. This is exactly the target water temperature for the test rig system, and thus presents major reliability concerns. The larger pump's body is available in either cast aluminum or bronze alloy variants and is therefore rated up to higher temperatures, though is less durable and would require additional piping adapters when compared to the stainless-steel gear pump alternatives.

Lastly, the R103M gear pump is assessed. The R103M gear pump comes from a different line than the S207 currently being used at the TRDC, but they share many similarities. Like the S207, the R103M housing, gears, and shafts are constructed from stainless steel and to higher tolerances than the available centrifugal pump alternatives. They are also both constructed using a three-part housing which allows for easy disassembly and service. As shown in Figure C-1, neither gear pumps come in pre-attached motor configurations, but both are built to standard NEMA motor mounting dimensions that allows for mounting to common motor sizes [3].

In terms of performance criteria, the R103M meets the flow and pressure requirements for the design at more feasible motor speeds than the larger S207 pump. The R103M is also more durably constructed, and is easier to maintain than the centrifugal pump variants considered. As a result of the scoring process, the R103M was selected for further development and integration into the final test rig design.

C-3.1.2 Water Pump Motor

Important factors specific to selecting the water pump motor were the motor's required power supply, the output torque and rotational speed provided by the motor, and the motor's capability to meet the pump requirements for one, two, or three nozzle configurations. Concept generation ideas included synchronous speed AC motors and direct drive DC motors, as well as their variable drive counterparts. TABLE C-5 shows the concept screening matrix for the general motor concepts considered.

TABLE C-5. WATER PUMP MOTOR SCREENING MATRIX

Test Rig Subsection: Water Pump Motor				
Criteria	**Variable Drive (AC)**	**Direct Drive (DC)**	**Variable Drive (DC)**	**Synchronous Speed (AC)**
Size	-	-	-	0
Cost	-	0	-	0
Safety	0	0	0	0
Reliability	0	+	+	0
Ease of maintenance	0	+	+	0
Power supply	+	0	+	0
Torque and speed (1 nozzle)	+	-	0	0
Torque and speed (3 nozzle)	+	0	+	0
"+"	3	2	4	0
"-"	2	2	2	0
"0"	3	4	2	8
Sum	1	0	2	0
Rank	**2**	**3**	**1**	**4**

TABLE C-5 shows the important trade-offs that must be considered for the selection of the test rig's water pump motor type. Scoring assignments are discussed in more detail throughout the remainder of this section.

The variable drive motors are generally more expensive and require the addition of external control units when compared to direct drive counterparts. Thus, both variable drive types would require some additional space for the controllers. However, the direct drive DC motor would also need an AC to DC converter, putting it on the same level as the variable drive motors in terms of space requirements.

For the pump motor, safety is generally related more to the housing assembly and installation configuration (use of overvoltage protections and e-stops) rather than to the general motor type, so all components scored equally in that category. The DC motor variants scored best in reliability and ease of maintenance because of the less complex operation principles involved and the fact that variable drive DC motor types are already being used and maintained at the TRDC.

All motor types are compatible with the 110/208 V power sources available at the TRDC, though installation of the DC motors would be less complex as they would not require three phase AC power. However, the variable drive AC motor type also scored well in the power supply category due to the signal conversions and filtering that would be provided by the motor's driver/controller unit, making it less susceptible to any noise or variations in in the input line.

Direct drive DC motors or synchronous speed AC motors are not feasible solutions for meeting both one and three nozzle configuration requirements. Three separate fixed speed motors would be required in order to achieve the desired flow rate variability. However, purchasing three direct drive DC motors or synchronous speed AC motors is not an economical option compared to the cost of a single variable speed motor.

Speed control of DC motors is performed simply by varying the voltage supplied to the armature, while the speed control of AC motors is more complex. Variable speed AC motors require the input of variable frequency signals and generally require some form of feedback control to the driver for the adjustment of torque and motor speed [4]. Therefore, variable drive DC motors are more attractive when compared to variable drive AC motors in terms of controller cost and complexity.

In summary, direct drive DC motors or synchronous speed AC motors are less expensive to purchase on a per unit basis and simpler to install due to the lack of driver or controller units, but can be set-up for only one nozzle configuration or the other. Between the two variable drive alternatives, the AC motors require more sophisticated and expensive control systems than the DC counterpart. In addition, the current pump motors used at the TRDC are variable drive DC. Thus, the client has previous experience in installing, operating and maintaining these motor types. As a result, the pump motor type selected for use in the test rig design is a DC powered motor with a voltage-varying driver.

C-3.1.3 Piping System

For the water and air piping systems, several different piping materials were considered such as copper, galvanized steel, black steel, stainless steel and polymers like PVC or PEX. Main considerations for the selection of pipe materials include their resistance to corrosion and compatibility with air and water flows, and their compatibility with the design temperatures in addition to the cost, safety, and ease of installation criteria that is common to all sections. The concept screening matrix used for deciding between them is shown in Table VIII.

TABLE C-6: SCREENING MATRIX FOR PIPING MATERIALS

Test Rig Subsection: Piping Materials						
Criteria	**Galvanized Steel**	**Stainless Steel**	**Black Steel**	**Polymeric (PVC)**	**Polymeric (PEX)**	**Copper**
Cost	-	-	0	+	+	0
Safety	0	0	0	-	-	0
Ease of installation	0	+	0	+	+	0
Compatibility with air flow (pass/fail)	-	+	+	+	+	+
Compatibility with water flow (pass/fail)	+	+	-	+	+	+
Temperature compatibility (180F) (pass/fail)	+	+	+	-	-	+
"+"	2	4	2	4	4	3
"-"	2	1	1	2	2	0
"0"	2	1	3	0	0	3
Sum	0	3	1	2	2	3
Rank	**4**	**1**	**3**	**2**	**2**	**1**
Continue? (YES/NO)	**NO**	**YES**	**NO**	**NO**	**NO**	**NO**

TABLE C-6 shows that stainless steel and copper are the highest scoring alternatives. Both materials have excellent corrosion resistance, and are suitable for both air and water flows. Both copper alloys and austenitic stainless steels (especially the 304, 316 series [5]) perform well under both low and high temperature extremes. Regarding costs, copper piping is less expensive than stainless. However, the stainless configuration incorporates better with the stainless-steel fittings for the chosen water pump, facilitating the installation process.

Black steels are not suitable for water flows due to corrosion concerns, and galvanized steels are not suitable for this application due to concerns over the zinc coating flaking off and contaminating the spray nozzle.

Other alternatives considered include polymeric materials such as PVC or PEX. The polymeric materials would be the cheapest and easiest to install in general due to their flexibility and ease of cutting and fitting. However, the pressure margins for PVC and PEX are small compared to the metal alternatives, and thus pose a safety risk for degradation and bursting. In addition, the maximum rated working fluid temperatures for PVC and PEX are 140°F and 180°F. This alone eliminates the feasibility of using PVC, and leaves zero safety margin relative to the design's fluid temperatures for PEX.

In summary, 304 stainless steel meets all the necessary performance requirements for the design. It is costlier than some of the other alternatives, but incorporates well with the chosen pump fittings for ease of installation. In addition, GE TRDC mainly uses stainless steel for their piping applications, and have thus proven manufacturing and pipe routing capabilities for this material. As a result, 304 stainless steel was selected as the piping material for both the air and water flow components of this design.

C-3.1.4 Water Storage Tank

The design's water storage tank will also be constructed from 304 stainless steel. This material was selected for similar temperature, corrosion, and contamination reasons that are presented in the previous section. Besides material, a major design factor to consider for the water tank was its overall size. The size of the water tank determines the length of time that spray nozzles can be tested continuously, as well as the frequency of required fill-ups. As a trade-off for the increase in water capacity for continuous testing, a larger tank will also decrease the mobility of the rig. This section first presents some rough calculations for estimating an adequate tank size for the design application, followed by the selection of a water tank design and the required fittings.

To calculate an effective tank size, input parameters are the number of nozzles that need to be tested sequentially, the average test duration, and the mass flow rate of water during the tests. Given that the longest spray bar on the TRDC wind tunnel contains 16 nozzles, and the test rig is able to troubleshoot up to three at a time, up to five sequential tests would need to be performed before the faulty nozzle on the bar can be identified. The client has estimated that on average, it should take roughly ten minutes of spray time to identify a faulty nozzle. In combination with the approximately 1 gpm flow rate through the test rig with three nozzles installed, this results in an estimated tank size of 50 gallons before a faulty nozzle on the largest spray bar can confidently be identified.

Using the density of water (8.3 lbm/gal at 70°F), the water weight for a 50-gallon tank can be estimated as $8.3 \times 50 = 415$ lbs. This mass provided some concern for the mobility of a fully integrated design since general operational health and safety guidelines suggest a maximum load of 500 lbs on four wheeled push carts [6]. Therefore, the concept of having a detachable cart for the water tank was pursued.

A vertical tank concept was selected over a horizontally oriented tank to provide low-pressure gravity fed flow to the inline heater and water pump.

C-3.2 Air Delivery System

The air delivery system, one subsection of the test rig, intends on delivering clean, dry and continuous supply of air to the in-line nozzle bar containing the mixing nozzle(s). One way to achieve this is to pay special attention when choosing the air compressor to meet the demands on the air delivery system. Factors such as discharge temperature and pressure, the flow capacity and the ability to maintain continuous supply of clean, dry compressed air, are different for different air compressors. As such, priority is on determining the air compressor most suited under the required conditions posed by the testing environment.

The organization of the following content is as follows: the concept development screening, where the list of proposed air compressors undergoes preliminary screening, followed by the concept evaluation, where the characteristics of each air compressor are scored based on several metrics to determine whether or not the air compressor can succeed in delivering clean, dry and continuous air, and benefit the end user(s).

C-3.2.1 Air Compressor Development

A list of air compressor concepts was generated, utilizing different compressor technologies, like positive-displacement or dynamic compression, different cooling schemes, as well as different lubrication environment such as, oil-free or oil-injected in order to determine the air compressor to be used in the air delivery system. The following is the list of air compressor concepts, and the general model description:

Concept #1 –

- *Compressor Model Description*: Single-acting reciprocating compressor.
- *Cooling Scheme*: Air-cooled
- *Lubrication Environment*: Oil-free

Concept #2 –

- *Compressor Model Description*: Double-acting reciprocating compressor.
- *Cooling scheme*: Liquid-cooled
- *Lubrication environment*: Oil-free

Concept #3 –

- *Compressor Model Description*: Rotary compressor.
- *Cooling scheme*: Air-cooled
- *Lubrication environment*: Oil-free

Concept #4 –

- *Compressor Model Description*: Rotary compressor.
- *Cooling scheme*: Liquid-cooled

- *Lubrication environment*: Oil-Injected

Concept #5 –

- *Compressor Model Description*: Vane compressor.
- *Cooling scheme*: Air-cooled
- *Lubrication environment*: Oil-free

Concept #6 –

- *Compressor Model Description*: Centrifugal compressor.
- *Cooling scheme*: Oil-cooled
- *Lubrication environment*: Oil-free

Concept #7 –

- *Compressor Model Description*: Scroll compressor.
- *Cooling scheme*: Air-cooled
- *Lubrication environment*: Oil-free

The following table contains the general characteristics for each concept, intending on providing a broad stroke of the related air compressor performance, market availability of low horsepower option, and the expected routine maintenance and upfront cost.

TABLE C-7. GENERAL CHARACTERISTICS FOR EACH AIR COMPRESSOR CONCEPT

	General Characteristics
Concept #1	• Relatively inexpensive initial cost
	• Sensible choice for server duty ambient conditions
	• Can cover low horsepower and demanding applications where high pressure is essential; limited duty cycle (< 70 %)
	• Periodic maintenance is high; internal operating temperature makes for highly fatigued valves and rings.
	• Limited duty cycle; and it is therefore crucial to size to meet the demand.
	• Sensible choice for 100-150 psig air applications.
Concept #2	• Relatively inexpensive initial cost
	• Dependable choice for harsh operating conditions
	• Reliable to meet jobs requiring low horsepower (below 30 hp), but high pressure (above 250 psig); duty cycle is less than 70 %.
	• Routine maintenance intensive. Partially due to extreme internal operating conditions. Much higher than single-acting alternative.
	• Limited duty cycle. Requires special attention to size unit to meet demand side requirement.
	• Sensible choice for 100-150 psig air applications.
Concept #3	• Expensive initial costs (> $4,000).
	• Can meet high capacity (scfm) demand, but does not normally operate at high pressures.
	• Higher rated horsepower; can be expensive to run on small jobs.
	• Routine maintenance is non-intensive. Less moving part means less to check/repair/replace
	• Can be rated for 100 % duty cycle
	• Can deliver high volume air in a compact space.
	• Offered in smaller sizes ranging from 5-30 hp.
Concept #4	• Expensive initial costs (cost 10%-15% less than oil-free option).
	• Designed to run at 100 % duty cycle.
	• Routine maintenance is non-intensive; partially due to the fact the compressor screws do not contact.
	• Requires oil/air separation to produce clean air.
	• Air pressure range is up to 150 psig.
	• Cooler internal operating temperature than do reciprocating compressors.
	• Can deliver high volume air in a compact space
	• Size available is diverse. HP ranging from 5-30 hp and above.

Concept #5	• Sensible choice for high pressure, low capacity applications. • Suited for variable drive systems. • Can be used in continuous air application that require high duty cycle. • Cover low horsepower applications. • Can endure a 100 % duty cycle • Routine maintenance is non-intensive. • Suitable for air pressure of 150 psig. Has difficulty with higher pressures. • Cheaper than the rotary screw compressor, but more expensive than the reciprocating compressor.
Concept #6	• Expensive initial cost (> $17,000). • High rotational speeds require special bearings, sophisticated vibration and clearance monitoring. • Sensible choice for high capacity (scfm) jobs. • Market availability of smaller sized compressor is limited. Size ranging from 20 hp up through 500 hp. • Designed to give oil-free air. • Has lower operating costs in terms of downtime, and repair due to few mover parts, and lack of contact between moving parts. • May be prone to performance issues in severe ambient environments
Concept #7	• Expensive initial cost • Runs smoothly, and able to deliver air continuously • Very few moving parts make for low maintenance • Clean air at the discharge • Covers low HP, and can deliver capacity much like the reciprocating compressor, but comes with additional benefits • Excessive vibration is a non-issue; requiring no special foundation • Sensible choice for high pressure applications

The intended use of the information contained in the table, outlining the general characteristic for each concept, is to evaluate the concept strength to continue development. To determine the strength of each concept relative to one another, a screening matrix was developed. For each, the concepts are evaluated by a few criteria and include such items as: horsepower range availability, the flow capacity at rated pressure, the maximum operating pressure, the cost associated with acquiring the technology, and requirement on operator(s) in terms of routine maintenance among others.

The following table intends on providing helpful information to define the pass/fail assignment for each of the screening criteria used in the screening matrix:

TABLE C-8. PASS/FAIL DEFINITION FOR COMPRESSOR SCREENING CRITERIA

Horsepower range availability:	Flow Capacity at Rated Pressure:	Oil-free variant
• Pass: > 10 HP	• Pass: High Volume Air	• Pass: Available in the market
• Fail: < 10 HP	• Fail: Low Volume Air	• Fail: Unavailable in the market
Maximum Pressure:	Initial Cost:	
• Pass: > 110 psig	• Pass: < $1,500	
• Fail: < 110 psig	• Fail: > $1,500	
Periodic Routine Maintenance:	Duty Cycle:	
• Pass: Intensive	• Pass: Continuous (100%)	
• Fail: Non-intensive	• Fail: Non-continuous	

TABLE C-9. AIR COMPRESSOR SCREENING MATRIX

Screening Criteria	**Air System Compression Unit “+” = Pass, “-“ = Fail**						
	Concept #1	**Concept #2**	**Concept #3**	**Concept #4**	**Concept #5**	**Concept #6**	**Concept #7**
Horsepower Range Availability	+	+	+	+	+	-	+
Flow Capacity (SFCM) @ rated psig	+	+	+	+	-	+	+
Maximum Pressure	+	+	+	+	+	+	+
Initial Cost	+	+	-	-	-	-	-
Duty Cycle	-	-	+	+	+	+	+
Oil-Free Variant	**N/A**	**N/A**	**N/A**	+	-	+	**N/A**
Periodic Maintenance Routine	-	-	+	+	+	+	+
“+” sum	**4**	**4**	**5**	**6**	**4**	**5**	**5**
“-“ sum	**2**	**2**	**1**	**1**	**3**	**2**	**1**
Net	**2**	**2**	**4**	**5**	**1**	**3**	**4**
Rank	**4**	**4**	**2**	**1**	**5**	**3**	**2**
Continue?	**YES**	**YES**	**YES**	**YES**	**NO**	**NO**	**YES**

Although Concept #6 achieved a higher ranking than Concepts #1, and #2 overall, the concept was rejected due to the high capital cost associated with acquiring a centrifugal air compressor.

Concept #5 was rejected to due low capacity and unavailability of oil-free variants to do the job. Concepts #1, #2, #3, #4, and #7 have been determined to be the strongest concepts of the seven, and later scored in the next step of the concept development. The following table summarizes the relative strengths and weaknesses of the five selected concepts:

TABLE C-10. AIR COMPRESSOR CHART – STRENGTHS VS WEAKNESSES

	Strength	Weakness
Concept #1	• Proven durability; can handle harsh ambient conditions • No oil carryover • Low initial costs	• Limited duty cycle • Many moving parts • Pulsation of air discharge • Material carryover is a problem; excessive internal rubbing
Concept #2	• Achieves higher pressure for smaller unit relative to single action • Capable of delivering higher capacity	• Periodic maintenance is high due to many moving parts; offsets any savings • Higher internal temperatures than single action • Contaminant traces is an issue
Concept #3	• Pulseless air discharge • Can supply continuous air • Less moving parts mean less periodic maintenance • Lower internal temperatures. • Lubricant carryover is minimal; counter rotating parts do not engage	• Expensive initial cost • Limited air-end life; expensive replacement part • Covers 20 HP and above.
Concept #4	• The oiled environment acts to cool the internal chamber, internal temperature lower than Concept #3, and also Concepts #1, and #2. • Less maintenance required than oil-free option • Covers a wide range of HP, includes the lower end (< 10 HP)	• Oil/air separation is required; additional features in the demand side air run are required • Expensive, but less than oil-free option on an initial cost basis. • Limited air-end life
Concept #7	• Can supply continuous clean, dry air at high capacity; duty cycle of 100 % • Relatively quiet in operation, minimal moving parts • Covers small HP range • lower operating temperatures than the reciprocating type	• Higher initial cost than Concepts #1 and #3 • Pulsation has to be dampened; may effect flow regime • Sensible choice for low flow rate application. Higher capacity is desirable

C-3.2.2 Air Compressor Selection Criteria

There are several selection criteria as determined by the previous phase, Phase I – Problem Definition. The selection criteria are used here to evaluate each of the concepts in order to determine the concept that achieves the highest weighted score. Weighted score is the product of the rating assigned to the concept in meeting a given criteria and the weight in percentage associated to that given criteria. The following table summarizes the selection criteria and their associated weight:

TABLE C-11. WIGHTED (%) SELECTION CRITERIA FOR AIR DELIVERY SYSTEM

Selection Criteria	Weight (%)
Size	10
Cost	20
Troubleshooting Time	15
Safety	15
Reliability	10
Performance	20
Ease of Use	10

A definition of the seven selection criteria is found in the following list:

- ***Size*** – Due to the relative size of the air delivery system to the system, space can be an issue for a couple of reasons. The functional layout must accommodate for the water distribution system. In addition, the mobility of the entire rig is a function of the associated weight. Consideration of the air storage and tolerable placement of the compression unit cannot be overlooked. Therefore, size has been assigned a weight of 15%.
- ***Cost*** – The factors determining the weight association for cost is a function of the initial and running costs, them being capital expenditure for acquiring the technology and the routine maintenance schedule, respectively, as well as cost for replacement parts. A relatively low weight has been assigned due to the higher importance of the other criteria, the justification is that performance, safety, and reliability are essential to the end use of the system as a whole.
- ***Troubleshooting Time*** – Features of an air delivery system include power systems, air-supply distribution lines, and associated compressor and in-line air treatment accessories. The symptoms that exist in a complicated system like this one have potential to cause variation in state properties (e.g. pressure and temperature) at the demand side of the system as a

whole. For this reason, troubleshooting time has been assigned a weight of 20% as it represents the downtime that can plague the air delivery system. Different compressors may require different routine maintenance scheduling.

- ***Safety*** – Since safety is of utmost importance, any necessary safeguard has been factored in to each of the concepts, safety is then judged on the expected noise levels encountered by the operator(s) and points of failure that exist in the compressor unit.
- ***Reliability*** – The reliability criterion is a function of the life cycle of key element in the compressor, as expected to be the most abused component in the air delivery system. Therefore, reliability is judged on the estimated life of the compression unit and includes life estimate on piston rings and air-end. A weight of 15 % has been assigned.
- ***Performance*** – The primary goal of the air system is to deliver clean, dry and continuous air to the in-line nozzles contained on the horizontal to mix with the water out of the nozzles. Factors such as drop in discharge temperature and pressure, indirectly the flow rate, must be minimized in order to deliver the correct quality of air. For this reason, a high weight of 20% has been assigned to the performance criterion.
- ***Ease of use*** – Ease of use as defined in the context of the air delivery system refers to the convenience to do something to the air delivery system and includes such items as, quick and easy placement of the air delivery system module, and a smart control feature for quick diagnostics and system control. The concepts will be judged to this standard to determine if the design is hassle free.

The next section includes all information related to: air compressor characteristics, the complexity in design and the cost appraisal, the air treatment instrumentation required by the oil-injected and oil-free compressors to produce clean, dry air, the reliability of key components as defined by their estimated life cycle to changeover, the symptoms of an air system and the possible causes caused by the concept, and the relative ease of use for each concept. This information is used in the weighted matrix to determine the relative ratings for a given concept per the above seven selection criteria. The weighted matrix determines the weighted score achieved by a given concept.

C-3.2.3 Compressor Characteristics

The following subsection rates concepts based on the physical space required by the concept (refers to Size), the safety based on generally accepted limit on allowable noise exposure (refers to safety), and followed by a preliminary performance assessment for each concept.

The following table summarizes the compressor characteristics pertaining to each of the selected concepts. Information is provided on maximum pressure, capacity at rated pressure, estimated weight and dimension (L x H x W) for a given nominal power (HP). In addition, the expected operating conditions are summarized in the following table and include the level of noise expected in operation from the air delivery system, the duty cycle, and internal operating and discharge temperature. The noise level dictates the maximum exposure time for an operator, where the generally accepted limit is bounded by 85 decibels for no long-term effect on human hearing. High internal operating and discharge temperature create unnecessary thermal stress, leading to expedited breakdown of seals, valves, and rings among others. The duty cycle determines whether the air delivery system can supply free-flowing, continuous air on demand, any duty cycle not rated at 100% is recommended to be shutdown to allow the oil to cool.

TABLE C-12. COMPRESSOR CHARACTERISTICS

	Compressor Characteristics	Values
Concept #1 (Single-Action)	Max Pressure (psig)	135
	Nominal Power (HP)	5
	Capacity FAD (cfm)	18.3 @ 90 psig
	Dimensions (inch)	30 x 23 x 34
	Weight (lbs)	300
	Operating Conditions	
	Noise Level (dB)	80
	Duty Cycle	< 70 % (Recommended)
	Internal Temperature (F)	300 - 400
	Discharge Temperature (F)	>> 200 above ambient
Concept #2 (Double Action)	Max Pressure (psig)	175
	Nominal Power (HP)	5
	Capacity FAD (cfm)	15.3 @ 90 psig
	Dimensions (inch)	48 x 40 x 36
	Weight (lbs)	600
	Operating Conditions	
	Noise Level (dB)	85
	Duty Cycle	< 70 %
	Internal Temperature (F)	350 - 450
	Discharge Temperature (F)	>> 200 above ambient
Concept #3 (Rotary screw, Oil-Free)	Max Pressure (psig)	145
	Nominal Power (HP)	10
	Capacity FAD (cfm)	37 @ 145 psig
	Dimensions (inch)	38 x 27 x 47
	Weight (lbs)	600
	Operating Conditions	
	Noise Level (dB)	< 70
	Duty Cycle	100%
	Internal Temperature (F)	250 - 300
	Discharge Temperature (F)	>> 200
Concept #4 (Rotary Screw, Oil-Injected)	Max Pressure (psig)	65-145
	Nominal Power (HP)	7.5
	Capacity FAD (cfm)	13.6-32.1
	Dimensions (inch)	38 x 27 x 47
	Weight (lbs)	628
	Operating Conditions	
	Noise Level (dB)	< 70
	Duty Cycle	100%
	Internal Temperature (F)	170-200
	Discharge Temperature (F)	170
Concept #7 (Rotary Scroll)	Max Pressure (psig)	145 (116)
	Nominal Power (HP)	7.5
	Capacity FAD (cfm)	16.1 (20.8)
	Dimensions (inch)	40 x 26 x 33
	Weight (lbs)	350
	Operating Conditions	
	Noise Level (dB)	< 65
	Duty Cycle	100%
	Internal Temperature (F)	> 200
	Discharge Temperature (F)	180

Based on the compressor characteristics table, Concept #2 has the largest physical space requirement, accounting for approximately 40 cubic feet of the total cubic footage of the entire system. As such, Concept #2 bounds the size assessment, where Concept #2 achieves the minimum rating of one. Concept #1 came in a size of 14 cubic feet, and 30, 28 and 20 cubic feet for Concepts #3, #4 and #7, respectively. The key takeaway is that, although Concepts #3 and #4 offer superior flow capacity, there is space savings of approximately 10 to 15 cubic feet for Concepts #1 and #7.

On part of safety, the expected noise levels encountered by the operator(s) in operation of the air delivery system is the determining factor. The noise created by a reciprocating compressor lie on the generally accepted standard, corresponding to noise level below 85 decibels. Although, the maximum exposure time far exceeds the expected time taken to complete nozzle evaluation via the test rig, there is the off-chance bystanders in the storage facility will not be wearing protective hearing devices. On the other hand, the rotary screw and scroll compressor produce little noise, and termed as smooth-running machines. The second part of safety bases on the points of failure. The rotary screw and scroll compressor feature much less moving parts than is featured in the reciprocating compressor. The reciprocating compressor has hundreds of parts, and even more in the case of two-stage compression, like valves, seals, rings, crankcase and crankshaft, the prime mover, and discharge ports among others. Due to high internal temperature, and high pressure, the collective parts and assembly are more likely to cause emergency shutdown, procedurally a dangerous move that has potential to result in over-pressurization that may result in catastrophic failure. As such, Concept #1 and #2 achieve the minimal rating of one. Concept #3, #4 and #7 have higher safety ratings.

The air delivery system intends on delivering continuous, clean, dry air to mix with the water in the in-line nozzles contained in the horizontal bar. Factors, like drops in discharge temperature and pressure, indirectly, the flow rate, must be minimized in order to deliver the correct quality of air. Continuous operation is a measure of the duty cycle, where 100% duty cycle indicates the compressor ability to run continuously and nonstop. Another factor relates to the maximum allowable pressure and flow capacity at rated pressure. These two factors determine whether the compressor sized correctly for its intended application. Based on this, and consulting the compressor characteristics table, Concepts #3 and #4 have favorable characteristics. The next in line is Concept #7, and then Concept #1 and #2, which feature matching characteristics.

C-3.2.4 Complexity in the design and the cost appraisal

Factors that determine the initial cost for a given compressor design is a function of the manufacturability effort to machine each compression unit. For the reciprocating compressor, which applies to Concept #1 and #2, feature a piston cylinder arrangement. The rotary screw features two screws that rotate opposite to one another. The scroll compresses air by two spiral elements, where one is stationary and the other moves and traces out eccentric circles. Each features a different means of compression, but all have the same objective, compress the air. The differences in design account for the initial cost. A summary of the relative complexity in designing of a compression unit for the various compressors featured in the Concepts is contained in the following table:

TABLE C-13. COMPRESSOR DESIGN FEATURES

Compressor Design	**Complexity Rating (LOW, MID, HIGH)**	**Design Features**
Reciprocating		• Made up of pistons connected to a crankshaft that drive in the cylinder liner.
Compressor	LOW	• Tolerance has to account for no gas escape and thermal expansion effects.
(Concepts #1 and #2)		• Hundreds of moving parts, but available off-the-shelf
Rotary Screw		• Consists of two counter-rotating screw
Compressor		• Tolerance for air pathway requires special attention
(Concepts #3 and #4)	HIGH	• The length, pitch of the screw, and the form of the air-end determine the pressure ratio
		• Requires precision cutting tooling
Rotary Scroll		• They compress air by two spiral elements, where one is stationary and the other moves in eccentric circles
Compressor	MID	• Features the involute, which requires precision to develop correctly
(Concepts #7)		• Intensive machining requirement to trace involute and keep true to shape

The following table summarizes the initial estimated cost associated to each of the compressor models featured in the concepts [7]:

TABLE C-14. INITIAL ESTIMATED COST OF COMPRESSOR MODELS

Compressor Model	Initial Estimated Cost	
	LOW	HIGH
Reciprocating Compressor (Concept #1 and #2)	$800	$2,200
Rotary Screw (Concept #3 and #4)	$3,900	$15,000
Rotary Scroll (Concept #7)	$5,000	$12,000

The high initial estimated cost of the rotary screw compressor is a function of the design. The rotary screw features two screws, where the length, pitch of the screw, and the form of the air-end determine the pressure ratio, requiring precision engineering. The reciprocating compressor is offered at cheaper cost and is cost saving only due to ease of manufacture of the compression unit. The scroll compressor is not manufacturing friendly, having high complexity in design much like the rotary screw compressor.

The reciprocating compressor features the most intensive maintenance schedule. Two primary factors that make for the intensive maintenance schedule is partly due to the hundreds of moving parts and the high thermal stresses created by the internal operating temperature. The internal operating temperature, which is hundreds of degrees hotter than ambient, breaks down the internal rubbing surfaces. In addition, the vibration leads to wear and tear due to cyclic loading, which can cause misalignment in the worst-case scenario. The rotary screw, on the other hand, has cooler internal operating temperatures and non-contact of internal rotating parts, and it is therefore less maintenance intensive on an 8-hourly basis (after 8 hours of operation). The scroll is much of the same. Since, the test rig is rolled out non-daily, on the high end, 5 times per icing season, the rig has tons of downtime. Seizure of parts can be a problem with to much downtime and no activity. Therefore, less maintenance intensive scheduling and proven durability is desirable.

The next section covers the air instrumentation necessary to produce clean, dry air, the reliability of the prime mover in the compression unit and discharge port, the associated troubleshooting, and the ease of use. There is hidden cost that will be relieved in these later sections.

C-3.2.5 Air Treatment Instrumentation

In order to deliver contaminant-free, dry air to the in-line nozzles, several in-line air treatment elements are recommended to cleanse the air of solid particulate, moisture, and lubricant carryover and have been summarized in TABLE C-15 and TABLE C-16 [8]. There is no toleration for contaminated air in the air delivery system, as the air/water mixture has strong dependency on the quality of air. Plus, untreated air contains debris and moisture that can lead to excessive wear to the nozzle, in-line supply lines, and cause excessive moisture load on the air delivery system to handle. The GE TRDC applies Class 1 standards to the air ingested by the air distribution system at their facility. As such, Class 1 air quality standards are applied to all concepts.

The following table contains information on the solid, moisture, and oil content for a given air quality class [9].

TABLE C-15. AIR QUALITY CHART

Air Quality Classes	Solid	Moisture		Oil	
	Maximum Mean Particle Diameter	Dew Point		Liquid and Oil	
	(microns)	°C	°F	mg/m^3	$ppm_{w/w}$
0	as specified	as specified		as specified	
1	0.1	-70	-94	0.01	0.008
2	1	-40	-40	0.1	0.08
3	5	-20	-4	1	0.8
4	15	3	38	5	4
5	40	7	45	-	-
6	-	10	50	-	-

The industry recommended in-line air quality instrumentation for the oil-injected compressor is contained in the following table and applies only to Concept #4:

TABLE C-16. AIR TREATMENT METHOD FOR OILED ENVIRONMENT

Inside the Compressor Enclosure		
Air Receiver	Wet and dry receivers	Removes moisture from the compressed air
Oil/Dirt Separator	Oil coalescing filters	Removes oil aerosol, wet dust and suspended water content
Air Dryer	Refrigerant dryer	Removes moisture from the compressed air
Dry Air Filter	Dry dust filters	Removes dry dust, and particulates suspended in dry air
In-line to nozzles		
Oil/Dirt Separator	Oil coalescing filters	Removes oil aerosol, wet dust and suspended water content
Adsorption dryer	Membrane or Heatless desiccant dryer	Eliminates moisture from the compressed air, and produces the desired pressure dewpoint
Dry Air Filter	Dry dust filters	Removes dry dust, and particulates suspended in dry air

The oil-free compressor does not feature the air/oil separator, but has common features. The following table summarizes the air quality instrumentation included for air treatment of oil-free compressors:

TABLE C-17. AIR TREATMENT METHOD FOR OIL-FREE ENVIRONMENT

	Options	Comment
Inside the Compressor Enclosure		
Air Receiver		
Oil/Dirt Separator	Oil coalescing filters	Removes oil aerosol, wet dust and suspended water content
Adsorption dryer	Membrane or Heatless desiccant dryer	Eliminates moisture from the compressed air, and produces the desired pressure dewpoint
In-line to nozzles		
Oil/Dirt Separator	Oil coalescing filters	Removes oil aerosol, wet dust and suspended water content
Adsorption dryer	Membrane or Heatless desiccant dryer	Eliminates moisture from the compressed air, and produces the desired pressure dewpoint

Concept #4, the oil-injected rotary compressor, requires air treatment to remove the oil out from the compressed air, making for a least cost-effective choice. Also, direct disposal of the water/oil mixture is prohibited, requiring a water/oil filtration system to filter the oil out of the water upon disposal. The oil-free compressors, Concepts #1, #2, #3 and #7 can deliver oil-free, clean air (Class 1 Air Quality) to feed the nozzle demand, and achieving relatively cheaper initial and running costs.

The following table compares the necessary instrument requirement for each, the oil-injected compressor and the oil-free compressor, and a quick comparison of the two oiled environments featured in the concepts:

TABLE C-18. OIL-INJECTED VS OIL-FREE COMPRESSOR

Air Treatment Instrumentation	Oil-injected Compressor	Oil-free Compressor
	Required (Y/N)	Required (Y/N)
Air Receiver	Yes	Yes
Oil/Dirt Separator	Yes	No
Adsorption Dryer	Yes	Yes
Dry Air Filter	Yes	No
Adsorption Dryer	Yes	Yes
Water/Oil Filtration	Yes	No

C-3.2.6 Air Compressor Reliability

The reliability of each concept is a function of the life cycle of key elements in the compressor for reasons that the compressor is continuously compressing air, creating high pressure and temperature conditions. For the reciprocating compressor, the piston ring is prone to material wear due to high internal operating temperatures and self-lubrication scheme. The air-end in the rotary screw is limited without care. With that said, compliance to the routine maintenance schedule extends the life of these units considerably. The estimated life is 50,000 to 60,000 hours. The following table summarizes the estimated life cycle of critical working components:

TABLE C-19. RELIABILITY OF KEY COMPRESSOR ELEMENT

Compressor Model	Critical Components	
	Estimated Life	Comment
Reciprocating Compressor	8,000 hours	Periodic maintenance. Compression ring is prone to material wear and fatigue.
Rotary Screw	50,000 to 60,000 hours	Noncompliance to timetable may lead to expensive forced shutdowns. Limited air-end life, not field serviceable.
Rotary Scroll	100,000 hours	Care and constant maintenance upkeep can extend lifetime almost indefinitely.

*Air-end replacement can cost up to 70% of the original equipment cost.

The reciprocating compressor, common to Concept #1 and #2, requires replacement after 8,000 hours, or after one year in operation. The rotary screw (Concept #3 and #4) and scroll compressor (Concept #7), almost last indefinitely, assuming 1 hour, 5 days a year of operation. As a result, Concepts #3, #4, and #7 have high reliability ratings based on endurance of key functioning parts.

C-3.2.7 Air Compressor – Ease of Use

The ease of use rating is a function of the appealing features offered in complete packaging as specified by the distributor. Some packages offer intelligent graphics controller features, allowing for reduced uptime and quick air system diagnostics [10]. The integrated intelligent design also offers data collection, further increasing the productivity. Other packages come ready built with air system cooling units, air ventilated enclosures, and/or automatic drain valves among others. The following table summarizes the most appealing features of compressor units matching that of the concepts:

TABLE C-20. APPEALING FEATURES FOR COMPLETELY PACKAGED COMPRESSOR

	Appealing Features
Concept #1 (Reciprocating, Single Stage)	· Relatively simple design
	· Offered in open concept; maximizing the serviceability
	· Typically offered with integrated intercooler, after-cooler.
	· Achieves high pressure for relative low initial cost
	· Automatic tank drain feature is offered, making for a controllable drain valve
Concept #2 (Reciprocating, Double Stage)	· Self-containment is available in market. Typically gauge monitored, making for relatively simpler design.
	· Can be loaded with rugged features. Features that can include intercooler, after-cooler, and/or air dryer elements
	· Able to achieve 80/20 duty cycle
	· Field tested; durable and known to operate in the cold condition
Concept #3 (Rotary Screw, Oil-Free)	· The containment unit usually features acoustic dampening walls
	· Features smart control – a diagnostics, data collection system.
	· Variable speed drive options exist. Allows for a wider operating envelope.
	· Complete air systems packaging offered. Can produce clean, dry air in a single package.
	· Design is kept compact, but room is accommodating to maintenance
	· Achieves Class 0 air quality designation
Concept #4 (Rotary Screw, Oil-Injected)	· Similar to Concept #3.
	· Self-containing feature takes care of the compressor unit layout. Ensuing a safe operating system
	· Power outage restart option
	· Outdoor enclosure, built to handle cold ambient conditions
Concept #7 (Scroll, Oil-Free)	· Features graphics controller for easy control and monitoring of the system.
	· Automatic start/stop when the required pressure is reached
	· Quiet and smooth running.
	· Diverse product packaging. Accessories are optional, either can a part of or not part of the package.
	· Achieves Class 0 air quality designation

The advantage of finding a complete package that contains the appealing features and uses the proposed air compressor for a given concept is realized by considering the intricacy of designing such a system from the ground up. The product placement for each component in the functional layout has been tested and proven to work. For this reason, the concepts were developed as per product packaging and assumed to contain the appealing features. Based on this, Concept #3 and #4 lend the most convenience and have high ease of use ratings. Concept #7 also has graphics interfacing, making for a hassle free design. Due to the limited intelligent control of Concepts #1 and #2, the assigned ease of use is lower than that of other concepts.

In the following section there contains the evaluation matrix, which determines the weighted score by taking the product of the assigned weight on the selection criteria and the relative rating and subsequent ranking.

C-3.2.8 Air Compressor Evaluation

The following table is the collective ranking of the proposed concepts. Note that a rating of one is considered low (not desirable) and a rating of five as high (desirable):

TABLE C-21. EVALUATION MATRIX FOR AIR DELIVERY SYSTEM

Test Rig Subsection: Air Delivery System											
		Concept #1		Concept #2		Concept #3		Concept #4		Concept #7	
Selection Criteria	Weight (%)	Rating	Weighted Score	Rating	Weighted Scroe	Rating	Weighted Scroe	Rating	Weighted Scroe	Rating	Weighted Scroe
Size	10	5	50	1	10	2	20	2	20	4	40
Cost	20	3	60	3	60	1	20	1	20	2	40
Toublesooting Time	15	3	45	3	45	3	45	1	15	3	45
Safety	15	2	30	2	30	4	60	4	60	5	75
Reliability	10	2	20	2	20	5	50	5	50	4	40
Performance	20	2	40	3	60	4	80	5	100	3	60
Ease of use	10	2	20	2	20	5	50	5	50	3	30
Total Score			265		245		325		315		330
Rank			**4**		**5**		**2**		**3**		**1**
Continue							**YES**		**YES**		**YES**

Based on the outcome of the static evaluation matrix, Concept #7 achieved a final score of 3.3, receiving the highest score of the five proposed concepts. In order of succession in descending fashion, second place ranking is given to Concept #3, having final score of 3.25. The third placed rank goes to Concept #4, achieving a final score of 3.15.

C-3.2.9 Air Delivery System Summary and Design Consideration

The selected air compressor to be used in the air delivery system is the highest scoring alternative – Concept #7. The important parameters and strengths of this concept are listed below:

- *Compressor Model Description*: Scroll compressor.
- *Cooling scheme*: Air-cooled
- *Lubrication environment*: Oil-free
- *Control Systems*: Semi-Automatic

- *Power System*: Fixed speed drive

Strengths

- Quiet and smooth running
- Can supply continuous, and clean, dry air
- No chance of direct transfer of oil; only due to abrasion, points of contact (high-pressure regions) eventual breakdown.
- Can be equipped with multiple scroll to achieve variable air delivery; this feature is controlled
- When the required modules working pressure is reached, an automatic starts/stops valve is actuated
- Ability to monitor and control unit

C-3.3 Water Heating System

The water heating system is responsible for rising the deionized water temperature to the required operating temperature of 180°F (82.2°C) at a flow rate of 0.33 GPM for a single nozzle and 1 GPM for all three nozzles. In the following sections, alternative concepts are generated and screened for water heater fuel sources and a comparison of tank and inline systems is provided.

C-3.3.1 Energy Source

The following section will determine an energy source that will drive the heating process. Both gas and electric energy sources are considered.

For a gas fired burner, either natural gas or propane would be required. These fuel sources can be electronically regulated to get an optimal discharge temperature, and can be automatically controlled using temperature sensors.

For an electric resistance heater, no additional energy source would be required, since electricity is already driving other components of the test rig. Additionally, similar to the gas system, the flow of energy into the electric resistance heater can be regulated and controlled automatically. Furthermore, electric heaters cost less than gas systems [11], and have slightly higher performance efficiency [12].

To compare these designs, they were applied to the following scoring matrix:

TABLE C-22. WATER HEATER ENERGY SOURCE SCORING MATRIX

Test Rig Subsection: Water Heater					
Criteria	**Weight (%)**	**Concept #1 Electric Score**	**Concept #1 Electric Weighted**	**Concept #2 Gas Score**	**Concept #2 Gas Weighted**
Implement Cost	15	4	60	3	45
Occupying Space	15	4	60	4	60
Ventilation	10	5	50	1	10
Maintenance	10	4	40	2	20
Energy Efficiency	20	4.5	90	4	80
Heating Potential	30	4	120	5	150
Total Score	**100**	**25.5**	**420**	**19**	**365**
Rank		**1**		**2**	

The scoring matrix shows that electric heat is the optimal energy source for the heating system. When compared to the gas alternative, an electric heating system costs less to procure, operate, and maintain, and requires no additional ventilation considerations.

C-3.3.2 Heater System

With an electric heater established as the optimal energy source, several different heater configurations were considered. This section first outlines concepts for electric heaters, then selects an optimal concept for the final design. The water heater configurations evaluated in this section are: a water tank with integrated heaters, a tank-less water heater (referred to as an inline system), multiple inline heaters in series, and a combination of a water tank and inline heaters.

The first concept considered is a water tank heating system. This type of system offers water storage and heating in one contained unit. Combining the two components results in a more compact design. Furthermore, commercial grade water heaters can meet the 180°F temperature [13]. The disadvantage of implementing a tank style water heater is the startup time. Testing cannot be performed until all the water in the tank is heated to operating temperature. As a result, this water heating process is slower when compared to other concepts. Alternatively, to reduce startup time, water must be stored in the system at elevated temperatures at all times. Continually storing water at the test temperature would result in a significant operating cost increase. Additionally, testing will have to halt if the system requires refilling. The fresh water will require time to come to temperature after refilling the tank before testing can continue.

The next concept considered is an inline heating system. These types of systems heat water only while water is flowing through their coil banks. These systems provide instant hot water, therefore removing startup time. Factors to consider when selecting an inline heating system consider are: the minimum and maximum flow rates, the required temperature rise, and the maximum output temperature. Commercial grade units can meet the required design parameters including supply temperature [13]. The disadvantage to this concept is being able to meet all the performance criteria in a single unit. Generally, to meet the required design criteria using a single unit will incur a high procurement cost [14]. Finally, when considering the same volume of water, inline systems compared to tank based heaters have very similar performance efficiency ratings [15]. Since the efficiency ratings are similar between the two systems, efficiency becomes a moot point.

Next, inline series heater concepts are considered. These systems use two or more inline heaters in series. By using smaller, more cost-effective heaters in series, the required system outlet temperature can be achieved [14]. The disadvantages of this type of system are the increased number of components, and the increase in design complexity. In addition, the higher number of components and greater complexity results in a greater risk of system failure and reduces the reliability of the system.

Finally, the combined tank and inline series concept is evaluated. This concept uses a heated water storage tank to elevate and store the water temperature at a midrange temperature, and an inline system is used to increase the water temperature to the required test conditions. This concept reduces the size of both the water tank heater and inline heater, relative to each of these systems independently. Thus, the cost of each individual component is reduced. Similar to the individual water tank concept, storing the water at an elevated temperature increases the operating cost of the system. As well, if the rig needs to be refilled mid test cycle, the refilled water tank will require time to return to operating conditions. However, the amount of time required will be lower that the isolated water heater system, due to the use of an additional inline heater.

TABLE C-23 shows the screening matrix used to evaluate the various different heater configurations.

TABLE C-23. WATER HEATER SYSTEM SCREENING MATRIX

Test Rig Subsection: Water Heater				
Criteria	Concept #1 Tank	Concept #2 Inline	Concept #3 Tank+Inline	Concept #4 Inline Series Baseline
Size	-	+	-	0
Cost	+	-	+	0
Toubleshooting Time	0	0	0	0
Safety	+	+	0	0
Reliability	+	+	0	0
Performance	-	+	0	0
Ease of use	+	+	0	0
"+" sum	4	5	1	0
"-" sum	2	1	1	0
"0" sum	1	1	5	7
Score	2	4	0	0
Rank	**2**	**1**	**3**	**3**

From this matrix, it can be seen that the single inline heater concept ranked best, followed by a single water tank.

To determine the final system concept, the top two ranked concepts are compared in a scoring matrix, shown in TABLE C-24, below. The factors for this matrix are the startup time, cost, response time for temperature changes, drainage time, complexity, performance to deliver required temperature, stored energy after emergency shut down, and energy efficiency. All factors are scored on a value of 1 to 5, with 5 as the optimal score. A weighting criteria is then applied to the scores, which shifts each factor's value based on its design importance.

TABLE C-24. WATER HEATER SYSTEM SCORING MATRIX

Test Rig Subsection: Water Heater					
Criteria	Weight (%)	Concept #1 Tank Score	Concept #1 Tank Weighted	Concept #2 Inline Score	Concept #2 Inline Weighted
Startup Time	25	1	25	5	125
Response Time	25	1	25	5	125
Drainage Time	10	3	30	5	50
Complexity	10	5	50	5	50
Performance	10	5	50	5	50
Stored Energy	10	1	10	4	40
Energy Efficiency	10	4.5	45	4.5	45
Total Score	**100**	**20.5**	**235**	**33.5**	**485**
Rank		2		1	

The matrix illustrates that the single inline heating system will be the optimal concept to use in the final design.

The specific part selection for the final design's inline heating system is provided in the following section.

C-3.3.3 Water Heater Selection

In this section, a water heater is sourced that is capable of meeting the design requirements from an available supplier. Both Hubbell Electric Heater Company and Wattco were approached for quotes for inline water heaters. The specifications sent to both companies are summarized in the following table:

TABLE C-25. WATER HEATER SPECS AS SENT TO WATTCO

Description	Spec	Units
Inlet Temperature	32	°F
Outlet Temperature	180	°F
Min Flow	0.2	GPM
Max Flow	1.3	GPM
Fluid	deionized water	
Supply Voltage	240	V
Power Phase	1 or 3	

Based on the supplied specification, Hubbell recommended their 27KW TX027-3S commercial inline water heater for $3950 USD. Wattco recommended a special built 30KW industrial horizontal inline water heater with a control module for $5975.50 US. Both quotes are provided in Appendix F.

Since this test rig is an industrial application and reliability is a key design criteria, Wattco's industrial grade heater is recommended. Furthermore, the TRDC currently utilizes Wattco inline water heaters for the wind tunnel's spray mast set-up, and the Wattco heater is more appropriately sized after considering heat losses in the system, as described in Appendix D.

C-3.4 Measurement and Control System

For the conceptual design process, the measurement and control system for the test rig was broken down into four sub-categories:

- Flow measurement
- Pressure measurement
- Temperature measurement
- Controller, data logging and user interface

In the following sections, several concepts for each sub-category are considered and a final concept is selected from each of these categories.

C-3.4.1 Flow Measurement

Four types of flow measurement devices were considered and evaluated through an initial screening process. Each type, along with its general strengths and weaknesses are listed as follows:

- **Vortex Shedding**
  - Strengths: These devices are relatively accurate, as they are not sensitive to variations in process conditions. They have much lower wear compared to conventional flowmeters such as turbine meters. They also have relatively low initial and maintenance cost.
  - Weaknesses: They are not ideal for low flow applications, as a high Reynolds number is needed for flowmeter to function. They also present a relatively large pressure drop across the sensor.
- **Turbine**
  - Strengths: These devices are moderate in cost and good at reading low flows relative to the maximum rated flowrate. They are reliable in clean fluids and the most widely used type of flowmeter. Therefore, lots of variety and sourcing options are available.
  - Weaknesses: They present some pressure drop across the sensor. Turbine bearings eventually wear out.
- **Positive Displacement**
  - Strengths: These devices are accurate at low flow rates and able to handle large range of viscosities.
  - Weaknesses: They are relatively expensive and can present issues with pressure drop across sensor.
- **Paddlewheel**
  - Strengths: The cost of accuracy in these devices is low compared to most other flowmeters. They can also accommodate flow in either direction
  - Weaknesses: They are less accurate when measuring flowrates where the velocity profile is non-uniform and at lower flow rates.

Factors used in evaluating flowmeter types were cost, reliability and ability to measure low flow rates. Ease of integration was also initially considered but after doing some initial research on the aforementioned types of flow measurement devices, the group learned it is possible to source any of the concepts to contain an integrated pipe fitting, and therefore this factor would not change from type to type.

TABLE C-26. FLOW MEASUREMENT SCREENING MATRIX

Criteria	Vortex Shedding	Turbine	Positive Displacement	Paddlewheel (Baseline)
Cost	0	+	-	0
Reliability	0	+	+	0
Ability to measure low flow	-	0	-	0
"+" sum	0	2	1	0
"-" sum	1	0	2	0
"0" sum	2	1	0	3
Score	-1	2	-1	0
Rank	**3**	**1**	**3**	**2**

As seen in TABLE C-26, turbine style flowmeters are the best option for this application. Current flowmeters used at the TRDC are Flow Technology (FT) series turbine flowmeters and would therefore make a good selection for a final flow measurement device concept. Using the same source for flowmeters as the TRDC wind tunnel is beneficial to the instrumentation team as they are familiar with these flowmeters and likely already have a contact and schedule for maintenance and calibration of their current flowmeters.

C-3.4.2 Pressure Measurement

Five types of pressure measurement devices were considered and evaluated through an initial screening process and are as follows:

- **Bonded Foil Strain Gauge (BFSG)**: These are the most common type of pressure sensor. They are good for high pressures and have quick response time to changes in pressure and temperature. However, they become more expensive at lower pressures.
- **Sputtered Strain Gauge**: These devices come with added protection from harsh environments. They are like BFSG in that they have quick response time to changes in pressure and temperature but become more expensive at lower pressures.
- **Semiconductor Strain Gauge**: These devices have a longer lifespan compared to other strain gauge pressure sensors. Again, they are like BFSG in that they have quick response time to changes in pressure and temperature but become more expensive at lower pressures.
- **Variable Capacitance**: These devices do not require signal amplification and provide a linear output. However, they do not respond well to large changes in temperature.
- **Piezoelectric**: These devices have a rugged design and quick response time to changes in pressure. However, they are sensitive to external vibration.

Factors used to evaluate these concepts were cost, reliability and ease of use.

TABLE C-27. PRESSURE MEASUREMENT SCREENING MATRIX

Test Rig Subsection: Pressure Measurement					
Criteria	**BFSG**	**Sputtered**	**Semiconductor**	**Variable Capacitance**	**Piezoelectric (Baseline)**
Cost	-	-	-	0	0
Reliability	+	+	+	-	0
Ease of use	+	+	+	-	0
"+" sum	2	2	2	0	0
"-" sum	1	1	1	2	0
"0" sum	0	0	0	1	6
Score	1	1	1	-2	0
Rank	**1**	**1**	**1**	**5**	**4**

TABLE C-27 shows there is not a large difference in pressure measurement devices, besides the variable capacitance type. For this reason, the specific type of pressure sensor does not play an important role in sourcing.

Since TRDC currently uses Rosemount 2088 pressure transmitters, the group decided to source a transmitter from the Rosemount 2088 series for ease of installation and maintenance by the TRDC instrumentation team. Using the Rosemount 2088 Data Sheet [16], the group sourced two different types of flowmeters: one (2088 G 2 S 22 A 1 M4) with a digital display and one (2088 G 2 S 22 A 1) without.

C-3.4.3 Temperature Measurement

Five types of temperature measurement devices were considered and evaluated through an initial screening process and are listed as follows:

- **Thermocouples (K, J, E and T type)**: In general, thermocouples are low-cost, rugged and able to operate in a wide range of temperatures. They are somewhat less accurate in relation to other temperature measurement devices. The following table demonstrates temperature ranges and typical accuracies for each type of thermocouple [17]:

TABLE C-28. TEMPERATURE RANGES AND LIMITS OF ERROR FOR COMMON THERMOCOUPLES

[redacted]

- **RTD's (Resistance Temperature Detector)**: RTD's are much more accurate, with the tradeoff of having a higher cost.
- **Thermistors**: Thermistors are similar in both cost and accuracy to thermocouples, but tend to have a slightly higher cost with slightly higher accuracy.

Factors used to evaluate types of temperature measurement devices include cost, reliability, accuracy and ruggedness.

TABLE C-29. TEMPERATURE MEASUREMENT SCREENING MATRIX

Test Rig Subsection: Temperature Measurement						
Criteria	**K-Type Thermocouple**	**E-Type Thermocouple**	**J-Type Thermocouple**	**T-Type Thermocouple**	**RTD's**	**Thermistor (Baseline)**
Cost	+	+	+	+	-	0
Reliability	+	+	+	+	+	0
Accuracy	-	-	-	0	+	0
Ruggedness	+	+	+	+	0	0
"+" sum	3	3	3	3	2	0
"-" sum	1	1	1	0	1	0
"0" sum	0	0	0	2	1	5
Score	2	2	2	3	1	0
Rank	**2**	**2**	**2**	**1**	**5**	**6**

Based on the results from TABLE C-29, T type thermocouples scored best due to its higher accuracy in the desired range.

Since thermocouples output a small, non-linear analog signal, the group must also use either a PLC that accepts thermocouple inputs, or a separate thermocouple conditioner. The group's selection between these options is discussed in the following subsection.

C-3.4.4 Controller, Data Logging and User Interface

Before looking at specific PLC's (Programmable Logic Controllers) to use, the group identified the main functions that the controller would need to perform. Since the pump, air compressor and heating system selected all have integrated control systems, the control of these systems will not need to be done with an external PLC. However, monitoring and logging of the system parameters will still need to be accomplished, and sending a signal to cut power to the pump, compressor and heating elements must be achievable as part of an emergency stop procedure. The following are all the parameters that the PLC will need to monitor and log:

- Water pressure after pressure regulator (to determine system pressure)
- Water pressure before each nozzle (to identify a faulty nozzle)
- Water level in tank
- Water temperature before all three nozzles (one sensor for reference)
- Water flow through all three nozzles (one sensor for reference)
- Air pressure before each nozzle
- Air pressure after pressure regulator (to determine system pressure)
- Air temperature before all three nozzles (one sensor for reference)

In total, nine inputs will be required into the controller: one frequency, two voltage (or two thermocouple) and six current. Only one output is required, since the signal can later be split to send to the electric motor, the compressor and the heaters. Note, that no input is required to measure the water level in tank as the sourced tank did not have a level switch. Instead, the selected PLC must use the flowmeter to measure the water used and subtract that number (either continually, or in specified increments) from the known tank capacity.

In total, the group considered three concepts that would monitor and log data, and control the system. These concepts are described in detail as follows:

A-1 Automation Direct 'CLICK PLC' C0-02DD1-D ***($129)*** [18]: This is a low cost modular PLC with free software available. The controller itself has four discrete inputs, two analog inputs (current or voltage), four discrete outputs and two analog outputs (current or voltage). Separate I/O modules would be required, as well as a frequency to voltage converter for the flowmeter. Also, an external data logger would be required.

A-1 GE RX3i CPE330*(~$11,000)* [19]: This PLC is currently used by GE TRDC for various controls on the wind tunnel. It is a high-cost powerful modular controller capable of data storage. I/O modules are available for all required signal types. However, its high price makes it undesirable for this project.

A-1 National Instruments cDAQ-9174 *($1,205)* [20]: This is a medium cost modular PC-based PLC. 4 slots available for I/O modules, some can include built in signal conditioning. Data logging and user interface can be accomplished with software. However, software is approximately $4,000 which adds a considerable amount of cost to the design.

Criteria used to evaluate these concepts were cost, reliability, ease of use and performance. Criteria were then weighted considering relative importance. Attributed weights as well as the concept evaluation process is shown in the following table.

TABLE C-30. PROGRAMMABLE LOGIC CONTROLLER SCORING MATRIX

Test Rig Subsection: Flow Measurement							
		Automation Direct		GE RX3i		cDAQ	
Criteria	**Weighting**	**Score**	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Cost	**0.4**	5	2	1	0.4	3	1.2
Reliatility	**0.2**	4	0.8	5	1	5	1
Ease of Use	**0.1**	3	0.3	4	0.4	4	0.4
Performance	**0.3**	4	1.2	5	1.5	4	1.2
	Sum		4.3		3.3		3.8
	Rank	**1**		**3**		**2**	

TABLE C-30 shows the Automation Direct CLICK PLC was clearly the best option to move forward with. Since the CLICK series does not have a frequency input module available, the group chose to source a frequency to voltage converter. An example of a CLICK PLC system is shown in Figure C-2. Example of a CLICK PLC System and includes the PLC, several I/O modules and a power supply.

Figure C-2. Example of a CLICK PLC System [21]

Now that the Automation Direct C0-02DD1-D was selected, the group made the required considerations for I/O module selection, data logging and sourcing a frequency to voltage converter. The PLC module can accept 2 of the analog inputs (1 from frequency to voltage converter, one from a pressure transmitter) and the digital output. To accept the other seven analog inputs, the group selected two C0-04AD-1 4-channel analog current input modules [22]. To accept the two thermocouple inputs, the group selected one C0-04THM 4-channel thermocouple input module [23]. Finally, the group decided to source one C0-01AC power supply [24]. This power supply is designed specifically for the click PLCs, and can support any configuration of I/O modules connected to the PLC. It requires 110-240 VAC input and outputs 24 VDC.

To log data from the CLICK PLC, the group sourced the FC-LOG Data Logger from InterConnecting Automation Inc. [25].

Finally, the group sourced the LM2907 frequency to analog converter from Texas Instruments [26].

C-3.5 Mobility

The mobility section addresses the need for the test rig to be easily portable. Concepts generated to address this need were the use of: rolling casters, rolling casters with brakes, forklift slots, and rail systems.

The first concept considered is the use of rolling casters. Drawing from factory experience, the majority of jigs and factory equipment incorporate rolling casters to increase mobility. Vast quantities of casters are available, for all types of applications, weight limits, and terrains. The drawback with using casters are the increased cost and requirements for maintenance on the test rig itself, when compared to other concepts such as forklift channels.

The next concept considered is the use of rolling casters with brakes. Rolling casters with brakes meet the mobility requirements of the design, and also increase the design’s safety. However, by sourcing casters with brakes, the overall cost of the caster will increase [27]. Thus, a tradeoff is produced between the importance of safety and cost, which is analyzed further in the screening matrix.

Next the forklift lifting channel concept is considered. This concept is simple and cost effective to implement. However, this concept relies entirely on an additional piece of machinery for mobility. From a lean design perspective, increasing the amount of equipment required to complete a task will reduce the effectiveness and reliability of the design. An example of this situation is if the forklift is down for maintenance, the test rig can no longer be moved.

Finally, the last concept considered to meet the test rig’s mobility requirement is to use a rail or a track based system. Depending on the weight of the equipment to be moved, rails are advantageous for low friction mobility, and also prevent damage to shop floors. Rails would increase the safety of the design by having the test rig on a fixed course. However, the range of mobility would be drastically reduced when compared to other concepts. Finally, the infrastructure required for a rail base system would have an extensive cost associated to it, in comparison to the other methods.

TABLE C-31 shows the screening matrix used to evaluate the various different mobility concepts for the test rig design.

TABLE C-31. MOBILITY SCREENING MATRIX

Test Rig Subsection: Mobility				
Criteria	**Concept #1 Casters with Brakes**	**Concept #2 Fork Lift Slots**	**Concept #3 Rail System**	**Concept #4 Casters Baseline**
Size	0	0	0	0
Cost	-	+	-	0
Toubleshooting Time	0	0	0	0
Safety	+	0	+	0
Reliability	+	+	0	0
Performance	+	+	-	0
Ease of use	+	+	+	0
"+" sum	4	4	2	0
"-" sum	1	0	2	0
"0" sum	2	3	3	7
Score	3	4	0	0
Rank	**2**	**1**	**3**	**3**

From this matrix, it is concluded that fork lift slots rank best, followed by casters with brakes.

To further evaluate which concept to include for the final design, specific criteria for mobility and outlying factors are identified. The criteria include be: cost associated with all labors and equipment for moving the test rig, ease for operator to move the rig, precision level of the move, how safe the moving procedure is, total maintenance cost, and total time taken for the moving procedure, and the setup cost. The criteria are scored from 1 to 5, with 5 being the optimal score. The score is then weighted based on the factor's importance to the overall design. The concept with the highest weighted score is considered the optimal concept for the final design. The results of the scoring process are presented in the following table:

TABLE C-32. MOBILITY SCORING MATRIX

Test Rig Subsection: Mobility					
Criteria	Weight (%)	Concept #1 Casters with Brakes Score	Concept #1 Casters with Brakes Weighted	Concept #2 Fork Lift Slot Score	Concept #2 Fork Lift Slot Weighted
Cost to Move Rig	20	5	100	1	20
Ease of Move	10	3	30	4	40
Precision of Move	10	3	30	3	30
Safety of Move	20	4	80	2	40
Maintenance Cost	15	4	60	2	30
Time Taken to Move	15	4	60	4	60
Setup Cost	10	3	30	5	50
Total Score	**100**	**26**	**390**	**21**	**270**
Rank		**1**		**2**	

The scoring matrix shows that casters with brakes are the optimal design for the test rig. As a result, detailed design aspects using casters with brakes are considered in the body of the report.

C-3.6 Insulation

An important need of the test rig is for it to consistently deliver water and air flows at the required test temperature. Heater concepts are reviewed in section C-3.3 , however, to maintain the elevated temperatures through the piping systems, additional insulation may be required. The addition of insulation is also intended to reduce the safety risk of exposed, high temperature components. Throughout this section, insulation concepts are evaluated and the recommended amount of insulation around piping components is justified through analytical heat transfer calculations.

C-3.6.1 Insulation Concept Evaluation

The three different insulation concepts considered are: no insulation, fiberglass insulation and polyethylene insulation.

No insulation is considered for sections of piping that do not carry high temperature fluids. These locations include the water storage tank, and the pipe line leading from the water tank to the water heater. Additionally, no insulation is used as a baseline for the comparison of insulation types for the high temperature regions. No insulation offers the most cost-effective option, though excessive heat loss reduces the temperature of the water delivered to the nozzles and presents a high safety risk for the operators.

The next concept considered is fiberglass insulation with a polymer jacket. Fiberglass is suitable for high temperature applications, and can withstand the temperatures form the test rig [28]. This concept offers the highest thermal conductivity (k value) of all the alternatives [29]. The drawback to this concept is that it also has the highest cost per foot [30]. This form of insulation comes in commercial rolls with a slit that gets slipped over the pipe, and is then wrapped with a polymer jacket that adheres to the fiberglass, locking the fiberglass in place.

The other concept considered is polyethylene. Polyethylene can withstand the testing temperature of the test rig [28], and offers improved thermal conductivity [31] compared to bare pipe, at an intermediate cost [31].

TABLE C-33 shoes the concept screening matrix used to select between the insulation alternatives.

TABLE C-33. INSULATION SCREENING MATRIX

Test Rig Subsection: Insulation			
Criteria	**Concept #1 Exposed Pipe**	**Concept #2 Fiberglass**	**Concept #3 Polyethylene Baseline**
Size	+	0	0
Cost	+	-	0
Toubleshooting Time	0	0	0
Safety	-	+	0
Reliability	-	+	0
Performance	-	+	0
Ease of use	0	0	0
"+" sum	2	3	0
"-" sum	3	1	0
"0" sum	2	3	7
Score	-1	2	0
Rank	**3**	**1**	**2**

The matrix shows that, when insulation is required that fiberglass insulation is the optimal choice.

Thermal analyses are provided in Appendix D to how thick of insulation is required on the high temperature components of the test rig. .

C-3.7 Frame Material and Geometry Selection

The frame housed the components for the test rig and provides a structural platform for component mounting.

Concept generation ideas for the frame materials and cross-sections included: round steel tubing, rectangular steel tubing, steel U channels, steel I beams, solid steel bars, machined blocks, and wood.

Steel was selected as the common metallic material to narrow down the initial screening process. This selection ensures that the test rig made from durable components, and provides adequate mechanical properties such as strength, availability, and machinability, in a cost effective manner [34].

The first geometry concept considered is round tubing. Round tubing offers similar mechanical performance as solid round bars and rectangular tubes. However, round tubes offer a greater stiffness to weight ratio than solid round bars, or rectangular tubing when the same weight per foot and wall thickness are used. The round cross-section does not have extra material where zero or minimal stresses occur [35]. These minimal stress locations occur in the corners of square cross sections, or near the centerline of the cross-section. Thus, the round hollow geometry contains less wasted material, and the shape is more efficient when compared to square or solid stock. The drawbacks to round tubes are that they complicate the design of brackets for joints, and require complex cutting techniques for welded unions.

The second geometry concept considered is rectangular or square tubing. This geometry offers simpler working techniques for joining members then round tube. Additionally, flanges, plates and other components can easily be mounted to flats on the rectangular tubes. Finally, these tubes offer similar performance to solid bars, but at a reduced weight [35].

The third geometry concept considered are U Channels. U-channels offer similar properties as rectangular tubing, but at a lesser weight [35]. Design considerations are needed to ensure that U-channels are oriented properly such that the material is used to its full potential. This adds complexity to the design optimization [35]. Furthermore, the mounting surfaces of the material are reduced compared to rectangular tubing.

The fourth geometry concept considered are I beams. If used properly, I-beams can meet the strength of the previously mentioned cross-sections, but with a lower weight [35]. Ideally, an I beam requires the load to be applied down along the web of the beam [35]. Therefore, the use of I beams will require additional care during the design stage.

The fifth geometry concept considered is solid bars. This cross-section offers a baseline for material property, and weight selection [35]. Solid bars provide best resistance to corrosion, due to the limited amount of exposed material, and eliminating any internal locations for moisture to collect.

The sixth geometry concept considered is a machined block. Machined blocks offer a seamless design, though would make transporting the frame to the testing site difficult. This concept would also have the highest relative cost due to the amount of machining and material removal required.

Finally, the last concept considered is wood. Wood offers the lowest relative cost [36]. The major drawback to this design is that wood's mechanical properties cannot be granted as accurately as metal. Additionally, wood is subject to swelling in moist environments, as well as deforming if not supported properly.

The following concept screening matrix used to select between the frame material and cross-sectional geometry alternatives.

TABLE C-34. FRAME MATERIAL SCREENING MATRIX

Test Rig Subsection: Frame							
Criteria	**Concept #1 Round Tube**	**Concept #2 Rectangular Tube**	**Concept #3 U Channel**	**Concept #4 I beam**	**Concept #5 Solid Bar**	**Concept #6 Solid Block**	**Concept #7 Wood Baseline**
Size	0	0	0	0	0	0	0
Cost	-	-	-	-	-	-	0
Toubleshooting Time	0	0	0	0	0	0	0
Safety	+	+	+	+	+	+	0
Reliability	+	+	+	+	+	+	0
Performance	+	+	+	+	+	+	0
Ease of use	-	0	-	-	-	-	0
"+" sum	3	3	3	3	3	3	0
"-" sum	2	1	2	2	2	2	0
"0" sum	2	3	2	2	2	2	7
Score	1	2	1	1	1	1	0
Rank	**2**	**1**	**2**	**2**	**2**	**2**	**3**

The matrix shows that rectangular steel tube is the optimal material choice. The exact grade of steel, and the member cross sections and wall thicknesses are selected in the following section.

C-3.7.1 Selection of Cross-Sectional Frame Dimensions

This section advances the rectangular geometry chosen in the concept selection by determining the material outside dimension, and grade. The wall thickness is based off calculations provided in Appendix D.

In order to simplify manufacturing and assembly, a square rectangular cross section was selected. By having a symmetrical cross-section complexity in part manufacturing is reduced. Additionally, by selecting a square cross-section, hardware selection is simplified. Furthermore, a 2x2” tube will be selected to minimize excessively long hardware requirements and to accommodate standard drill bit lengths.
For grade of steel, A513 was selected. A513 steel is was chosen for it’s: commonly availability, good welding and machining characteristics, and is suitable for structural applications [37]. Additionally, from Metals Depot the required 2x2” square tube is available in a variety of gauges, with pricing for variable lengths [37].

The material properties for A513 are as follows:

- Young’s Modulus of Elasticity is between 27557-30458 Ksi, average modulus is 29007.56 Ksi [38]
- Yield strength is 84.1 ksi [38]
- Density is 0.282 lb/in^3 [39]

The values listed above for A513 are consistent with values for alternative steels listed in Tables found in Appendix B of “*Mechanics of Materials”* [40]. This text book was also used to derive the analytical analysis equations provided in Appendix D.

C-4 References

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APPENDIX D

Design Calculations

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D-1 Introduction

This appendix presents the design calculations performed throughout the component selection and validation processes of the design project. The calculations are referenced within the body of the report, and are summarized here for convenience for interested readers.

D-2 Minimum Pipe Thickness Calculations

Several standard piping wall thicknesses exist at that outer diameter, and different sizes of pipe cross-sections are referred to as schedules. Common 3/8" stainless steel pipe schedules range from the thinnest 10S up to 80S for heavy duty applications. As the schedule is increased, the outer diameter of a nominal pipe size remains constant, while the inner diameter decreases. Therefore, an appropriate pipe schedule was determined by first checking the minimum thickness requirements and then adjusting that value up to a standard size.

Piping standard, ASME B31.1 [3, 3] was consulted to determine the minimum allowable pipe wall thicknesses for the design's maximum operating pressure. The following equation is presented in the standard to calculate the minimum wall thickness for length of straight pipe under a given internal pressure:

$$t_m = \frac{PD_o}{2(SE + Py)} + A \qquad \text{(D1)}$$

where, P is the internal design pressure, D_o is the outside diameter of the pipe, SE is the maximum allowable stress (13.4 ksi for 304 stainless at 200°F), y is a correction factor (equal to 0.4 for austenitic steels), and A is additional thickness to account for material removed in threading, grooving, etc. or to account for erosion and corrosion.

Assuming minimal corrosion allowances for the selected corrosion resistant stainless steel material, the minimum wall thickness for the highest design operating pressure of 100 psig is calculated as:

$$t_m = \frac{100(0.675)}{2\left(13400 + 100(0.4)\right)} \rightarrow t_m = 0.003"$$

Therefore, from a design pressure standpoint the thinnest available schedule 10S pipe is more than adequate with a wall thickness of 0.065". However, threaded pipe was only found from suppliers starting at schedule 40S [1], [2]. As a result, schedule 10S pipe would require the use of butt-weld fittings, but threaded fittings were preferred to minimize the difficulty of assembly and disassembly for maintenance. Therefore, the final pipe cross-section selected for the majority of the pipe routing is size 3/8", schedule 40S having a nominal wall thickness of 0.091".

D-3 Maximum Unsupported Pipe Length Calculations

Threaded adapters and fittings are used as necessary for the integrated design's pipe routing. In this section, calculations for the maximum allowable loads between pipe supports are presented.

The maximum allowable distance between fixtures to support the weight of the piping system was calculated using the following equations (from ASME B31.1 [3]):

$$S_L = \frac{PD_0}{4t_m} + \frac{0.75iM_A}{Z} \qquad \text{(D2)}$$

$$S_L \leq SE \qquad \text{(D3)}$$

Here, S_L represents the maximum longitudinal stress in the pipe's cross-section due to internal pressure and the bending moment from transverse loads; i is a stress intensification factor (to account for stress concentrations at fittings or bends); M_A is the resultant moment on the cross-section due to weight and any other sustained loads; and Z is the section modulus (equal to 0.02160 in^3 for 3/8" 40S pipe).

The simplified load case considered is pictorially shown in Figure D-1, below.

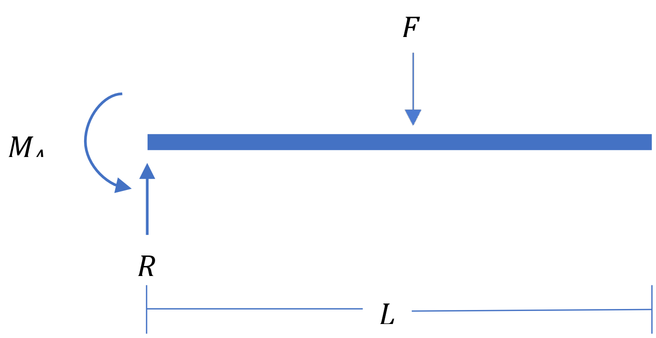

Figure D-1. Simple schematic of pipe vertical pipe loading

In Figure D-1, F represents the weight of the unsupported (water filled) piping, and L is the maximum unsupported length that can be run off of a fitting (providing reaction force R, and reaction moment M_A). For the selected threaded fittings, ASME 31.1 recommends using a stress intensification factor of 2.3.

The bending moment at the fitting in the simplified load case is calculated as

$$M_A = wL\left(\frac{L}{2}\right) = \frac{wL^2}{2} \qquad \text{(D4)}$$

where, w is the per foot weight of the piping. The pipe material itself weighs 0.57 lbs/ft and the corresponding amount of water in the pipe weighs 0.083 lbs/ft [4] for a total weight of 0.653 lbs/ft, or 0.0544 lbs/in.

Therefore, Eq. (D2) can be rearranged to show:

$$L = \sqrt{\frac{2(S_L - \frac{PD_0}{4t_m})Z}{0.75iw}} \qquad \text{(D5)}$$

Inserting values for the chosen pipe material and cross-section at a maximum design pressure of 100 psi and a conservative temperature of 200°F:

$$L = \sqrt{\frac{2\left(13400 - \frac{100(0.675)}{4(0.091)}\right)0.0216}{0.75(2.3)(0.0544)}}$$

$$L = 78'' = 6'\,6''$$

Thus, at a minimum, supports should be placed between every six and a half feet of unsupported piping. This length of pipe corresponds to a maximum allowable bending moment of:

$$M_A = \frac{0.0544(78.0)^2}{2} = 165.5 \text{ lb-in}$$

Therefore, the maximum allowable bending moment from any fittings or equipment placed between supports is 165.5 lb-in.

D-4 Heater Size Justification

To confirm the heater unit size, the total minimum energy to heat the water is calculated in this section. The following equation determines the heat flux required based on the mass flow rate and specific heat of water, along with the temperature required temperature rise:

$$q_w = mC_p(T_{out} - T_{in}) \qquad \text{(D6)}$$

Where q_w is the heat flux, m is the mass flow rate, c_p = 4199 [J/KgK] is the specific heat of water at 355K [5], and T is the water inlet and outlet temperatures. The water is heat water from 0 to 82.2°C, at a flow rate of 1.3 gpm (0.08 kg/s). Selecting a minimum value of 0°C and a flow rate of

1.3 gpm provides margin with respect to the nominal operating conditions of the test rig. The required heater size is therefore calculated as:

$$q_w = mC_p(T_{out} - T_{in}) = 1.3 * 4199 * (82.2 - 0) = 27.6\ kw$$

Therefore, the heater requires approximately 27.6 kW to raise the water temperature to the operating conditions. If losses are considered, then the Wattco quote is a sufficiently sized heater.

D-5 Insulation Thickness Calculations

In this section, a justification for the use of insulation in high temperature regions is provided, followed by analytical heat transfer analyses to determine the required insulation thickness.

First, a high temperature region is defined as a section of pipe that can cause a burn on human skin. A burn can occur in less than a second from a surface at 80°C, or at 44°C over a longer period of time. Since the required temperature of the test rig's working fluids is 82.2°C, the risk of burning on the outer surface of the piping systems is clearly possible.

By setting the design surface temperature at 44°C, heat transfer calculations can be performed to determine the required insulation thickness. A safety factor is applied to the calculated insulation thickness, to ensure that the surface temperatures do not exceed 44°C.

The following heat transfer calculations are derived from "*Fundamentals of Heat and Mass Transfer*" [5]. The heat transfer mechanisms identified are: fully developed turbulent convective internal flow from the heated water, conduction through the pipe wall and insulation, and free convection to air outside the pipe. Since a low value for emissivity and the external pipe surface temperature is assumed, radiation off the pipe is neglected. Furthermore, thermal effects from the insulation jacket are neglected due to the jacket's low thermal resistance and minimal thickness.

The thermal conductivity represented by K, were found for: 304 stainless steel K_{ss} = 14.9 [W/mK] [5], water K_w = 0.671 [W/mK] [5], and fiberglass insulation K_{ins} = 0.0358 [W/mK] [6]. The properties of water were taken at 355K (82.2°C) and are summarized in the following table:

TABLE D-1. PROPERTIES OF WATER AT 355K [5]

Term	Value	Units
kinematic viscosity [ν]	$1.03*10^{-3}$	m^2/s
dynamic viscosity [μ]	$343*10^{-6}$	Ns/m^2
specific heat [C_p]	$4.199*10^3$	J/KgK
thermal conductivity [K_w]	$671*10^{-3}$	W/mK
Prandtl Number [Pr]	2.14	

The properties of air were assumed at a worst case to shed heat from the test rig, via an indoor, stagnant environment. Thus, the room temperature was set at 293K (20°C). The heat transfer coefficient of static gases (air) range between 2-25 [W/m^{2}K] [5]. This heat transfer coefficient, represented by h_∞ in the following calculations is assumed to be the average of the previous range, resulting in h_∞ = 13.5 [W/m^{2}K]. The following image, illustrates the situation described above:

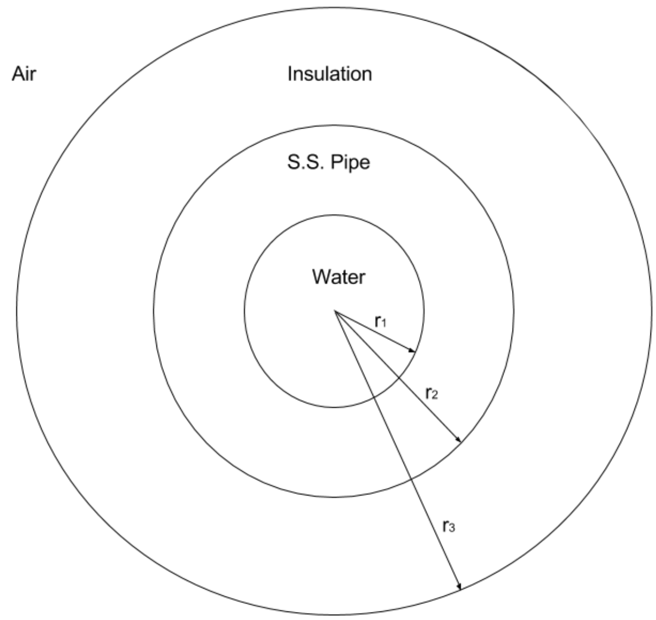

Figure D-2. Heat Transfer Diagram

Where r_1 = 12.5212 mm is the inner pipe radius where the 355K water will flow through, r_2 = 17.145 mm is the outer radius of the 304 stainless steel pipe, r_3 is the outer radius of the insulation, and the surrounding environment is 297K static air. The calculations solve for the required insulation outer radius (r_3) that will yield a 44°C surface temperature. The following thermal resistance network was created to represent the scenario shown in Figure D-2:

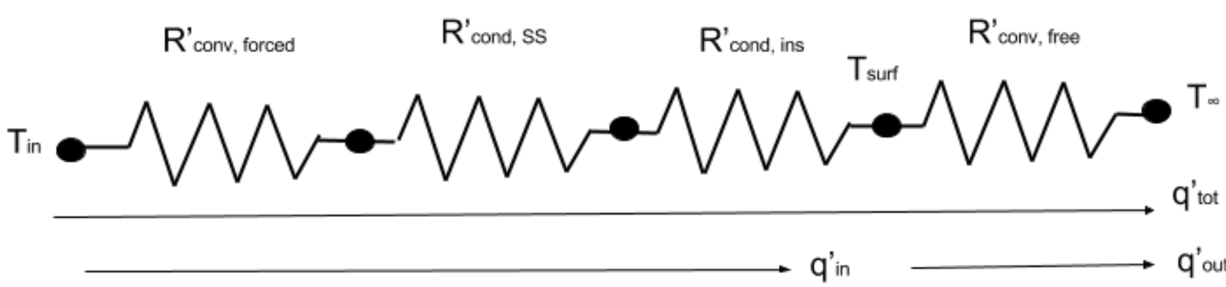

Figure D-3. Thermal Resistance Network for Piping System

Where T_{in} = 355K is the temperature of the water, T_∞ = 297K is the temperature of the ambient air, $R'_{conv, force}$ is the thermal resistance per unit length from forced convection from the fluid flow, $R'_{conv, free}$ is the thermal resistance per unit length from free convection from the ambient air, $R'_{cond, SS}$ is the thermal resistance per unit length of the conduction from stainless steel pipe, $R'_{cond, ins}$ is the thermal resistance per unit length of the conduction from fiberglass insulation, q'_{tot} is the total heat transfer per unit length for the system, q'_{in} is the heat transfer gain per unit length of the outer surface of the insulation and q'_{out} is the heat transfer loss per unit length from the outer surface of the insulation.

The following equations are derived from "*Fundamentals of Heat and Mass Transfer"* [5], in accordance to the situation above. First, the equation for the total heat transfer per unit length is presented:

$$q'_{tot} = \frac{A(T_{in} - T_\infty)}{R'_{tot}} \tag{D7}$$

Where A is the surface area per unit length at the outer insulation radius, and R'_{tot} is the total thermal resistance. Since the thermal resistance network is in series, the thermal resistances can be combined into R'_{tot} through summation:

$$R'_{tot} = R'_{conv,forced} + R'_{cond,ss} + R'_{cond,ins} + R'_{conv,free} \tag{D8}$$

The thermal resistances for the convection terms are described by the following equation:

$$R'_{conv,x} = \frac{1}{hA} \tag{D9}$$

Where h = $\bar{h}$ which is the average heat transfer coefficient for forced convection, and the surface areas are for each respective location were the resistance takes place. The thermal resistances for the conduction terms are calculated as:

$$R'_{cond,x} = \frac{\ln\left(\frac{r_{outer}}{r_{inner}}\right)}{2\pi K_x L} L \tag{D10}$$

In order to get a value for $\bar{h}$ for forced convection, a Nusselt number $\overline{Nu}$ for the flow is required. The equation relating $\bar{h}$ to the Nusselt number is shown below:

$$\bar{h} = \frac{\overline{Nu} K_w}{D} \tag{D11}$$

Where D is the diameter of the pipe containing the fluid. To determine a Nusselt number, a Reynolds Number Re_D is required.

$$Re_D = \frac{\text{mD}}{\mu A_c} \tag{D12}$$

Where m is the mass flow rate = 0.063 Kg/s, and A_c is the cross-sectional area of the pipe. With the Reynolds number, the following empirical correlation is used to find the Nusselt number:

$$\overline{Nu} = \frac{\left(\frac{f}{8}\right)(Re_D - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)} \qquad \text{(D13)}$$

Where f is the friction factor, Pr is the Prandtl Number. This empirical equation provides a Nusselt Number with +/-10% accuracy. Furthermore, the equation is only valid if the following conditions are met:

$$3000 \leq Re_D \leq 5 * 10^6 \qquad \text{(D14)}$$

$$0.5 \leq Pr \leq 2000 \qquad \text{(D15)}$$

$$L/D \geq 10 \qquad \text{(D16)}$$

The following equation is used to find the friction factor:

$$f = (0.790 LnRe_D - 1.64)^{-2} \qquad \text{(D17)}$$

Now that the total heat transfer can be accounted for the system in terms of r_3, the required length of r_3 to achieve a maximum surface temperature of 44°C is calculated as follows.

Since the heat transfer value is equal at all temperature nodes, the heat transfer leaving the insulation surface can be set equal to the total system heat transfer:

$$q'_{out} = q'_{tot} \qquad \text{(D18)}$$

Where q'_{out} is equal to $q'_{conv,\ free}$.

$$Re_D = \frac{\text{mD}}{\mu A_c} = (0.063 * 12.5 * 10^{-3})/(343 * 10^{-6} * \frac{\pi}{4} * (12.5 * 10^{-3})^2)$$
$$= 18675.658$$

$$\frac{L}{D} = \frac{L}{12.5 * 10^{-3}} \geq 10$$

Re_D > 2300 therefore the flow is turbulent, and conditions (D14), (D15), (D16) are met for any lengths greater than 0.125 m. Since the conditions are met, equation (D13) can be applied to solve for the Nusselt number.

$$f = (0.790 LnRe_D - 1.64)^{-2} = (0.790 Ln18675.658) - 1.64)^{-2} = 0.026615$$

$$\overline{Nu} = \frac{\left(\frac{f}{8}\right)(Re_D - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{\frac{1}{2}}\left(Pr^{\frac{2}{3}} - 1\right)} = \frac{\left(\frac{0.026615}{8}\right)(18675.658 - 1000) * 2.14}{1 + 12.7\left(\frac{0.026615}{8}\right)^{\frac{1}{2}}\left(2.14^{\frac{2}{3}} - 1\right)}$$
$$= 84.8038$$

$$\bar{h} = \frac{\overline{Nu}K_w}{D} = \frac{84.8 * 671 * 10^{-3}}{12.5 * 10^{-3}} = 4544.2 \ \frac{W}{m^2K}$$

$$R'_{conv,froced} = \frac{1}{hA} = \frac{1}{4544.2 * \pi * 12.5 * 10^{-3}} = 0.005594K/w$$

$$R'_{conv,freex} = \frac{1}{hA} = \frac{1}{13.5 * \pi * r_3} = \frac{0.02358}{r_3}$$

$$R'_{cond,ss} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi K_{ss}L}L = \frac{\ln\left(\frac{17.145}{12.522}\right)}{2\pi * 14.9} = 0.003356K/w$$

$$R'_{cond,ins} = \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi K_{ins}L}L = \frac{\ln\left(\frac{r_3}{17.145 * 10^{-3}}\right)}{2\pi * 0.0358}$$

$$= 4.446 \ln\left(\frac{r_3}{17.145 * 10^{-3}}\right) K/w$$

$$R'_{tot} = R'_{conv,forced} + R'_{cond,ss} + R'_{cond,ins} + R'_{conv,free}$$

$$= 0.005594 + 0.003356 + 4.446 \ln\left(\frac{r_3}{17.145 * 10^{-3}}\right)$$

$$+ \frac{0.02358}{r_3} = 0.00895 + \frac{0.02358}{r_3} + 4.446 \ln\left(\frac{r_3}{17.145 * 10^{-3}}\right)$$

$$q'_{tot} = \frac{A(T_{in} - T_\infty)}{R'_{tot}} = \frac{\pi r_3^2 (82.2 - 20)}{0.00895 + \frac{0.02358}{r_3} + 4.446 \ln\left(\frac{r_3}{17.145 * 10^{-3}}\right)}$$

$$q'_{out} = q'_{tot} \rightarrow \frac{\pi r_3^2 (82.2 - 20)}{2}$$

$$= \frac{\pi r_3^2 (82.2 - 20)}{0.00895 + \frac{0.02358}{r_3} + 4.446 \ln\left(\frac{r_3}{17.145 * 10^{-3}}\right)}$$

$$r_3 = 0.0262195m$$

From the above calculations, it is concluded that an external radius (r_3) of 26.2 mm is required to ensure that the exposed surface temperature is maintained under 44°C. The minimum required insulation thickness is then:

$$t = r_3 - r_2 = 26.22 - 17.145 = 9.07\ mm$$

Therefore, a minimum insulation thickness of 9.07mm is required over the nominal 3/8" pipe sizes selected for the water system.

D-6 Analytical Analysis of Frame

This section analyzes the members in the frame that experiences the highest stress potential. The frame is 6x4 feet to ensure enough room for equipment and service workers. The 6 foot run consists of two symmetrical beams running the length of the test rig on either side. For analysis purposes, the two members will be assumed to support the entire equipment load as an evenly distributed load. Furthermore, as stated in the body of the report, a common tube material will be utilized to minimize manufacturing complexity. Since all members are the same material and geometry, the location most likely to experience material failure is the longest span. The 6-foot side member is the longest span experiencing loading. Therefore, the analytical analysis will focus on these two members. In addition to the distributed equipment load, two 200 LBS service worker loads will be applied, and the weight of the frame itself is accounted for in the numerical solver. The worker load will act as a point load acting at the center of each span. The minimum required safety factor for the analysis is 1.5.

Due to symmetry of the beams, the analysis can be simplified to one member. The one member will see half of the distributed equipment load, and half of the point load. The beams are both supported by casters at each end. One locked caster on the left will act as rigid pin support. The caster on the right will be unlocked, and will act as a rolling pin support. The analysis is visualized by the following figure:

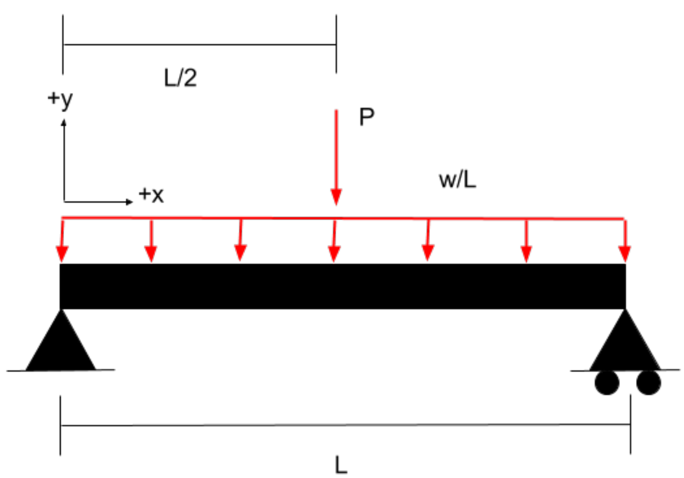

Figure D-4. Member Loading Case Depiction

Where L is the length of the member (= 72 in), w/L is the estimated distributed load (= 325 LBS/72in = 4.51 lbs/in), P is the point load (= 200 lbs) applied at 36 in from either end.

For the analysis, the failure criteria of the frame will be determined by the yield stress of the steel, including a minimum safety factor of 2. The following equations are derived from "*Mechanics of Materials*" [7].

The safety factor for an applied load case is determined with the following equation:

$$S.F. = \frac{\sigma_{yld}}{\sigma_{applied}} \tag{D19}$$

Where S.F. is the safety factor, σ_{yld} is the yield stress of the material in psi, and $\sigma_{applied}$ is the total applied stress in psi.

The applied stress for the load case shown in Figure D-4 is calculated from the following equation:

$$\sigma_{applied} = \frac{\Sigma Mc}{I} \tag{D20}$$

Where ΣM is the sum of the maximum applied moments in lb-in, c is the distance from the neutral axis to the top of the material perpendicular to the loading axis, and I is the cross-sectional moment of inertia. Since both the point load and equivalent distributed load are in the same direction and applied at the center of the beam, ΣM can be calculated as:

$$\Sigma M = P\frac{L}{2} + wL \times \frac{L}{2} = (P + W)\frac{L}{2} \tag{D21}$$

In the above equation, the total distributed load, W, has been substituted for wL for simplicity.

The moment of inertia for a square cross-section is calculated from the following equation as:

$$I = \frac{h_o^4 - h_i^4}{12} \tag{D22}$$

Where h_o is the outer length of the cross-section and h_i is the inner length of the cross-section, both in inches.

Several gauges of steel were considered for the application and iteratively solved for using an Excel spreadsheet. The calculations for the final selected tubing cross-section (14 gauge) are presented below.

$$I = \frac{h_o^4 - h_i^4}{12} = \frac{2^4 - (2 - 2 * 0.083)^4}{12} = 0.390541 inch^4$$

$$\Sigma M = (P + W)\frac{L}{2} = (200 + 325) * \frac{72}{2} = 18900\ lb - in$$
$$\sigma_{applied} = \frac{\Sigma Mc}{I} = \frac{18900 \times 1}{0.390541} = 48394\ psi = 48.4\ Ksi$$
$$S.F. = \frac{\sigma_{yld}}{\sigma_{applied}} = \frac{84.1}{48.4} = 1.7$$

Since the required safety factor of 1.5 has been met, A513 2x2” 0.083” (14 gauge) steel tubes are used for the test rig design.

To estimate the amount of deflection at the center of the longest frame member, the following calculations were also performed.

By utilizing the principle of superposition, the maximum deflection at the center of the beam can be calculated with the following equation:

$$y_{max,tot} = y_{max,dist} + y_{max,point} \qquad \text{(D23)}$$

Where $y_{max,\ tot}$ is the total deflection, $y_{max,\ dist}$ is the deflection from the distributed load, and $y_{max,\ point}$ is the deflection from the point load, all measured in inches. To solve for the deflection from the distributed load the following equation is used:

$$y_{max,dist} = \frac{-5\mathrm{w}L^4}{384EI} \qquad \text{(D24)}$$

Where E is the Young’s Modulus of Elasticity in psi, w is the disturbed load in LBS/in, L is the length of the beam in inches, and I is the moment of inertia of a square cross-section in $inches^4$. To calculate the moment of inertia, the following equation is used:

To calculate the deflection from the point load, the following equation is applied:

$$y_{max,point} = \frac{-\mathrm{P}L^3}{48EI} \qquad \text{(D25)}$$

Where P is the applied load.

$$y_{max,point} = \frac{-\mathrm{P}L^3}{48EI} = \frac{-200 * 72^3}{48 * 29.00756 * 10^6 * 0.390541} = -0.137in$$
$$y_{max,dist} = \frac{-5\mathrm{w}L^4}{384EI} = \frac{-5 * \frac{325}{72} * 72^4}{384 * 29.00756 * 10^6 * 0.39054} = -0.139in$$
$$y_{max,tot} = y_{max,dist} + y_{max,point} = -0.137 - 0.139 = -0.277\ in$$

Therefore, the final expected downward deflection at the center of the beam is 0.277”

D-7 References

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APPENDIX E

Details on Establishing the Client Needs and Metrics and Evaluating the Final Design

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List of Tables

E-1 Introduction

This appendix presents the process used by the MECH 4860 design group to create a table of client needs, and the process used to translate these needs into a list of metrics to evaluate the final design. This appendix then discusses the actual design value for each metric and states whether it met or exceeded design specifications. Furthermore, this appendix evaluates each section of the design's compliance with the needs and tabulates where in the design each need was met. Finally, this appendix highlights the changes made from the phase II lists.

E-2 Creating the List of Needs

The group met with GE as a part of phase I of this project to establish the needs of this project. From that meeting, the group identified needs and organized them in a table. Preliminary tables were reviewed and approved by GE in phases I and II of this project. The final table along with changes made in phase III can be found in E-6.

E-3 Creating the List of Metrics

Through brainstorming sessions, the group came up with a list of metrics that could be used in evaluating the final design. The group then worked to establish realistic ideal values to aim for while designing the rig as well as marginal values to give the group a maximum or minimum acceptable value for the design. Preliminary tables were reviewed and approved by GE in phases I and II of this project. The final table along with changes made in phase III can be found in E-6.

The process used in establishing these ideal and marginal values is explained in the remainder of this section.

The client provided several target specifications directly to the group, including water flow through nozzle, air pressure near nozzle, and air and water temperature near nozzle. The client did not provide a specification for water pressure near nozzle. However, looking at capacities of various nozzles from a Spraying Systems air atomizing nozzle catalog [1], the group found a nozzle rated for 90 psi air pressure, 60 psi water pressure and 0.3 gpm water, which closely matched the air pressure and water flow values provided by GE. Therefore, this water pressure value was used to approximate a range of target values.

The client quoted a required accuracy of +/- 5°F for water and air temperature. Therefore, the team assigned a marginal value of 175°F for water and air temperature. The client also quoted a required accuracy of 5% for measurement devices, therefore the group used 95% of the target specification as a marginal value for the rest of these metrics. In these cases, the system must be rated to and be able to output a minimum of the marginal value to be deemed acceptable.

The client tasked the design group with determining target specifications for the remaining metrics, and the method of doing so for each remaining metric is described as follows:

- **Subjective:** All subjective metrics are based on a scale from one to 10, where one is the worst conceivable design pertaining to that metric and 10 is the best. Marks would be deducted from 10 for every potential design improvement in that category.
- **Height**: Having assumed a water tank would be used to store water, the group decided it reasonable that the rig would need to be at least four feet tall. If the rig was taller than ten feet, it would become substantially difficult to maneuver and therefore would not be an acceptable design.
- **Length**: For stability reasons, it would not be reasonable to have a base of less than two feet in either direction, and therefore the minimum realistic length would be two feet. If the rig were longer than ten feet in either direction, it would be substantially difficult to maneuver and therefore would not be an acceptable design.
- **Number of power supply circuits**: Ideally, the group would power all components with one circuit. However, due to the variation in system requirements from component to component, the group decided it would be reasonable to require three separate power circuits.
- **Maximum power supply current**: As not to require power upgrades to the facility where the rig will run, the rig would run off 15A circuits. However, due to the power necessary to heat water to 180°F, the group decided it would be reasonable to recommend power upgrades up to 100A circuits.
- **Maximum power supply voltage**: Ideally, the rig would be powered by 120V circuits but the group decided it would be acceptable to power the rig with 240V circuits as well.
- **Minimum operating temperature**: The client specified that the rig would run in an indoor heated facility. However, it would be prudent to be prepared for unanticipated moving of the rig during subzero outdoor conditions. For this reason, the design team chose a target of 40 °F for this specification, with an acceptable value of 60 °F.
- **Component cost**: Ideally, the design would be a more cost-effective alternative than the TRDC's current troubleshooting methods. The client requested a design life of the rig of 15 years. If a nozzle failure occurs three times per year, takes two hours and costs $100/h in salary to identify, the current troubleshooting method would have an overall associated cost of $9,000. However, considering the added value of reliability, data collection during troubleshooting and spray patterns testing, the reduced troubleshooting time, and reduced downtime for the wind tunnel, an acceptable cost for the design would be $50,000.
- **Time to access operating instructions**: Assuming the instructions would be located on the outside of the rig, it would take less than 10 seconds to locate them. If the group had decided to store the instructions somewhere else, they should still be accessible in under 90 seconds.
- **Duration for complete emergency stop**: Stopping the pump and compressor in under one second could damage them, and therefore it would be ideal to ramp down for at least one second during an emergency stop. Due to the nature of an emergency, the design team decided the upper limit for the duration of the emergency stop should be five seconds.

- **Water storage size**: The client informed the group that it should take approximately 10 minutes to identify a faulty nozzle with the test rig. With a flow of 0.317 gpm per nozzle and a maximum of 16 nozzles per spray bar, the rig would ideally store 51 gallons of water. However, most spray bars have fewer than 15 nozzles and it would be possible to run a nozzle for less than 10 minutes if necessary, and still identify a faulty nozzle with some certainty. Therefore, a marginal size for water storage would be 30 gallons.
- **Supply water and air pressure**: Ideally, the rig would supply water and air at the exact pressure required at the nozzles, to reduce pressure at the outlet of the pump and compressor to increase the life of those components. However, 10 psi allowance has been deemed acceptable to account for losses in the lines.
- **Data Storage**: The system should be able to store data for the entirety of testing (50 mins). Assuming a sample rate of 1Hz, 8-bit analog to digital converters on the selected PLC and approximately 10 inputs from sensors, the design should be able to store at least 100 kB of data at a time. Ideally, the design should be able to store 2 MB of data in case multiple nozzle failures occur in a short period of time, and more sensors and higher sample rates end up being used than assumed.
- **Troubleshooting time**: Assuming 3 nozzles could be tested simultaneously, testing all nozzles on the longest spray bar should take approximately 50 minutes of continuous spray time. Considering time to switch out nozzles and time to heat up the air and water, it would be difficult to quote a maximum troubleshooting time of under one hour. Due to the time required to heat the water and air, a design that would take a maximum of 90 minutes to detect a faulty nozzle would be acceptable.

E-4 Evaluating the Actual Design Metrics

The process used in determining the actual design specifications is discussed in this section. The following table can be used as reference when looking at this process.

TABLE I. LIST OF METRICS WITH ACTUAL DESIGN VALUE

#	Metric	Units	Marginal Value	Ideal Value	Actual Value
1	Water flow through nozzle	gpm	0.3012	0.317	0.317
2	Height	ft	10	5	5
3	Length	ft	10	2	9
4	Rated water pressure	psi	60	100	150
5	Air pressure near nozzle	psi	85.5	90	90
6	Number of Power Supply Circuits	#	3	1	3
7	Maximum Power Supply Current	A	100	15	75
8	Maximum Power Supply Voltage	V	240	120	240
9	Water temperature	°F	175	180	180
10	Air temperature	°F	175	180	180
11	Safety	Subj	8	9.5	9
12	Serviceability	Subj	7	10	8
13	Minimum operating temperature	°F	60	40	60
14	Mobility	Subj	7	10	8
15	Manufacturability	Subj	7	10	9
16	Component Cost	$CDN	50,000	9,000	49,900
17	Duration for complete emergy stop	sec	5	1	0
18	Reliability	Subj	9	10	10
19	Water storage size	gal	30	50	50
20	Data storage	MB	0.1	2	4
21	Troubleshooting time	min	90	60	63

- **Water Flow Through Nozzle:** Since the pump and water heater are both rated for flow rates above 1 gpm and since the pump motor has a variable speed controller, it is possible to achieve the target specification of 0.317 gpm through each nozzle.
- **Height:** The final height of the test rig is approximately 5 feet, within target specifications.
- **Length:** The final length of the test rig is approximately 9 feet, within target specifications.
- **Rated Water Pressure:** The limiting component for rated water pressure is the pressure transmitter which has a pressure rating of 150 psig. Therefore, the design exceeds the target specifications.
- **Air Pressure Near Nozzle:** Since the compressor, tank and air heater are all rated for pressures above 90 psig and since a pressure regulator combined with a digital pressure transmitter will be used to set the system air pressure, it is possible to achieve the target specification of 90 psig near each nozzle.
- **Number of Supply Power Circuits:** In total, three supply power circuits will be required for the design: a three phase 240V, 75A circuit to power the water heater; a single phase, 240V,

15A circuit to power the air heater and air compressor; and a single phase 120V, 15A circuit to power the water pump motor. Therefore, the design meets the target specifications.

- **Maximum Power Supply Current:** The maximum power supply is that for the water heater (75 A), which is within target specifications.
- **Maximum Power Supply Voltage:** The maximum power supply voltage is that for the water heater, the air heater and the air compressor (240V), which is within target specifications.
- **Water Temperature:** Since water heater is rated to outlet temperatures above 180°F and since a built-in feedback controller will be used to set the system water temperature, it is possible to achieve the target specification of 180°F water temperature.
- **Air Temperature:** Since air heater is rated to outlet temperatures above 180°F and since a PID controller will be used to set the system air temperature, it is possible to achieve the target specification of 180°F air temperature.
- **Safety:** The group incorporated safety in the design in three main ways. First, by insulating the lines, the user is protected from high temperature components. Second, by sourcing relays to cut power to the components, the level of system protection is essentially limited to the designer of the PLC software. Third, by recommending a list of operating instructions, the group has ensured the design will be used as intended and the rig will be started and stopped in the correct order. However, because of the weight of the design, two people are required to maneuver the rig. For this reason, the group docked one mark out of 10, resulting in a final score of nine, meeting the target specification.
- **Serviceability:** For much of the design, the group was able to source standard components from a single supplier (McMaster-Carr). Furthermore, the group sourced, where possible, components from suppliers and part series already being used on the TRDC. However, a few components were sourced from international suppliers with no known relationship with the TRDC. For this reason, the group docked two marks out of 10, resulting in a final score of eight, meeting the target specification.
- **Minimum Operating Temperature:** The limiting components for this specification are the two heaters, which were purposely sourced to 60°F to limit the supply power required while still meeting the target specification.
- **Mobility:** The group was successful in creating a mobile design by sourcing caster wheels for all components. Furthermore, the modularity of the design allows for components to be rearranged when the rig is not in use. However, the final weight of the design was too heavy for the rig to be moved by a single person. Furthermore, the lack of structural connection between the air compressor and the main frame requires the rig to be moved in two parts. Therefore, the group docked two marks out of 10m resulting in a final score of eight, meeting the target specification.
- **Manufacturability:** Most components are mounted to the rig with standard hardware. Therefore, most of the assembly can be done without the use of specialised tools. However, the frame requires welding. For this reason, the group docked one mark out of 10, resulting in a final score of nine, meeting the target specification.
- **Component Cost:** The final cost of all components where cost information was available was $49,900 CAD. The addition of components where cost was not available would likely put the

final component cost above $50,000 CAD. Therefore, the target specification was not met. However, one recommendation made by the group was to use an existing compressor at the TRDC to charge the air tank, reducing the component cost by over $18,000 CAD which would be within target specifications.

- **Duration for a Complete Emergency Stop:** By using relays to cut power to all components during an emergency stop, the group lost the ability to slow down the components before cutting the power completely. However, since the need stems from the safety of the user, the specification is still met as it is below the marginal value.
- **Reliability:** By souring electronic sensors, the group removed human error from all measured properties. Assuming the means of determining a faulty nozzle is unexpected pressure readings, the group could not think of an instance where, if the design works as intended, the rig would not identify a faulty nozzle. Therefore, the group assigned a mark of 10, meeting the target specification.
- **Water Storage Size:** The group sourced a water tank with a specified storage capacity of 50 gallons, meeting the target specification.
- **Data Storage:** The group sourced a data logger with a specified storage capacity of 4 MB, exceeding the target specification.
- **Troubleshooting Time:** By running three nozzles simultaneously during testing, the maximum amount of running time before a faulty nozzle is detected will be the maximum nozzles per spray bar (16) multiplied by the 10 minutes to troubleshoot one nozzle divided by three, equating to 53 minutes. Assuming it will take an additional 10 minutes to warm up the rig and swap out nozzles, the maximum troubleshooting time would be 62 minutes, within target specifications.

E-5 Overall Compliance of the Design

TABLE II compares the needs listed in with the final design specifications applicable to the overall rig. Similar compliance matrices are available following TABLE II that evaluate the needs specific to each subcategory.

TABLE II. FINAL DESIGN NEED'S COMPLIANCE MATRIX

Need#	Need	Description of Compliance
13	Design is compatible with range of nozzles types	Design is compatible with two nozzle types
14	Design performs under required environmental conditions	Components are rated for indoor use, and meet working fluid temperature ratings
18	Design is affordable	Design is under marginal budget of $50,000
19	Design fits required dimensions	Assemblies fit through overhead doors at the TRDC
21	Design is made from durable components	Steel construction, quality oversized components
22	Design is manufacturable with compatible compents	All components compatible with adpter fittings
23	Design contains operating instructions	Preliminary instructions included
24	Design contains instructional work procedure (SOP)	Preliminary instructions included
26	Design runs for length of test without intervention	All components sized to run entire test duration
27	Design uses standard components where possible	All components are varitations of off the shelf parts

TABLE II shows that the overall rig is compliant to needs 13, 14, 18, 19, 21, 22, 23, 24, 26 and 27.

The water system's compliance to the relevant overall design needs is shown in TABLE III.

TABLE III. WATER SYSTEM COMPLIANCE MATRIX

Need#	Need	Description of Compliance
28	Design regulates water flow rate	AC to DC motor speed controller is included
30	Design regulates water pressure supplied to nozzle(s)	Adjustable water pressure regulator is included in pipe routing
31	Design is capable of testing a single nozzle	Selected pump and motor can turn-down to 0.3 gpm setting for a single nozzle
32	Design is capable of testing multiple nozzles	Pump, motor, and routing accommodate up to three nozzles
34	Working fluids can be removed from system	Drain port is provided
35	Design has accessible water supply	Portable 50-gallon water tank is included
36	Design supplies water to desired flow rate and pressure	Pump and motor can produce the maximum design pressure of 100 psig with margins
39	Pipe dimensions are able to withstand 1.5 design specifications	All pipe routing components are rated to a minimum of 150 psig
41	Design stores required amount of water	50-gallon tank provides adequate capacity for testing a full spray bar
42	Design considers drainage of water	Design will operate in a building with floor drains. Drain ports are provided

TABLE III shows that the water system is compliant to needs 28, 30, 31, 32, 34, 35, 36, 38, 39, 41 and 42.

The water heating system's compliance to the relevant overall design needs is shown in TABLE IV, below.

TABLE IV. WATER HEATER COMPLIANCE MATRIX

Need#	Need	Description of Compliance
8	Electrical systems are protected from water	Control box positioned away from water lines
9	Design measures water temperature	Heater has internal temperature sensors
21	Design is made from durable components	Industrial grade unit designed for long service life
26	Design runs for length of test without intervention	Industrial grade unit intended for continuous running
27	Design uses standard components where possible	standard pipe fittings and mounting hardware
31	Design is capable of testing a single nozzle	Can run at 0.33 GPM
32	Design is capable of testing multiple nozzles simultaneously	Can run at 1 GPM
34	Working fluids can be removed from system	Contains 3/4" drain plug
40	Design heats water to required temperature	0F to 180F heating
42	Design considers drainage of water	Contains 3/4" drain plug

TABLE IV demonstrates that the selected water heater helps meet needs 8, 9, 21, 26, 27, 31, 32, 34, 40 and 42.

The insulating system's compliance to the overall design needs is shown in TABLE V.

TABLE V. INSULATION NEED'S COMPLIANCE MATRIX

Need#	Need	Description of Compliance
11	Design is safe for user(s)	Prevents burns form contact with pipes
14	Design performs under required environmental conditions	Maintains heat in pipes even in outdoor conditions
21	Design is made from durable components	Jacket protects insulation fibers
22	Design is manufacturable with compatible compents	standard sized insulation sized to fit standard pipes
27	Design uses standard components where possible	standard sized insulation sized to fit standard pipes

TABLE V demonstrates that the selected insulation helps meet needs 11, 14, 21, 22 and 27.

The air system's compliance to the relevant overall design needs is shown in TABLE VI below.

TABLE VI. AIR SYSTEM COMPLIANCE MATRIX

Need#	Need	Description of Compliance
29	Design regulates air pressure supplied to nozzle(s)	Pressure regulator is included in pipe routing
37	Design supplies air to required pressure	Air compressor has an operating range that includes the maximum design pressure

TABLE VI demonstrates that the design air system meets needs 29 and 37.

The air heating system's compliance to the overall design needs is shown in TABLE VII.

TABLE VII. AIR HEATING SYSTEM COMPLIANCE MATRIX

Need#	Need	Compliance
14	Design performs under required environmental conditions	Heating system is rated to inlet air temperatures down to -4°F
31	Design is capable of testing a single nozzle	Heating system is rated to 50 cfm
32	Design is capable of testing mutiple nozzles simultaneously	Heating system is rated to 50 cfm
43	Design heats air to required temperature	Heating system is rated to outlet air temperatures up to 752°F

Therefore, the group was able to source an air heating system in order to meet the needs 14, 31, 32 and 43.

The measurement and control system's compliance to the overall design needs is shown in TABLE VIII.

TABLE VIII. MEASUREMENT AND CONTROL SYSTEM COMPLIANCE MATRIX

Need#	Need	Compliance
1	Design measures flow rate of water near nozzle(s)	Flowmeter measures flow rates down to 0.01 gpm
2	Design measures pressure of air near nozzle(s)	Pressure transmitters measure pressures up to 150 psig
5	Design collects and logs data	Logger logs up to 4 GB of data
7	Design transmits data	All sensors transmit a signal proportional to the measured value
9	Design measures water temperature	T-type thermocouples measure temperature up to 662°F
25	Design can be shut down in case of an emergency	Solid State Relays and PLC allow full control of power supply

TABLE VIII shows the measurement and control system was compliant to needs 1, 2, 5, 7, 9 and 25.

TABLE IX. SPRAY PATTERN MEASUREMENT COMPLIANCE MATRIX

Need#	Need	Description of Compliance
3	Design measures spray angle	Video camera and Envision software can be used to measure spray angle
4	Design measures overall pattern	2-D pattern can be recorded and analyzed with camera and Envision software
10	Design measures droplet size	N60V system provides the necessary capabilities
33	Design can determine if a nozzle is defective	Can be seen qualitatively from spray videos or pressure/flow readings. Defective droplet sizes can only be captured with N60V system

TABLE IX demonstrates that the selected spray pattern measurement system helps meet needs 3, 4, and 33. However, the only need not met using the baseline design configuration is need 10, as the recommended additional N60V system is required to measure droplet sizes. This N60V system presents a significant cost increase over the nominal test rig components, and is therefore recommended as an optional add-on feature should GE TRDC absolutely require droplet size measurement capabilities.

TABLE X. FRAME AND MOBILITY COMPLIANCE MATRIX

Need#	Need	Compliance
8	Electrical systems are protected from water	HDPE panels shield the controllers from back spray
15	Design is structuraly stable under test	Calculations resulted in factor of safety of 2 for frame design
16	Design is easily portable	Casters allow for ease of portability
17	Design is easy to assemble / disassemble	Components are bolted to the frame
20	Design has sufficient space for performing maintenance	Frame is large enough to leave room between components
21	Design is made from durable compents	Frame is purposely overdesigned

TABLE X shows the frame and mobility section is compliant to needs 8, 15, 16, 17, 20 and 21.

A summary of all of the needs along with which sections address which needs is shown in TABLE XI.

TABLE XI. OVERALL COMPLIANCE OF DESIGN

#	Need	Section(s) Addressing Need
1	Design measures flow rate of water near nozzle(s)	Measurement
2	Design measures pressure of air near nozzle(s)	Measurement
3	Design measures spray angle	Patternator
4	Design measures overall pattern	Patternator
5	Design collects and logs data	Measurement
6	Design delivers adequate power to all components	Recommendations
7	Design transmits data	Measurement
8	Electrical systems are protected from water	Heating
9	Design measures water temperature	Heating, Measurement
10	Design measures droplet size	Patternator
11	Design is safe for user(s)	Insulating
13	Design is compatible with range of nozzles types	Overall
14	Design performs under required environmental conditions	Overall, Heating, Insulating
15	Design is structuraly stable under test	Frame
16	Design is easily portable	Frame
17	Design is easy to assemble / disassemble	Frame
18	Design is affordable	Overall
19	Design fits required dimensions	Overall
20	Design has sufficient space for performing maintenance	Frame
21	Design is made from durable compents	Overall, Heating, Insulating, Frame
22	Design is manufacturable with compatible compents	Overall, Insulating
23	Design contains operating instructions	Overall
24	Design contains instructional work procedure (SOP)	Overall
25	Design can be shut down in case of an emergency	Controls
26	Design runs for length of test without intervention	Overall, Heating
27	Design uses standard components where possible	Overall, Heating, Insulating
28	Design regulates water flow rate	Water
29	Design regulates air pressure supplied to nozzle(s)	Air
30	Design regulates water pressure supplied to nozzle(s)	Water
31	Design is capable of testing a single nozzle	Water, Heating
32	Design is capable of testing mutiple nozzles simultaneously	Water, Heating
33	Design can determine if a nozzle is defective	Patternator
34	Working fluids can be removed from system	Water, Heating
35	Design has accessible water supply	Water
36	Design supplies water to desired flow rate and pressure	Water
37	Design supplies air to desired pressure	Air
38	Pipe dimensions are economical	Water
39	Pipe dimensions are able to withstand 1.5 times design specifications	Water
40	Design heats water to required temperature	Heating
41	Design stores required amount of water	Water
42	Design considers drainage of water	Water, Heating
43	Design heats air to required temperature	Heating

As seen in TABLE XI, all needs are met through the various subsection designs as well as the overall design integration, except for need 6. The delivery of adequate power can only be achieved if the TRDC performs the recommended power upgrades to the facility.

E-6 Changes from Phase II

As the project progressed, the list of needs and metrics were updated to reflect new information. This information included research done into component selection, baseline heat transfer and fluid flow calculations and group discussions where old decisions were reconsidered as a means of continuous improvement.

The summary of all changes made between the concept development phase and the final design phase can be seen in the following tables.

TABLE XII shows the final list of needs, with changes from phase II highlighted.

TABLE XII. CHANGES TO LIST OF NEEDS IN PHASE III

#	Need	Importance (1-5) 1 = low, 5 = High
1	Design measures flow rate of water near nozzle(s)	5
2	Design measures pressure of air near nozzle(s)	5
3	Design measures spray angle	5
4	Design measures overall pattern	3
5	Design collects and logs data	4
6	Design delivers adequate power to all components	3
7	Design transmits data	3
8	Electrical systems are protected from water	5
9	Design measures water temperature	3
10	Design measures droplet size	2
11	Design is safe for user(s)	5
13	Design is compatible with range of nozzles types	1
14	Design performs under required environmental conditions	4
15	Design is structuraly stable under test	4
16	Design is easily portable	2
17	Design is easy to assemble / disassemble	2
18	Design is affordable	2
19	Design fits required dimensions	1
20	Design has sufficient space for performing maintenance	3
21	Design is made from durable compents	3
22	Design is manufacturable with compatible compents	4
23	Design contains operating instructions	3
24	Design contains instructional work procedure (SOP)	4
25	Design can be shut down in case of an emergency	5
26	Design runs for length of test without intervention	5
27	Design uses standard components where possible	4
28	Design regulates water flow rate	5
29	Design regulates air pressure supplied to nozzle(s)	5
30	Design regulates water pressure supplied to nozzle(s)	5
31	Design is capable of testing a single nozzle	5
32	Design is capable of testing mutiple nozzles simultaneously	3
33	Design can determine if a nozzle is defective	5
34	Working fluids can be removed from system	3
35	Design has accessible water supply	4
36	Design supplies water to desired flow rate and pressure	4
37	Design supplies air to desired pressure	4
38	Pipe dimensions are economical	4
39	Pipe dimensions are able to withstand 1.5 times design specifications	4
40	Design heats water to required temperature	5
41	Design stores required amount of water	4
42	Design considers drainage of water	1
43	Design heats air to required temperature	5

The only change made from phase II was the addition of need #43: Design heats air to required temperature. This need was added to demonstrate the difference in water and air heating systems.

TABLE XIII shows the list of metrics from phase III on the left and the list of metrics from phase II on the right. Changes made are highlighted in the list of metrics from phase II.

TABLE XIII. CHANGES TO LIST OF METRICS IN PHASE III

#	Metric	Units	Marginal Value	Ideal Value		#	Metric	Units	Marginal Value	Ideal Value
1	Water flow through nozzle	gpm	0.3012	0.317		1	Water flow through nozzle	gpm	0.3012	0.317
2	Height	ft	10	5		2	Height	ft	10	5
3	Length	ft	10	2		3	Length	ft	5	2
4	Rated water pressure	psi	60	100		4	Water pressure near nozzle	psi	71.25	75
5	Air pressure near nozzle	psi	85.5	90		5	Air pressure near nozzle	psi	85.5	90
6	Number of Power Supply Circuits	#	3	1		6	Data collection rate	bps	500	1000
7	Maximum Power Supply Current	A	100	15		7	Power supply	Watt	3600	1800
8	Maximum Power Supply Voltage	V	240	120		8	Water temperature	°F	175	180
9	Water temperature	°F	175	180		9	Air temperature	°F	175	180
10	Air temperature	°F	175	180		10	Safety rating	Subj	8	9.5
11	Safety	Subj	8	9.5		11	Serviceability	Subj	7	10
12	Serviceability	Subj	7	10		12	Minimum operating temperature	°F	60	40
13	Minimum operating temperature	°F	60	40		13	Mobility	Subj	7	10
14	Mobility	Subj	7	10		14	Manufacturability	Subj	7	10
15	Manufacturability	Subj	7	10		15	Component and manufacturing cost	$CDN	20,000	9,000
16	Component Cost	$CDN	50,000	9,000		16	Time to access operating instructions	sec	90	10
17	Duration for complete emergy stop	sec	5	1		17	Duration for complete emergy stop	sec	5	1
18	Reliability	Subj	9	10		18	Reliability rating	Subj	7	10
19	Water storage size	gal	30	50		19	Water storage size	gal	30	50
22	Data storage	MB	0.1	2		20	Supply water pressure	psi	85	75
23	Troubleshooting time	min	90	60		21	Supply air pressure	psi	100	90
						22	Data storage	MB	0.5	2
						23	Troubleshooting time	min	90	60

The reasoning for the changes made to the list of metrics are as follows:

- The marginal value for length was increased from 5 to 10 because after discussing, the group decided the rig could still be somewhat maneuverable up to a maximum of a 10 feet by 10 feet footprint, although mobility would be affected negatively by this.
- Water pressure near nozzle was changed to rated water pressure because the group learned the water cap used at the TRDC was custom made and therefore specifications for water pressure capacity were not available in the Spray Systems catalog. This way, as long as the rated water pressure was in the range of estimated values for the actual water pressure near the nozzle, the rig would be able to function as required.
- Data collection rate was removed, since the group did not consider it helpful in the evaluation of the design, due to variability in the actual data collection rate and quality of data to be collected. The group decided to leave the actual value up to the instrumentation team at the TRDC who would be more suited in setting up the logger to record what they deem valuable information.
- Power supply was broken up into number of power supply circuits, maximum power supply circuit voltage and maximum power supply circuit current. The group decided that the three

separate power supply characteristics provided more information about the design than just the overall power consumption.

- Component and manufacturing cost was changed to just component cost, since the group decided that manufacturing cost would be too difficult to estimate without contacting manufacturers for quotes for which time did not permit. The marginal value for component cost was also increased to $50,000 CAD due to further considerations by the group into what reasonable values for various components would be.
- Reliability rating was increased because the group changed its definition from 'the reliability of all components to work within their rated performance' to 'the reliability of the design identifying a faulty nozzle'. The group deemed the latter definition more valuable in evaluating the design since it adhered better to the problem statement.
- Supply water and air pressures were removed from metrics as they will be very hard to predict, and will have to be determined after the manufacturing is complete.

References

[1] Spraying Systems Co., "Automatic & Air Atomizing Spray Nozzles," [Online]. Available: http://www.spray.com/cat76/automatic/. [Accessed 26 October 2017].

APPENDIX F

Quotes and Technical Specification Packages

Table of Contents

List of Figures

F-1 Introduction

This appendix contains the quotes and specifications sheets for the major components of the test rig. Quotes are presented first in section F-2, followed by the relevant specification sheets in section F-3.

F-2 Quotes

Hubbell™

Hubbell Electric Heater Company
45 Seymour Street
P.O. Box 288
Stratford CT 06615-0288

Phone: 203-378-2659
Fax: 203-378-3593
www.hubbellheaters.com

Quote Number: 47053

Page: 1 of 1

PROSP

To: GE TRDC

Job Reference: Nozzle spray bank
EMail: c-d-f@outlook.com
Phone: **Fax:**

Quote Date: 11/15/2017
Expires: 02/13/2018
FOB: FCA Stratford, CT
Ship Via: Best Way
Terms: To Be Decided
Sales Rep: House Account

Line	Model No. / Description	Quantity	Unit Price	Ext. Price
1	**TX027-3S**	1	3,950.00	$3,950.00

Tankless Water Heater
27 kW 240 Volt / 1Phase - 50/60Hz

The heating chamber shall be all sil-brazed copper and bronze construction. Water heater heating chamber shall be rated for a design pressure of 150 psi. The immersion heating elements shall be high quality incoloy sheathed and sized to obtain the rated capacity. Each element circuit is to be independently operated and controlled using zero cross over solid state controls. The heating elements shall be fully modulated from 0-100% to provide precise temperature control through the full range of flows. A Hi-Limit control with automatic reset shall be factory installed to disconnect each heating element in the event of an over-temperature condition. An electronic digital display temperature controller shall be user adjustable in 1° increments in either °F or °C and shall display flow, temperature and error indication. A turbine-type flow meter shall be factory installed to provide precise temperature control for wate flows as low as 0.2 GPM up to a maximum flow of 8 GPM.

Lead Time: 2 Weeks ARO

All accepted purchase orders related to this quote shall be governed by the Seller's Terms and Conditions of Sale, viewable at www.hubbellheaters.com/termsofsale

Quote Total: $3,950.00

For financing options, go to:
www.hubbellheaters.com/lease

Quoted By: *Maggie Cumings*
mcumings@hubbellheaters.com
203-378-2659 ext.124

Figure F-1. Hubble Water Heater Quote

WATTCO™

QUOTE Q1

Date	REF EST #
11/21/2017	26036

TEL: 800-492-8826
TEL: 514-488-9124
clients@wattco.com

Invoice To	Ship To
UNIVERSITY OF MANITOBA Department of Electrical & Computer Engin Room E3-544, EITC Building, 75A Chancello WINNIPEG, MB R3T 5V6	

Email: [redacted]
NAME:
TEL:

REP	Terms
JM	ADVANCE

Description	Qty	Rate	Total	Ta
T1= 32F, T2 = 180F, 1.3 GPM, INLINE, 240V, Deionized water, Watt denity corrected for Deionized water				
WATTCO 4" FLANGE HEATER (9 HAIRPIN ELEMENTS) 30 KW, 240 V, 3 PH (72.17 AMPS) (DENSITY 62 WATTS/SQ. IN.) (APPLICATION WATER) (1 CIRCUITS) ANSI 150 LBS (STAINLESS STEEL 304 MATERIAL) FLANGE 0.430" O.D. TUBE DIA. STAINLESS STEEL 316 SHEATH MATERIAL 24" IMMERSED LENGTH, 4" COLD SECTION PILOT DUTY THERMOSTAT (50-250 DEG. F) FOR TEMPERATURE CONTROL NEMA 4 (MOISTURE PROOF) ENCLOSURE WITH GASKET MODEL # FLS930X2825-T OPERATING PRESSURE: 60 PSI OPERATING TEMPERATURE: 180 F	1	3,595.00	3,595.00	G
WATTCO 4" FLANGED CIRCULATION VESSEL ANSI 150 LBS. x 28" LENGTH (OVERALL LENGTH "G" DIMENSION), MATERIAL STAINLESS STEEL 304 1 1/2" NPT INLET/OUTLET CONNECTIONS (NIPPLES) INLET 4" FROM VESSEL END; OUTLET 4" FROM VESSEL END; INLET/OUTLET DISTANCE (CENTER TO CENTER "B" DIMENSION) 20" MOUNTING HORIZONTAL WITH INSULATION 1/2" NPT DRAIN (NIPPLE) MODEL # MFLS930X2825-T OPERATING PRESSURE: 60 PSI OPERATING TEMPERATURE: 180 F	1	0.00	0.00	G

Total

Please complete the "Client Master File" form to expedite the opening of your account. Page 1

Figure F-2. Wattco Water Heater Quote 1 of 2

WATTCO™

QUOTE

Q1

Date	REF EST #
11/21/2017	26036

TEL: 800-492-8826
TEL: 514-488-9124
clients@wattco.com

Invoice To

UNIVERSITY OF MANITOBA
Department of Electrical & Computer Engin
Room E3-544, EITC Building, 75A Chancello
WINNIPEG, MB R3T 5V6

Ship To

Email:
NAME:
TEL:
[redacted]

REP	Terms
JM	ADVANCE

Description	Qty	Rate	Total	Ta
WATTCO CONTROL PANEL TERMINAL NEMA 4 BOX TYPE (MOISTURE RESISTANT) OTHER COMPONENTS: - MAIN DISCONNECT - CTRL TRANSFORMER - (1) CONTACTORS AND FUSES FOR - (1) LOADS OF 30 KW, 240 V, 1 PH - (1) 2 POSITION SELECTOR SWITCH "OFF-ON" - (1) GREEN LIGHT "HEATER ON" - WIRING DIAGRAM CSA CERTIFIED	1	2,095.00	2,095.00	G
LEAD TIME: 5 - 7 WEEKS		0.00	0.00	G
Please be advised that our production facility will be closed for 2 weeks during the 2017-2018 holiday period				
5% GST/HST # 101089480		5.00%	284.50	

DELIVERY: TBD Freight at your expense – Please notify us of your preferred transport along with your account number.
F.O.B. OUR PLANT

Quote Valid for 15 days

Total $5,974.50

Please complete the "Client Master File" form to expedite the opening of your account.

Page 2

Figure F-3. Wattco Water Heater Quote 2 of 2

O.E.M. HEATERS

739 Kasota Ave
Minneapolis, MN 55414
Tel 866-685-4443
Fax: 612-767-1046

Quotation No. 906943

Page 1 of 1

Quote Date: 12/01/2017
Valid Until: 01/01/2018

Customer:
University of Manitoba
MB
CANADA
Attn: Nevin Neil
Tel

By placing this order, you agree to the Terms and Conditions that were transmitted with this Quote

Lead Time: 3-5 working days
Payment Terms: Credit Card

Salesperson: OEM Heaters Website
All Items FOB Minneapolis

Item Code	Description	Min Qty for Price Shown	Price/Each
K310031	Air Process, 2.375 x 12", 1500W, 240V, 158 w/sq.in., 7.0#, S&N w/enclosure	1	761.78
K520021	Digital PID, SSR driver out, cabinet mountable, 1/16DIN face, RS485 port	1	80.00
K500065	Compact SSR Din Mount, 10A 600VAC capacity, 15VDC input signal	1	67.68

*
Quoted items will ship complete 3 - 5 business days after order.
*
Items quoted are considered Standard items. Restocking charges apply to returns. See Terms and Conditions for further details.

Please submit your order by fax to (651) 288-0497 or by e-mail to salessupport@oemheaters.com

Figure F-4. O.E.M Air Heater

2600 River Green Circle
Louisville, KY 40206
(812) 202-4047

TANK DESIGNER QUOTE
QT001384 11/23/2017

S4TSC0050-0969 **$4,032**

Lead time: 8-10 Weeks After Drawing Approval (Expedited Delivery Available. Please contact the Sales Department for more information)

50 Gal, 304SS, Cone Bottom Tank, #2B Finish

For: ***Thomas Bishop***
2047811512
bishopt@myumanitoba.ca

This quote is good for 30 days. However, we will keep it on file should you ever wish to call it up again. At any time you can convert a quote to an order and begin the process of design and build. Simply log into your account at Mixer Direct and access the Your Account link at the top. On the dashboard you will see a link for "Your Quotes". From the quotes page click on VIEW to see the quote or ORDER to have us begin the design and build process. Of course, you can always email sales@mixerdirect.com or call us with the quote number shown above.
If you did not have an account with Mixer Direct when you created the quote, we created an account for you. You should have received an email with your user name (email address) and password.
Of course you can always give us a call at 812-202-4047 if you have any questions or need additional help.

CONE BOTTOM

Fittings:

1	1 1/2"	NPT Half Coupling	outlet

Instructions:

SUPPORT:
3 Legs
Casters

SHELL

Dimensions:

SSH	36"
DIA	21"

Fittings:

1	2"	NPT Half Coupling	drain

No Baffles

Instructions:
SHELL:

FINISH:

TOP

Lid Type:
1 pc

Mixer Mount Type
None

Fittings:

1	2"	NPT Half Coupling	inlet

Instructions:
LID:

MOUNT:

This quote has been generated from your design session on our website today. We have listed all the design criteria you selected and produced a configured part number and price. Should you elect to purchase this tank, Mixer Direct will produce a drawing in the first week in collaboration with you by phone and email. Once you have approved the drawings, your process tank will be scheduled into production. Of course, should you request additional modifications and options during the design process, the price of the tank may change. In that event, we will send you a revised confirmation of your order with the approved drawing.

WWW.MIXERDIRECT.COM

Figure F-5. Mixer Direct Water Tank Quote

MOTION CANADA
Keeping Industry in Motion

QUOTE

MOTION CANADA
UNIT 1 75 MERIDIAN DRIVE
WINNIPEG, MB R2R 2V9
PHONE : 204-694-0050
FAX : 204-694-1066

Date: 11/08/17

Quote Status

Note: This estimate is valid for 30 days from the date shown above. Prices quoted are for quantities shown. Stock is subject to prior sale. MTO quantities considered complete 10% under/over unless noted.

To: UNIVERSITY OF MANITOBA
66 CHANCELLORS CIRCLE
WINNIPEG, MB R3T 2N2

PO: [redacted]

QUOTE NUMBER: MB21 - 394231
CUSTOMER RFQ: THOMAS
F.O.B.: FOB ORG,FRT PP&ADD
QUOTE SENT BY: BARBARA PUGH
TERMS: . NET 30
DELIVERY: STOCK UNLESS NOTED
SHIPPING: COURIER

Description	Manufacturer	Quantity	Unit	Unit Price	Amount
LINE ITEM: 001 R10316CA-C1 PUMP ITEM NO: 99999999 FREIGHT: 125.00 2 TO 3 WEEKS FOB USA	OBERDORFER	1	EA	$4,385.990	$4,385.99

Subtotal:	$4,385.99
Freight:	$125.00
GST.........10398 7889 RT0001	$225.55
PST.........MB# 305452-7	$360.88
Total:	$5,097.42

Figure F-6. Motion Canada Water Pump Quote

CALGARY
CB Engineering Ltd
5040 12A St. SE
Calgary, AB T2G 5K9
P: (800) 992.2364
F: (403) 259-3377

EDMONTON
CB Engineering Ltd
100, 18142-105 Avenue
Edmonton, AB T5S 2T4
P: (780) 465-9370
F: (780) 469-9217

VANCOUVER
CB Engineering Ltd
PO Box 36089
Surrey BC V3S 7Y5
P: (800) 992-2364
F: (888) 259-1666

Proposal

Date 11/20/2017
Proposal # Q1711W63549

Prepared For

[redacted]

RFQ No.	Expires	Currency	Payment Terms
	12/20/2017	CA	Net 30

Shipping Method	Ship Payment	INCO Terms
Best Way Ground	To Be Advised	FCA Calgary

Notes

Delivery:

This order will ship complete from Calgary in approximately 6 weeks ARO/ARAD. If you require expedited delivery, please contact us at 800-992-2364.

Contact Info

This quote has been prepared by Anita Stuart. Anita Stuart can be reached at (403) 640-3109 or via email at astuart@cbeng.com regarding commercial or pricing questions.

For technical inquiries regarding this quote, please contact Abigail Kosowski at (403) 640-3119 or via email at akosowski@cbeng.com

Sydney Henrikson is responsible for CB Engineering's overall business relationship with University of Manitoba in Winnipeg. Sydney Henrikson can be reached at (403) 640-3107 or shenrikson@cbeng.com

Line	Sub	Qty	Model and Description	Unit Price	Ext Price
1		1	FT4-8NENW-LEA-2 Manufacturer: FlowTech 1/2" Turbine Flow Meter - NPT External Threads - Calibration: 10 points, Normal 10:1 Range, In Water - Liquid service - Housing/: 316ss, Rotor: 430ss - Ball Bearings, 440C ss or equiv. - MS connector ***Please note this unit does not have CRN***	1,584.00	1,584.00

Subtotal	1,584.00
Tax	79.20
PST	126.72
Total	$1,789.92

END USER NAME AND INSTALL LOCATION REQUIRED BEFORE ACCEPTANCE OF PO.
Delivery after receipt of order & subject to credit approval. New accounts may require deposit prior to order. Credit card payments are subject to 6% surcharge & max order value $5000.
Revisions to purchase orders are subject to a $100 min change order fee.
2 weeks free storage at CB Calgary is included, over that storage fees will apply.
Same day shipments are subject to $100.00 fee per order.
Minimum order charge is $200.
Documentation requirements beyond a single hard copy with shipment are subject to a minimum $250.00 charge per order.
Invoices will be provided in CB standard format. Alternative invoicing procedures are subject to a $50 administration fee per invoice.
WITH REGARDS TO PRICING VALIDITY, PLEASE SEE CLAUSE 4. EXCHANGE FLUCTUATION OF CB STANDARD TERMS AND CONDITIONS
Standard CB Engineering Ltd commercial notes apply, they can be viewed at http://www.cbeng.com/terms.pdf.

Figure 7. FT Flowmeter Quote

[redacted]

Figure F-8. Baldor DC Motor Quote

Proposal

Date: 20th November 2017

To: [redacted]

Oxford Lasers Inc.
"Complete Imaging Solutions"

QUOTATION NUMBER	PREVIOUS QUOTE	CUSTOMER ENQUIRY	SHIP VIA	DDP	TERMS
QI171121RJB1			Best	Customer Site	See Below

ITEM NO	MODEL	DESCRIPTION	PRICE ($)
IMG031		**VisiSizer N60S system – Class 1 laser safe system** *"Sizing Analysis, Velocity and Direction of fast moving small droplets"* ***Online – Real Time measurement of Particle Size and Velocity*** *Fully Integrated particle sizing system, to provide information on particle size, particle shape* *Particle size range* ***2um to 4506um*** *(subject to lens option)* *Particle Velocity range* ***50um @ 700m/s***. ***CLASS 1 Laser safe system***	$98,000
		Velocity Measurement Capability Adder (optional)	$17,000
		Installation and Training Installation visit to set up system and train two people from customer in use (minimum of 2 days). Demonstration of system operation may be on subject supplied by Oxford Lasers. Price includes engineer expenses.	$4,500
		Shipping	$1,500
		Total	**$121,000**

Conditions: Oxford Lasers General Terms and Conditions of Sale dated 13 November 2013 apply.
Sales are subject to any prevailing government regulations.

Warranty: Oxford Lasers 12 month warranties conditions of Sale dated 24 April 2013

Price: Is in US dollars and excludes VAT, State and Federal taxes.

Shipment: 16 Weeks after order acknowledgment

Validity: 30 days from quote date

Payment Terms:
a.) 50% payable with order
b.) 50% payable prior to shipment

Quotation issued by:

Robert Barger
Oxford Lasers Inc.
Unit B201 Shirley
MA 01464
Tel: (978) 425-0755
Fax: (978) 425-4487

Figure 9. Oxford Lasers N60V System Quote