Compressed Air Foam Fire Grounds Evolution Tests

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Abstract

Compressed air foam firefighting technology has been purchased by a number of urban fire departments in the United States. These departments have curtailed their use of these systems until potential safety hazards associated with the use of compressed air foam systems in interior structure fires are evaluated. This project is part of a greater effort to evaluate the efficacy and practicality of compressed air foam systems for use in structural firefighting. This project focused on developing test apparatuses and test methods for measuring the following safety-related parameters: 1.) nozzle reaction force of a fire nozzle, 2.) the force required to kink a fire hose, 3.) fire stream throw and distribution, and 4.) friction forces between wetted surfaces. The test apparatuses and test methods developed were then used to measure these four parameters for water and compressed air foam. Results of tests for water and compressed air foam were then compared.

Chapter 1
Introduction

Sponsor Background and Needs

This project is part of a nationwide study sponsored by the US Department of Homeland Security. Our immediate sponsors are Professor Christopher Pascual (California Polytechnic State University, San Luis Obispo) and Professor Fred Mowrer (California Polytechnic State University, San Luis Obispo).

A number of fire departments in the United States have invested significant resources in compressed air foam systems (abbreviated "CAFS") for use in structural firefighting. However, these fire departments have curtailed the use of their CAFS units because of safety concerns associated with using CAFS in an interior attack on a structure fire. Until CAFS safety concerns are addressed, these fire departments will not be able to utilize their CAFS units. Our sponsor has tasked us with evaluating CAFS safety concerns, specifically with regards to fire grounds evolutions and hose handling.

Formal Problem Definition

Data on the hose handling properties of CAFS is needed to determine appropriate practices for safely using CAFS in interior attack on structure fires.

Project Objective

To address the problem, our objective is to measure the following parameters related to fire hose handling, and compare the results for CAFS versus water:

- Nozzle reaction force (i.e. how much force the fireman must provide to hold the nozzle in place)
- Hose kinking (i.e. how easy it is to kink a fire hose)
- Stream throw (i.e. how far fluid is projected from the nozzle)
- Stream distribution (i.e. the distribution of fluid delivery rate at the end of the stream)
- Surface friction (i.e. how slippery surfaces are when wetted with water and foam)

Project Justification

This project is justified because there is currently a severe lack of reliable data on hose handling characteristics associated with CAFS.

Stakeholders

Stakeholders in this project include firefighters, firefighter trainers and educators, and firefighting researchers.

Engineering Specification Development

To develop our formal engineering specifications, we first spent time brainstorming potential customer requirements. We then collected the results of our brainstorming into a survey which we presented to our sponsor. The survey asked our sponsor to rate different suggested customer requirements based on priority level. Using the sponsor's feedback, we then developed formal, quantitative engineering specifications.

The results of the suggested customer requirements survey are provided in Appendix A. Our formal engineering specifications are provided in Appendix B.

Chapter 2
Background

Literature Review

The following literature review covers the chemical mechanisms of CAFS, overviews current mechanical systems used to dispense CAFS, reviews a brief history of the use of CAFS in fire suppression, discusses the current perceived advantages and disadvantages of CAFS, and outlines current CAFS uses in contemporary structural firefighting.

Compressed Air Foam Chemical Overview

Three elements define the firefighting capabilities of Compressed Air Foam. Water provides the capacity to absorb large quantities of heat. Foam solution decreases the water's surface tension, allowing the water to better penetrate fuel sources. Compressed air forms bubbles in the hose line to increase the surface area of the water and throw of the finished foam. (Brooks, 2005)

Fire requires fuel, heat, and oxygen to burn. These three components make up the 'fire triangle.' Attacking any side of this triangle will extinguish a fire. Water-only attack lines remove heat from a fire, which causes the fire to extinguish. CAFS, however, isolates each element of the fire triangle from the others. Finished foam soaks deep into the fuel source, prohibiting ignition. It also blankets the fuel source, effectively separating the fuel from the oxygen supply. Water still absorbs heat from the fire. CAFS effectively dismantles the fire triangle, whereas water can only remove heat from the fire. (Darley, 1995)

CAF Systems can operate using either Class A or Class B foam. Firefighters use Class A foam to combat Class A fires, and Class B foam to combat Class B fires. Class A fires are fueled by solid carbon based fuel sources, while Class B fires are fueled by liquids. Structural fires almost exclusively fall into the Class A category. Class A foam concentrate contains three basic ingredients: a foaming agent, a wetting agent, and an emulsifying agent. The foaming agent gives finished foam the bubble structure it needs to effectively increase the surface area of the water. The wetting agent decreases surface tension of the water in finished foam. By introducing a small amount of foam concentrate to the water, the surface tension decreases dramatically. This allows the finished foam to bond with fuel, rather than beading off the surface. (Brooks, 2007) The emulsifying agent makes the foam bind to carbon molecules, effectively blocking oxygen from reaching the fuel source (Montgomery County 2008). The foaming agent causes foaming action that increases the surface area of the water, thus increasing the heat dissipation rate.

Class A foam will degrade over time when mixed with water, limiting the effectiveness of the finished product. It has a slightly caustic nature, and will erode equipment unless the system is flushed out after each use (Stern and Routley 1996).

Compressed Air Foam Systems Mechanical Overview

A CAFS equipped fire engine has the ability to run water, nozzle aspirated foam, or CAF through its attack lines. For all of these options, the main pump provides water pressure to the attack lines. Typically, a separate foam pump adds foam concentrate to the stream after the main pump, creating a foam solution. The foam pump proportions the foam to a user defined concentration ranging from 0.1% to 3.0% of the liquid stream volume. After the introduction of foam concentrate to the stream, an air compressor charges individual attack lines with compressed air, creating finished foam at the nozzle. Fire engines do not typically store pre-mixed foam solution.

History of Compressed Air Foam Systems

The Royal Navy first developed Compressed Air Foam Systems for maritime fire suppression in the 1930s. By the 1940s the British and United States Navy had both developed high energy (compressed air) Class B foam systems to fight fuel fires (Coletti 1998, Darley 1995). Early designers of CAFS focused on extinguishing Class B fires, specifically fuel spill fires and oil tanker fires. The fire industry did not investigate CAFS for use on the mainland until the early 1970s. Mark Cummins invented the first modern CAF System for use on Class A wild land fires while working for the Texas Forest Service. Cummins holds US Patent 4318443 for his invention. Firefighters nicknamed his system the "Texas Snow Job" because the finished foam resembled fresh snowfall. The Texas Snow Job produced finished foam using water, pine oil soap, and compressed air. Pine soap is not a true Class A foam, but rather a byproduct of paper manufacturing processes. It has limited effectiveness compared to products available today, and requires higher mix ratios up to 9% (Coletti 1998). Although rudimentary compared to today's technology, this early system proved CAFS worked in the wild land environment and set the stage for modern technological developments. It also created demand for a true Class A foam, as well as incentive for further development of CAFS technology. Foam companies responded with the first true Class A foams for firefighting in the early 1980s. This new foam concentrate required mix ratios from 0.1% to 1.0% thus increasing the economic viability of foam systems. (Stern and Routley 1996)

Wild land firefighters originally used Class A foam to increase the effectiveness of available water and to stretch thin water supplies farther, but firefighters soon noticed that CAFS had other advantageous applications. In the late 1980s firefighters began using foam systems to pre-treat structures endangered by wild land fires. CAFS gained public notoriety in 1988 when firefighters successfully protected the Old Faithful Lodge in Yellowstone National Park from a particularly notorious wild land fire by blanketing the structure with a layer of finished foam. (Darley, 1995). The successful application of CAFS in the urban/wild land interface prompted forestry officials to suggest the use of CAFS in structural fires. In the early 1990's municipal fire departments began implementing CAF systems and testing their limits and capabilities in structural fires. (Coletti 1998) At this time very few manufacturers developed exclusive CAF systems due to small market size, and many were simply retrofits to existing systems. Early CAF

systems were unpredictable and difficult to adjust. In structural fires the engineer controlling hose flow characteristics often lost visual contact with the firefighters handling the attack line. This created a dangerous situation. CAF systems with improper settings can provide ineffective fire suppression during interior attack, or in the worst case inadvertently fuel a structural fire. If the water flow shuts off and the compressed air supply does not an attack line pumps air onto a fire effectively fueling it. Either situation potentially endangers firefighters' lives. (Miller 2011) A report by The Boston Fire Department notes difficulty operating controls on a fire engine retrofitted with CAFS, but suggests systems originally designed for CAFS operation would alleviate this problem. The automation of foam portioning and air compressor flow have contributed greatly to the increased reliability and safety of modern CAF systems. (Routley 1994)

Advantages and Disadvantages of Compressed Air Foam Systems

CAFS provides many advantages when compared to traditional water-only attack lines on Class A structural fires. The system also has some dangers associated with its use. This section outlines the potential advantages and disadvantages of CAFS when compared to water-only attack.

Fire Suppression

Available live burn tests indicate CAFS outperforms both water and nozzle aspirated foam in fire suppression ability. Tests report faster knockdown time and decreased water usage, as well as faster temperature degradation. Several live burn tests have been conducted to compare the effectiveness of CAFS to nozzle aspirated foam and water-only attack lines.

In the Salem Tests a group of fire departments and fire equipment manufacturers compared the fire suppression ability of CAFS to plain water and foam solution. The tests measured temperature decline at the ceiling and at four feet above floor level in identical rooms burned in acquired structures. After flashover, the tests ran all three attack lines flowing 20 GPM of water, with a 60 second initial attack on the ceiling of the structure followed by 60 seconds of attack on the interior room. Both water and foam solution flowed through an adjustable fog nozzle set to straight stream, while the CAFS attack line used a smooth bore nozzle. The test results show that at the ceiling all attack methods lower temperature very quickly. Because the firefighter directed initial attack at the ceiling, thermocouple contact with water or foam solution caused a rapid reduction in temperature. At the four foot level the test shows that CAFS reduces temperature from 1000 F to 212 F almost 6 times faster than a water-only attack. Water took 222.9 seconds to create this reduction in temperature, foam solution took 102.9 seconds, and CAFS took 38.5 seconds. The test notes that the efficiency of the foam solution could increase with an air-aspirating nozzle, but this test replicated similar streams for each working fluid to isolate the differences between them. (Coletti 1993)

Tests conducted by the Los Angeles County Fire Department indicate CAFS produces knockdown four times faster than water, decreases temperature four times faster than

water, and uses one fourth of the water supply when compared to a water-only attack. The tests were conducted on three full scale room burns in identical acquired structures. All attacks used a 1-1/2" hose. Nozzle aspirated foam and water only tests used a combination nozzle, while the CAF test used a 1" smooth bore nozzle. The tests indicate that CAFS cools rooms more quickly than water-only jets. Additionally, water exhibits a lag time before cooling begins, whereas CAFS begins cooling almost immediately. CAFS also outperformed nozzle aspirated foam. The Los Angeles County Fire Department (LACFD) noted the following observations of effective CAFS methods for interior structural attack: 1.) CAF attacks require the same flow rate as water-only attacks, 2.) CAF also reduces temperatures faster than water-only jets (not fog) but upper portions of rooms remain hot, thus the attack team should stay low once entering the interior, 3.) CAF generates a large volume of steam. LACFD recommends using low foam concentrations on interior attack, as high foam concentrations produce finished foam that does not penetrate very well. (Cavette 2001)

A report by FEMA in 1994 compares room burning tests using CAFS and water. The tests indicated quicker extinguishment times for CAFS in two out of three tests and lower total water usage by CAFS in two out of three tests. The report states that the field tests of CAFS do not provide conclusive results because of the limited extent and duration of the program. (Routley 1994)

Finished Foam Overview

The finished foam produced by CAFS offers other advantages in addition to chemically enhancing the effectiveness of water. The bubbles produced by CAFS form a highly visible solution, allowing Firefighters to easily see where foam has and has not been applied. Additionally, the foam adheres to vertical and horizontal surfaces instead of running off as water does. Finished foam stays where the firefighter needs it, and works more effectively than water to extinguish fires.

The chemical advantages of foam do not come without some drawbacks. Foam concentrate can cause irritation to the skin and eyes, and the foam solution and finished foam can decrease the life of leather products and corrode some metals and paint finishes. Foam systems require flushing with water after every use. Although considered biodegradable, large concentrations of foam solution can negatively impact the environment. (Darley 1995) Finished foam also has the potential to increase slip hazards to firefighters. Not all firefighters acknowledge this hazard as significant. The Boston Fire Department notes that foam concentrate creates extremely slippery surfaces when spilled on deck rails of fire engines. They also state that a trial run of CAFS produced very few problems. One out of 146 calls resulted in slipperiness being a problem, five resulted in skin irritation, and one resulted in a "strong foam odor". (Routley 1994) Because finished foam is opaque it has the potential to obstruct floor hazards. In an already dimly lit environment, several inches of foam can obscure view of hazards lying on the floor.

Water Usage

CAFS reduces the total amount of water required to effectively extinguish a fire by providing a quicker knockdown, not by using a lower flow rate. Because CAFS uses water more effectively than nozzle aspirated foam or water only attack lines, an attack requires less total water. (Coletti 1993) The Los Angeles Fire Department conducted tests that determined CAFS used a quarter of the water to extinguish a fire when compared to water-only attack. (Cavette 2001) The Salem Tests indicate CAFS only needs one sixth of the water to reduce room temperature 788 °F when compared to water only attack. (Colletti 1993)

Water usage becomes less critical in an urban environment due to close proximity of fire hydrants to most structures. The advantage that CAFS gives to stretch thin water supplies farther is no longer significant in urban fires, however the reduction in water consumption associated with lower water usage is. CAFS results in less water damage to structures by using less water to extinguish fires. The danger of structural collapse due to added water weight significantly decreases with the use of CAFS. According to The Boise Interagency Fire Center, insurance companies pay out 75 cents of every dollar to cover water damage, not direct fire damage (Brooks 2005). Reducing water damage has significant money-saving potential.

Nozzle Reaction, Line Handling, and Hose Throw

Most operators notice a significant increase in line mobility comparing CAFS attack lines to water-only attack lines. A 1.75" CAF attack line weighs on average 61% of a typical water-only attack line. (Taylor 1997) The Boston Fire Department indicates on a trial run of a CAFS system in an urban environment, out of 146 instances of CAFS being used, 133 times CAFS was reported easier to maneuver than water only, 10 times CAFS was reported same, and 2 times CAFS was more difficult to maneuver. Their report only indicates some problem with CAFS hose line kinking on 2 out of 146 uses. (Routley 1994)

The Los Angeles County Fire Department reports higher nozzle reaction forces and increased hose throw when using CAFS. Focusing the initial attack through an open window or doorway capitalizes on the advantage of greater hose throw. The Los Angeles County Fire Department recommends pistol grip nozzles to combat the increased reaction force, as well as protective eyewear to shield the user from objects kicked up by the CAF stream. (Cavette 2001)

A separate report by the Morristown Fire Bureau indicates CAF attack lines produce greater reaction forces than water only attack lines at equivalent water flow rates. The report also indicates charged CAF lines resist bending more than water-only attack lines. (Taylor 1997) Although this report references bending forces, the experimental methods used to determine these forces are questionable. Further investigation is required.

Line Burst

Compressed Air Foam lines pose an increased threat of line burst. Two firefighters were killed in Germany in 2006 using CAFS to combat an interior structural fire. Among several other factors, line burst from exposure to radiant heat contributed to their deaths. The police investigation of the firefighters' deaths found that in radiant heating conditions, such as those produced by a bed of coals, CAF lines burst in under a minute at 394 degrees Fahrenheit. It took water-only lines several minutes to burst in the same conditions. (de Vries 2007) CAF lines have a much lower heat capacity compared to water-only lines, especially when foam solution is not flowing through the line. CAF lines also have the potential to burst more violently than water only lines due to the stored energy of the compressed air.

Contemporary Use in Structural Fires

Firefighters in departments outfitted with CAFS units utilize CAFS at the discretion of the company manager. Although CAFS has gained acceptance by many fire departments, others hesitate to implement the new technology. The fire departments that do implement CAFS report positive results.

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Applicable Codes and Standards

No directly applicable codes or standards exist for measuring nozzle reaction, hose throw, area of influence, or kinking forces.

Several ASTM tests that exist to measure friction apply to the friction measurement portion of this project. ASTM G115-10 gives an overview of the various ASTM test methods used to measure coefficients of friction and gives standards for reporting them. ASTM F609-05 covers the procedure for using a standard horizontal pull slip meter, and includes guidelines for reporting statistical analysis. This test method uses rubber samples to simulate shoe soles. ASTM C1028-07 outlines a similar method intended to measure the static coefficient of friction on tile, ceramic and other like surfaces using a horizontal dynamometer pull-meter. ASTM D4103-90 covers the standard practice for preparation of substrate surfaces for coefficient of friction testing. Other friction tests exist that are applicable to some degree. ASTM D2047-11 tests the static coefficient of friction for polished surfaces using the James Machine. ASTM F462-79 covers the use of a NIST-Brungraber Machine to determine safety specifications for slip-resistant bathing facilities.

Existing Products and Solutions

Although individual components exist to aid in the design of each test apparatus, no complete apparatus exists to gather data for any of the required tests. Existing components include hose couplings, force transducers, fire hose flow meters, dynamometers, and pull meters. Various groups of firefighters have measured parameters important to this project; however none of these groups produced results with scientifically significant results. None include uncertainty or confidence intervals, and some were purely qualitative. These tests could be used as a starting point for developing test parameters in the tests conducted in this project.

Chapter 3
Design Development

This chapter documents our top concept designs for each apparatus. It focuses on the strengths and weaknesses of each concept, and provides justification for the selected concept.

Nozzle Reaction Force Measurement Apparatus

There were three top concepts for the reaction force measurement apparatus. They are listed below, with a brief discussion. Sketches of each concept are included.

Top Concepts

Linear Slide Concept

The linear slide concept secures the nozzle in a linear slide mechanism. When fluid is flowing through the nozzle, the slide moves back slightly, but is resisted by the force measurement device. The force measurement device is zeroed in position before the nozzle shut-off is opened. Once the nozzle shut-off is opened, the force measurement device measures the additional force applied by the flowing fluid. See Figure 3.1 for a sketch of the linear slide concept. See Table 3.1 for an overview of pros and cons of the linear slide concept.

Table 3.1 – Pros and cons of the linear slide concept for the nozzle reaction force measurement apparatus.

Pros	Cons
Entire apparatus may be very small, and could possibly be mounted on a pitch and yaw device.	Has a moving part that needs to be kept clean.
	Only measures one component of force.

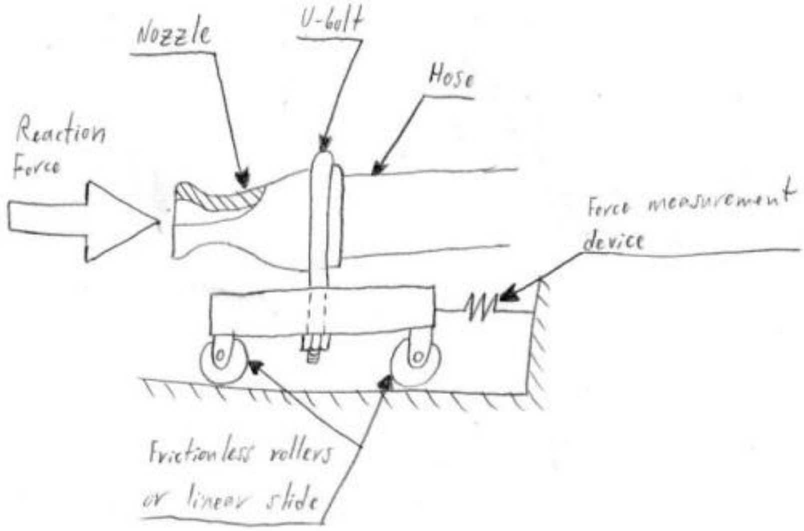


Figure 3.1 – Sketch of the linear slide concept for the nozzle reaction force measurement apparatus.

Moment and Lever Arm Concept

The moment and lever arm concept fixes the nozzle to the end of a lever arm. Then, the force measurement device is located on a lever arm that is perpendicular to the original lever arm. When fluid flows through the nozzle, the reaction force creates a moment which is measured by the force measurement device. See Figure 3.2 for a sketch of the moment and lever arm concept. See Table 3.2 for an overview of pros and cons of the moment and lever arm concept.

Table 3.2 – Pros and cons of the moment and lever arm concept for the nozzle reaction force measurement apparatus.

Pros	Cons
Allows for adjustable force amplification, since you can adjust the distance at which the force measurement device is located.	Has a hinge that needs to be kept clean.
	Device is large/unwieldy compared to other devices.
	Only measures one component of force.
	Difficult to mount on a pitch and yaw device.

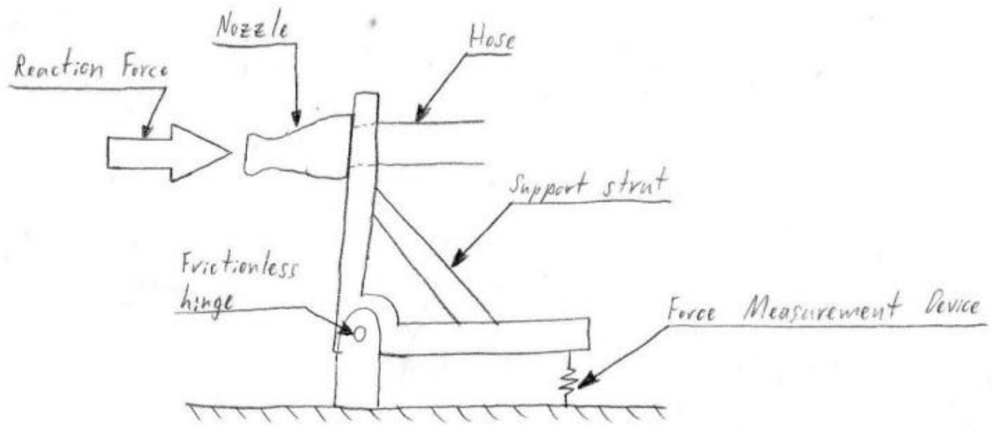


Figure 3.2 – Sketch of the moment and lever arm concept for the nozzle reaction force measurement apparatus.

Cantilever Beam Strain Concept

The cantilever beam strain concept secures the nozzle to the end of a cantilever beam. The other end of the cantilever beam is secured to a rigid base plate. The cantilever beam is instrumented with strain gauges that indicate the load state in the cantilever beam. These strain gages are used to measure the nozzle reaction force. See Figure 3.3 for a sketch of the cantilever beam strain concept. See Table 3.3 for an overview of pros and cons of the cantilever beam strain concept.

Table 3.3 – Pros and cons of the cantilever beam strain concept for the nozzle reaction force measurement apparatus.

Pros	Cons
No moving parts.	Requires strain gage reader.
No maintenance.	Requires expensive instrumentation.
Potential for high accuracy and repeatability due to lack of moving parts.	
Able to measure full three-dimensional forces and moments.	

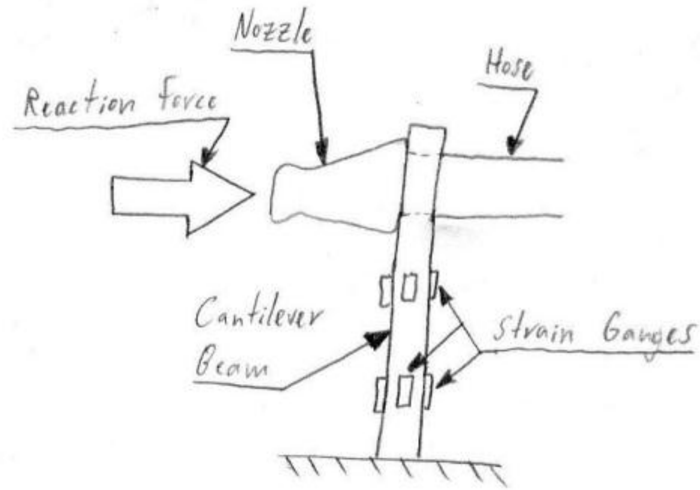


Figure 3.3 – Sketch of the cantilever beam strain concept for the nozzle reaction force measurement apparatus.

Selected Concept and Justification

Selected Concept for Preliminary Tests

For preliminary testing, we selected the moment and lever arm concept. We selected this concept because it is the concept that is the easiest to manufacture. Manufacturing speed was a top priority for our preliminary testing because we only had four weeks to go from conceptual design to final manufactured and functioning product.

The cantilever beam strain concept was not desirable for our preliminary testing because of its high cost (its cost was estimated to be at least $1400). Since the preliminary tests were intended to uncover errors/issues in our measurement procedure, and were never intended to produce the final data set, the high cost of the cantilever beam strain concept was unacceptable. The cantilever beam strain concept would also take a long time to manufacture, and we would probably not have had it done by our preliminary test date.

The linear slide concept did not have an issue with high cost, but it was ruled out because it was more difficult to manufacture than the moment and lever arm concept since it needs a relatively frictionless linear slide mechanism, which requires small dimensional tolerances and precise alignment of components.

Selected Concept for Final Tests

Before selecting our concept for the final round of testing, we wanted to test to see if there were any significant nozzle reaction forces in the lateral direction (i.e. if there were any components of nozzle reaction force that were not directed straight back along the axis of the nozzle). If there were no significant lateral nozzle reaction forces, we would

stick with the moment and lever arm concept we used in the preliminary tests. If we found that there were significant lateral nozzle reaction forces, then we would have to choose the more expensive cantilever beam strain concept for our final testing since it is the only concept that is able to measure transverse nozzle reaction forces.

We devised a simple test for determining if there were significant lateral nozzle reaction forces. This test is illustrated in Figure 3.4 below. We took a fire hose nozzle, oriented it so it would shoot straight horizontally, and held a point on the hose about two feet back from the nozzle so that the hose and nozzle were cantilevered. The water pressure in the hose made the hose stiff enough that the nozzle was easily held up off of the ground, and remained nearly horizontal. Next, we observed that the hose and nozzle were straight (when viewed from above) when we did not have water flowing through the nozzle. Therefore we took the straight hose and nozzle to be our equilibrium position (i.e. the position that indicated that no lateral forces were acting on the nozzle). Then we opened the nozzle and observed that the hose and nozzle were still aligned in a straight line when viewed from above. If there had been lateral forces at the nozzle, then the hose would have deflected to the left or right when water flowed through the nozzle. Finally, we pulled laterally on the nozzle with a spring scale until we got a noticeable lateral deflection in the cantilevered hose. By measuring the lateral force required to create a noticeable deflection in the hose, we could safely assume that any lateral forces created by the nozzle must be less than the lateral force we applied, since the hose did not have any noticeable lateral deflection before we applied a lateral force with the spring scale.

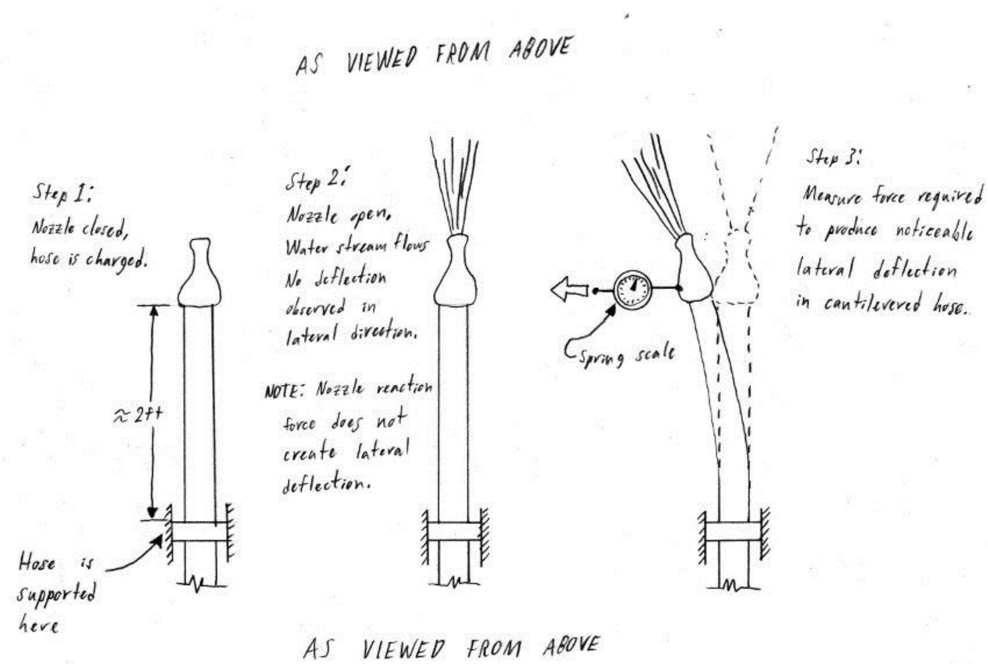


Figure 3.4 – Illustration of our test for lateral nozzle reaction forces.

In conclusion, we found that the lateral nozzle reaction forces were less than three pounds of force. Since this force is negligible compared to the axial nozzle reaction force, we determined that lateral nozzle reaction forces are negligible and need not be measured.

Since we determined that lateral nozzle reaction forces were negligible, the cantilever beam strain concept was not needed. So, we used the moment and lever arm concept in our final tests.

Hose Kink Force Measurement Apparatus

Conceptual Design

In designing the apparatus, the main objective I had in mind was that the kinking force had to remain perpendicular to the hose. I considered a hinge motion and a rotary motion for the test. Upon further consideration, I learned that the hinge test would not provide a constant perpendicular force. This lead to the rotary-style test, and a large pulley was the natural choice. I tried to keep the contraption as simple as possible, so there is not much more to it.

Stream Throw and Distribution Measurement Apparatuses

To measure the throw and distribution of the stream, I decided to use an array of collectors to capture the fluid. A variety of receptacles were considered, listed below.

Top Concepts

<u>Rain Gauge</u>

A typical rain gauge, typically measures up to 5 inches of fluid with an opening of about 1 inch diameter. Table 3.4 gives the pros and cons of this concept.

Table 3.4 – Pros and cons of the rain gauge concept for the stream throw and distribution tests.

Pros	Cons
Cheap.	Very small collection volume.
Accurately measures volume of fluid collected.	Small collection area; would need many gauges.
	May get knocked over.

<u>PVC pipe</u>

Use cut lengths of PVC pipe in a grid. Would have to construct a grid/holder for these, and cap each tube section. Table 3.5 gives the pros and cons of this concept.

Table 3.5 – Pros and cons of the PVC pipe concept for the stream throw and distribution tests.

Pros	Cons
Can be cut to optimum length.	Need an array to hold up pipes.
Can choose optimum collection area.	Cannot sight-check volume.
	May get knocked over.

<u>5-Gallon Buckets</u>

Typical 5-gallon buckets from Home Depot. Table 3.6 gives the pros and cons of this concept.

Table 3.6 – Pros and cons of the 5-gallon bucket concept for the stream throw and distribution tests.

Pros	Cons
Cheap.	Low resolution.
Can choose optimum placement.	Cannot sight-check volume.
Large collection area.	
Can weigh down.	

<u>Souvenir Cups</u>

Vegas-style, hourglass shaped cups. Have a reservoir in the bottom and a large opening on top. Table 3.7 gives the pros and cons of this concept.

Table 3.7 – Pros and cons of the souvenir cup concept for the stream throw and distribution tests.

Pros	Cons
Has collection reservoir.	Can get knocked over.
Can choose optimum placement.	Have to order large batch.
Large collection area.	Long lead time.

Selected Concept for Preliminary Test

For the preliminary test I chose the 5-gallon bucket. I chose this receptacle because it is the most versatile. I was unsure about how the flow distribution would behave, so I wanted to be able to adjust the test as much as I could. The rain gauges and PVC pipes don’t hold very much volume, and I wasn’t sure how much water would have to be collected.

I was also not sure how forceful the water would be when it hit the ground. The 5 gallon buckets are big enough to fit known amounts of weight inside of them, providing an anchor. The buckets were also the easiest to obtain, and inexpensive. The souvenir cups had to be ordered in a large batch from a manufacturer, and would require a long lead time. The PVC pipe would require a stand, which would lock the tubes in an array, limiting the versatility of the test. The rain gauges were also inexpensive, but they were very lightweight. I was concerned about the gauges falling over in the water stream.

For the test I bought 5 buckets and recorded their longitudinal and lateral distances from the nozzle. I originally placed them in a cross-type pattern with once bucket in the middle, but then changed it to 5 in a row, in line with the stream.

Selected Concept for Final Test

When we performed the preliminary test, I learned that the water falls almost vertically on the ground and it is very much dispersed. The buckets had a miniscule amount of water in them at the end of each run, making the collected fluid amount immeasurable. The wind is a major factor in the distribution, making the water or CAFS fall almost like rain. Therefore, if we proceed with a final distribution test, I think extra-large rain gauges would be the best option for measuring the amount of fluid collected.

Friction Force Measurement Apparatus

There were five top concepts considered for the friction testing measurement apparatus. They are listed below, with a brief discussion. Visual representations of each concept are included. There were also three top concepts for partitioning a test surface to conduct friction testing in a wet and/or submerged environment. We used a preliminary design to investigate the feasibility of various options, and based the final design concept on the information we gained from the preliminary design.

Top Concepts for Measurement of Friction

Nist-Brungraber Mark II

The Nist-Brungraber Mark II is a pre-existing device designed to measure the coefficient of friction of bathing surfaces. It applies a force to a test specimen in order to determine the static coefficient of friction. Figure 3.5 shows a picture of the device. The device was originally intended to measure the slipperiness of various bathing surfaces in dry, wet, and soapy conditions, and an ASTM test method exists outlining the use of the device. Table 3.8 lists pros and cons of this device.

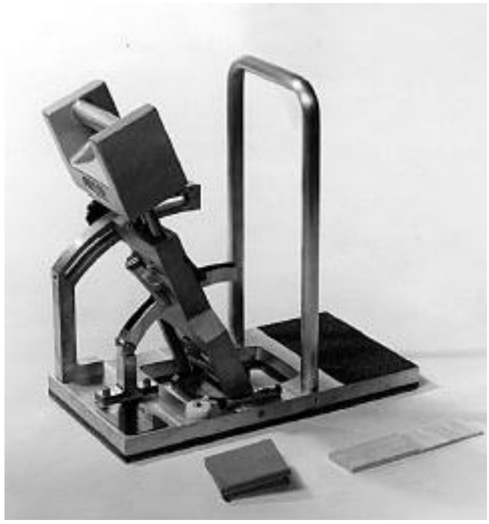


Figure 3.5 – Nist-Brungraber Mark II friction testing apparatus.

Table 3.8 – Pros and cons of the Nist-Brungraber Mark II friction testing apparatus.

Pros	Cons
Already manufactured.	Expensive.
Designed for wet/soapy surfaces.	Only measures static friction coefficient.
Existing test method (ASTM F462-79).	Not designed for submerged surfaces.
Portable.	

James Machine

The James Machine is another pre-existing device that operates similarly to the Mark II. Instead of being portable like the Mark II, the James Machine is large and was designed for laboratory testing. Figure 3.6 shows a picture of the James machine. It was originally designed to measure the coefficient of friction of polished floor surfaces. An ASTM test method also exists for the James machine. Table 3.9 lists pros and cons of this device.

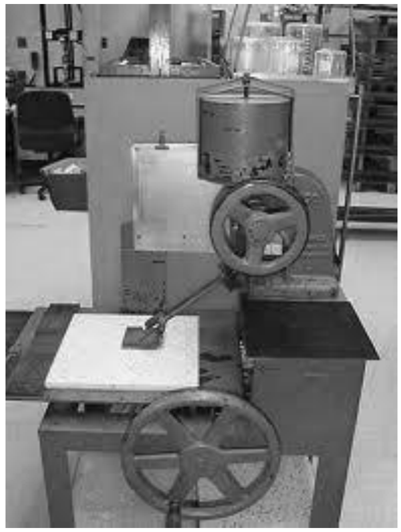


Figure 3.6 – James Machine friction testing apparatus.

Table 3.9 – Pros and cons of the James Machine friction testing apparatus.

Pros	Cons
Already manufactured.	Expensive.
Existing test method (ASTM D2047-11).	Only measures static friction coefficient.
	Not designed for submerged surfaces.
	Not portable.

Horizontal Pull Slip-Meter/Dynamometer

This section groups together two very similar designs in which a weighted test specimen is dragged across a surface to determine the static and/or dynamic coefficient of friction. The design can use different weights for the sled and different force measurement devices to determine the friction forces. The specimen may be propelled by hand or by mechanical means. Figure 3.7 shows an example of a horizontal pull slip-meter driven by a mechanical device. Several ASTM specifications exist outlining the use of these devices. Table 3.10 lists pros and cons of this device.

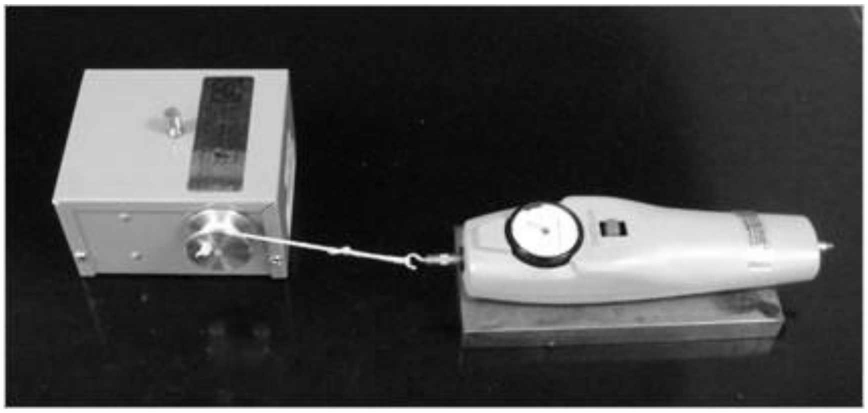


Figure 3.7 – Horizontal pull slip-meter testing apparatus.

Table 3.10 – Pros and cons of the horizontal pull slip-meter testing apparatus.

Pros	Cons
Some parts already manufactured.	
Existing test methods (ASTM C1028-07 and ASTM F609-05).	
Versatile.	
Static and dynamic friction measurements.	

Spring Scale Horizontal Pull

Instead of using any measurement devices included in the slip-meter/dynamometer design, this design uses a spring scale and requires the operator to take measurements by sight. The user pulls the sled by hand to generate friction forces. We included this design as a benchmark for other designs. Table 3.11 lists pros and cons of this concept.

Table 3.11 – Pros and cons of the spring scale horizontal pull concept.

Pros	Cons
Cheap.	Low accuracy.
Low tech.	High human error factor.
Static and dynamic friction measurements.	Low repeatability.

Top Concepts for Partitioning a Test Surface

Design I – No Partition

This design is included as a benchmark, and includes no partition barrier to maintain a wet and/or submerged surface. To maintain such a surface the user must apply

water/foam solution by hand from a bucket. Table 3.12 lists pros and cons of this concept.

Table 3.12 – Pros and cons of the no partition concept.

Pros	Cons
Cheap.	Low accuracy.
Low tech.	High human error factor.
	Low repeatability.
	Messy.

Design II – Test Tray

This design involves the construction of a tray to conduct wet and submerged friction testing in. By conducting tests in a controlled environment, this design also requires a test sample to be manufactured for each surface. Table 3.13 lists pros and cons of this concept.

Table 3.13 – Pros and cons of the test tray concept.

Pros	Cons
Highly controllable environment.	Build-intensive.
Clean.	Not portable.
	Must manufacture test specimens.

Design III – Test Barrier

This design involves the construction of a barrier to hold fluid in a controlled area. The barrier may be placed on any surface and thus allow the testing of any surface without manufacturing a test specimen. Table 3.14 lists pros and cons of this concept.

Table 3.14 – Pros and cons of the test barrier concept.

Pros	Cons
Versatile.	Leakage.
Portable.	Not as much control.

Selected Concept and Justification

Selected Concept for Preliminary Test

For preliminary testing, we selected the spring scale horizontal pull and test barrier concept. We selected this concept because it is the concept that is the quickest to manufacture. Manufacturing speed was a top priority for our preliminary testing because

we only had four weeks to go from conceptual design to final manufactured and functioning product. See Appendix C for the decision matrices used to make this decision.

Although the horizontal pull slip-meter/dynamometer concept showed more viability in the decision matrix, we chose to advance with a spring scale design for preliminary testing because of reduced cost and simplicity of design/manufacture. Purchasing a commercial horizontal pull friction test kit costs over $1000, and this high cost is unacceptable for preliminary testing. By using the simplest design possible for preliminary testing we were able to identify critical design parameters for the final design.

Chapter 4
Description of the Final Design

This section describes the apparatuses that we constructed for our preliminary and final field tests.

Nozzle Reaction Force Measurement Apparatus

This section describes the final design of the nozzle reaction force measurement apparatus. This is the prototype that we originally built for our first field tests on March 2^{nd}, 2012. Since it performed well enough in the preliminary tests, we used the same prototype in the final tests on May 5^{th}, 2012.

Refer to Appendix E for dimensioned drawings of each part and sub-assembly, as well as the names of each part.

Operation and Layout

The nozzle reaction force measurement apparatus uses the moment and lever arm concept to transfer force from the nozzle to the weight scale via a hinge. A few annotated layout drawings will make the details more clear.

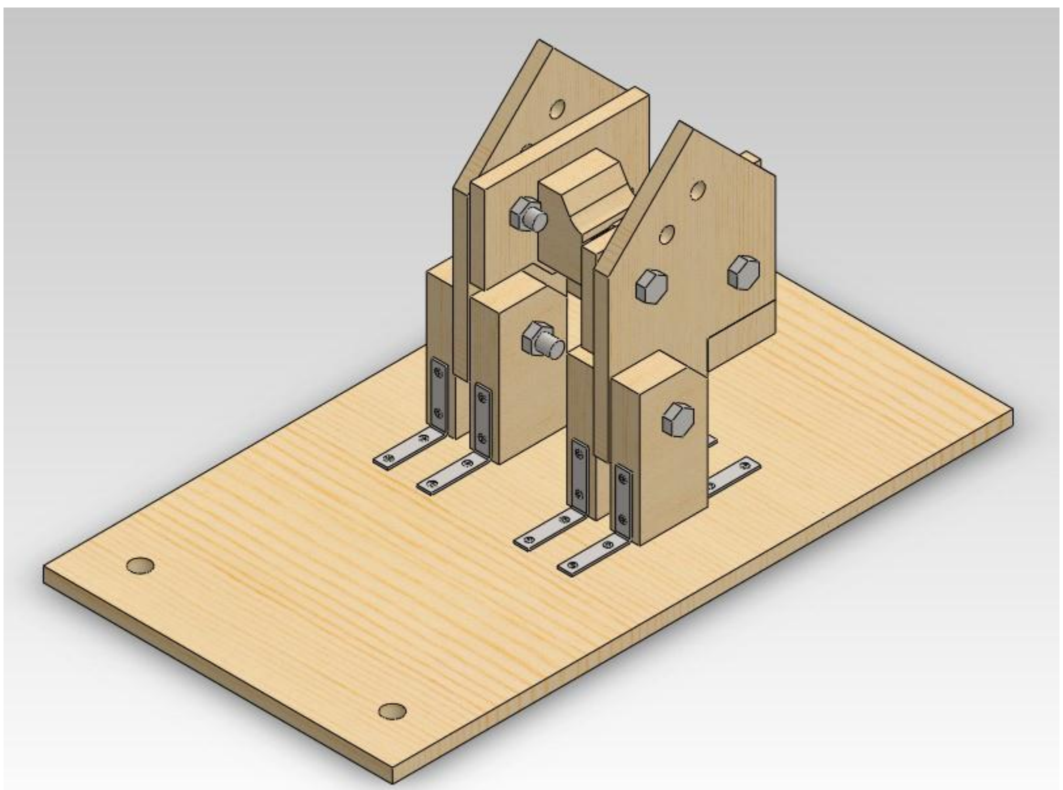


Figure 4.1 – Isometric view of the nozzle reaction force measurement apparatus.

Figure 4.1 shows the overall appearance and layout of the nozzle reaction force measurement apparatus. The supports that protrude straight up from the base (the ones that are supported by L-brackets) support the main hinge. This is the pivot for the lever arm.

Besides the two bolts that make up this main pivot, there are four bolts that hold the Holder Sub-Assembly (the part that the fire hose nozzle is secured to) to the Angle Plates. The Angle Plates are the plates that pivot on the main hinge.

There are two “extra” holes in each Angle Plate. These holes are for tilting the nozzle at a 22.5° angle, and a 45.0° angle. While we only carry out reaction force tests at 0.0° above horizontal, we use the 22.5° and 45.0° angle settings to angle the nozzle during the stream throw and distribution tests. This allows us to quickly transition into stream throw and distribution tests without having secure the nozzle to a different apparatus first.

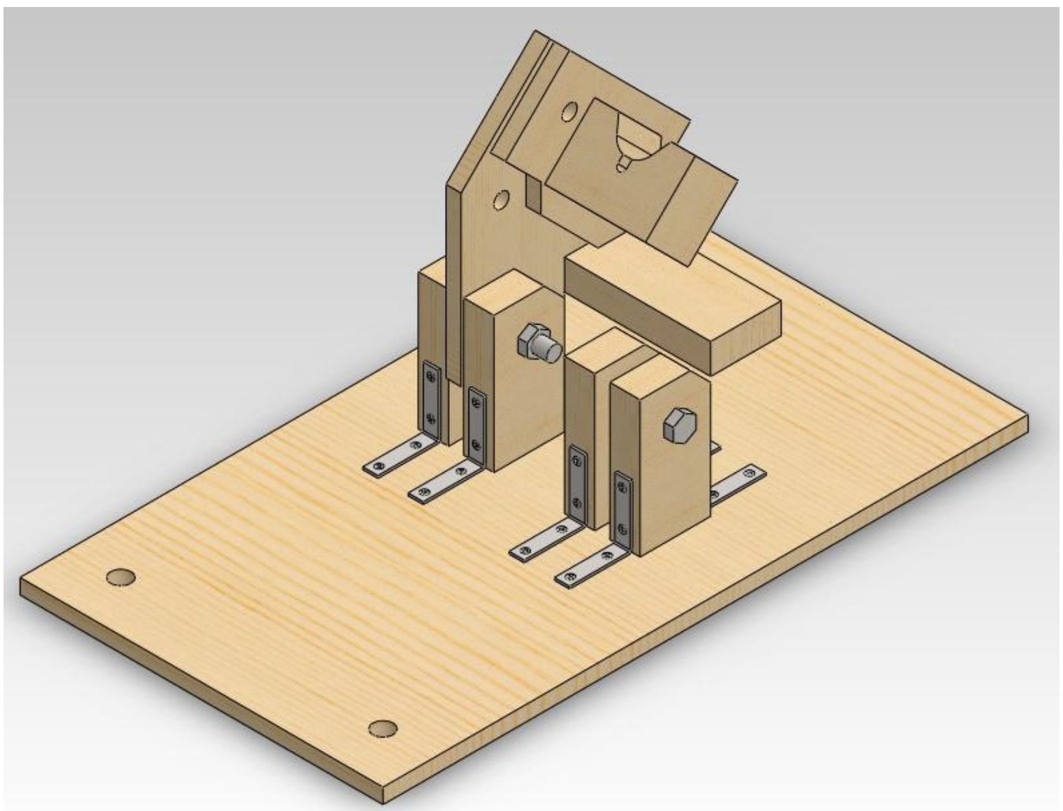


Figure 4.2 – Reaction force tester apparatus, showing the V Holder channel and demonstrating the 45.0° angle setting.

In Figure 4.2, some parts are removed from the apparatus to better show the channel in the V Holder, as well as how the apparatus is able to angle the nozzle at 45.0° above the horizontal.

The channel in the V Holder is designed to receive the female hose coupling that the fire hose nozzle is attached to. To secure the nozzle to the reaction force tester apparatus, you set the female hose coupling into the channel in the V Holder, then strap it down with a screw type hose clamp that is installed around the entire V Holder (the hose clamp is omitted from these diagrams). To reiterate, the hose clamp is already installed around the entire V Holder, and runs through a channel between the V Holder and the two Sliding Plate parts.

The holes in the front part of the Base are for securing the entire reaction force tester to the ground. During setup, the operator must drive 0.75" diameter stakes into the ground through the holes in the front of the Base. These stakes keep the reaction force tester from sliding when subjected to the nozzle reaction force. The front of the Base must also be weighted down to keep the front of the base from lifting off the ground during loading.

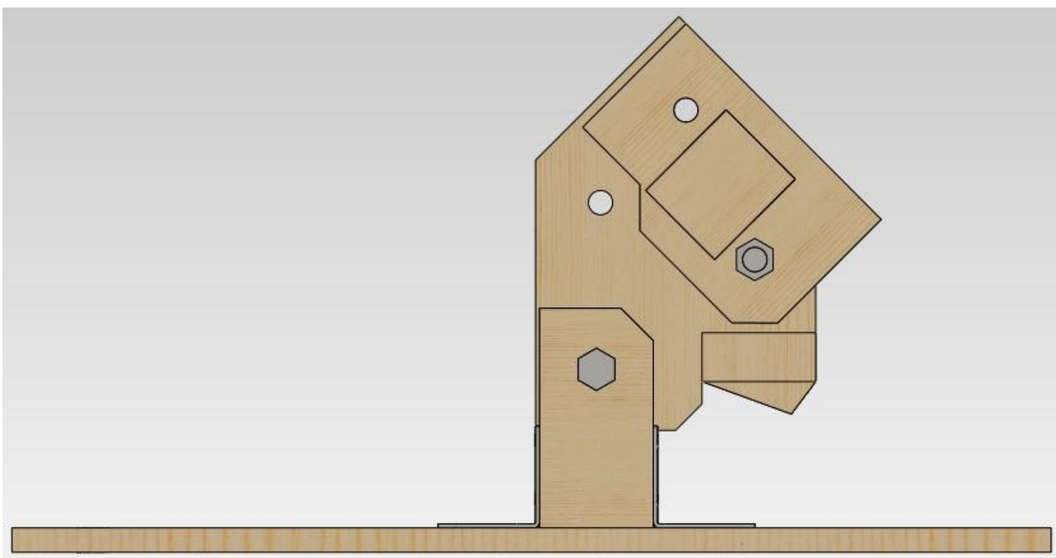


Figure 4.3 – Side view of the reaction force tester with some parts removed for clarity.

Figure 4.3 shows a side view of the reaction force tester. The point at which the load is applied to the weight scale is clearly shown in this figure. The load is applied to the load scale via the point at the tip of the triangle on the bottom of the Crossbeam. At this point, the lever arm of the vertical force applied to the weight scale is 6.0 inches from the main pivot. When the reaction force tester is set at 0.0° above horizontal, the lever arm from the centerline of the nozzle is also approximately 6 inches from the main pivot (this is only approximate because it depends on the outer diameter of the specific female hose coupling you set in the V Holder). Since the two lever arms are approximately equal, there is a force amplification factor of about 1.0 for most hose coupling sizes.

The operator can set any scale down between the Base and the point at the bottom of the Crossbeam. There is 3.5 inches of space between the Crossbeam load transfer point, and the top surface of the Base, so any scale that will fit in that space can be used with this

apparatus. A shorter scale does have to be elevated though, in order to keep the entire apparatus level and ensure that force is applied directly downward on the scale.

Load Analysis Results

Since we have very loose weight requirements for our product, and reliability was an important requirement, we designed the reaction force tester to have safety factors of at least 3.0 at all probable points of failure.

Our analysis looked at the following possible points of failure.

- The hose coupling lugs that transfer the force to the V Holder part.
- The screw joint between the V Holder and Sliding Plate parts.
- The bolted joint between the Sliding Plate parts and the Angle Plate parts.
- The main pivot joint.
- The screw joint between the L-brackets and the Base Support parts.
- The screw joint between the L-brackets and the Base part.

The statics of the analysis was first carried out on paper, then the equations were entered into a MATLAB script that computed safety factors for each joint, as well as other pertinent information. The full MATLAB script is provided in Appendix F.

The results are as follows for the design load of 150 lbf of nozzle reaction force. (Note: the analysis was performed for 150 lbf at 0.0°, 22.5°, and 45.0° above horizontal. Also, safety factors listed are the lowest safety factor encountered in the joint for any design condition.)

- Safety factor on coupling rocker lug failure is 3.28.
- Safety factor on V Holder/Sliding Plate screw joint is 2.15.
- Safety factor on Sliding Plate/Angle Plate bolted joint wood bearing stress is 5.99.
- Safety factor on Sliding Plate/Angle Plate bolted joint wood tensile stress is 3.60.
- Safety factor on the main pivot joint wood bearing stress is 3.53.
- Safety factor on the main pivot joint wood tensile stress is 2.12.
- Safety factor on shearing of the screw joint between the L-brackets and the Base Supports is 3.35.
- Safety factor on shearing of the screw joint between the L-brackets and the Base is 4.20.

Further relevant results of this analysis are as follows.

- The weight scale must be able to handle 211.47 pounds of force (with a safety factor of 1.0).
- The stakes in the ground must handle a load of 75.00 pounds of shear force each (with a safety factor of 1.0).

- The front of the base plate must be weighted with 55.30 pounds of downward force to prevent the reaction force tester from tipping (with a safety factor of 1.0).

Cost Analysis

In truth, we did not perform any formal cost analysis for this prototype because the development cycle was so fast (four weeks to move from a conceptual idea to fully functioning hardware), and the predicted cost of materials was so low. It simply was not a priority in our case.

That being said, Table 4.1 provides a breakdown of the actual material costs we incurred in building the first prototype of the nozzle reaction force measurement apparatus.

Table 4.1 – Material costs for a single nozzle reaction force measurement apparatus.

Material	Price Per Unit	Quantity	Cost
23/32" Thick ADX Plywood Sheet	$9.89	1	$9.89
2X4 Dimensional Lumber, 9' Length	$1.79	1	$1.79
4X6 Dimensional Lumber, 1' Length	$1.61	1	$1.61
3X3 L-Bracket	$1.49	8	$11.92
0.75"X2.5" Hex Head Bolt, Coarse	$2.40	4	$9.60
0.75"X5" Hex Head Bolt, Coarse	$3.19	2	$6.38
0.75" Hex Nut, Coarse	$0.75	6	$4.50
#8X2" Countersink Head Sheet Metal Screw	$0.17	8	$1.36
#10X1.5" Countersink Head Sheet Metal Screw	$0.14	16	$2.24
#10X0.75" Countersink Head Sheet Metal Screw	$0.11	16	$1.76
4-3/32" to 6" Stainless Steel Screw Type Hose Clamp	$2.49	1	$2.49
		Total Cost of Materials:	$53.54

We did incur the following additional costs as well: 32" long round stake (Qty. 2 @ 7.19 ea.), and analog weight scale (Qty. 1 @ 12.99 ea.). However, these materials are not considered to be part of the apparatus itself, as they are provided by the user at the time of apparatus deployment.

Manufacturing costs are unknown at this point. It took us 12 man hours in the Cal Poly machine shop to construct the first prototype. With proper production line, the production cost can probably be reduced significantly. Regardless, analysis of potential production costs in a mass production environment is irrelevant because our project is not producing a product that is intended for mass production.

So, for now, we'll consider production time to be 12 man hours at $10 per hour, which gives us $120 in labor, and a final total cost per unit of $173.54.

Material Selection

Our goal in material selection for this prototype was to select materials that were cheap, easy to obtain, quick to obtain, and easy to work with.

We did not have time to wait for materials to ship through the mail, so we opted to limit ourselves to materials that we could buy within San Luis Obispo. We selected wood for the reaction force tester because it is well able to handle the forces we are designing for, and it is cheap, readily available, and easy to machine.

Safety Considerations

The weakest part of the reaction force measurement apparatus is the hose clamp that wraps around the V-Block part. If we neglect friction, the safety factor on yield for the hose clamp at 150 pounds of load is 1.8, and the safety factor on ultimate strength at 150 pounds of load is 4.2. Given these relatively low safety factors, the hose clamp may experience fatigue failure under repeated loading after many testing sessions. We recommend that the hose clamp be replaced after every testing session to prevent unexpected fatigue failure of the hose clamp.

Hose Kink Force Measurement Apparatus

Preliminary Test Design

In order to test the force necessary to kink a firehose I chose a pulley type apparatus to fold the hose. The center axle is square in order to simulate the corner of a wall like those that will be encountered in an interior structural fire attack. The round roller to the left in Figure 4.4 provides a constant force that is always perpendicular to the hose, which ensures the force recorded is purely the force required to kink the hose. The stand is purely for stability, with stake holes included for anchoring the device to the ground. A cable and force scale were used to generate and measure the force needed to kink the hose.

The pulley radius and the moment arm to bend the hose are equal, which simplifies the analysis. The force recorded is equal to the force needed to kink the hose.

For the preliminary model, the apparatus was made mainly of plywood and PVC pipe. The base and top circle were made of plywood, and for the pulley I used a 22" bicycle rim. The roller and pulley axles were both 1.5" square wood bars, and 2" PVC pipe fit perfectly around the wood. L-brackets were used to secure the square rods to the plywood, and Gorilla Glue © was used to adhere the bicycle rim to the plywood pulley.

At the preliminary test in Cambria on March 2, 2012, the apparatus was used to test the kink force for a firehose, and it performed excellently. An unforseen variable in the kinking force measurement was the position of the hose that is not being kinked. The hose has to be aligned with the folding movement in order to keep the data genuine. This means that someone has to move the hose around the device as it kinks the hose. Otherwise the device not only has to provide the force to kink the hose, but it also has to provide the force required to drag the hose across the ground.

A loop-style kink test was also attempted, but with limited success. The idea was to measure the tension required to pull a loop in the hose into a full hose kink. The firehoses are designed not to kink in this mode, so getting a measurement was difficult as the loop unfurled instead of kinking.

Final Design

The preliminary design performed so well that changes were not necessary for the final design. The same apparatus was used to kink the hose, the only difference this time being that the method of putting tension in the line was different. For the final test we used an electrical winch to pull the cable and kink the hose instead of manpower. We did this to decrease the subjectivity of the testing method, since the winch will pull the cable at the same speed every time. The spring scale was still used to measure the kinking force.

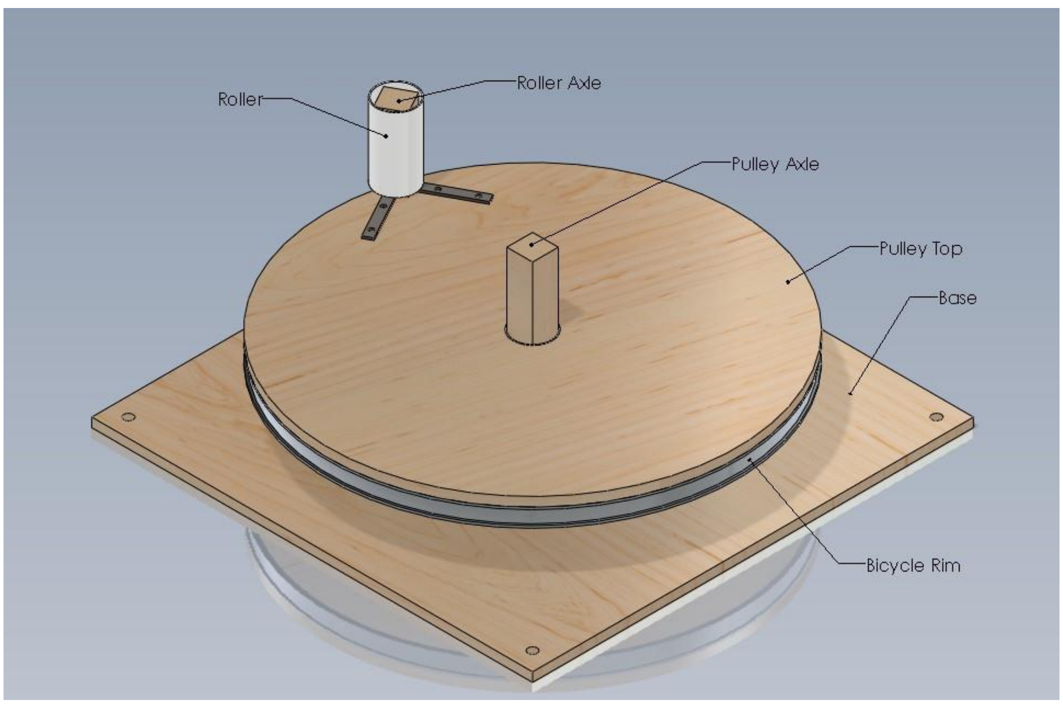


Figure 4.4 – Layout of the hose kink force measurement apparatus.

Cost Analysis

Table 4.2 Provides a cost breakdown for a single hose kink force measurement apparatus.

Table 4.2 – Material cost for a single hose kink force measurement apparatus.

Material	Price Per Unit	Quantity	Cost
1/2" Thick OSB Plywood Sheet	$8.99	1	$8.99
3X3 L-Bracket	$1.49	6	$8.94
2X2 Dimensional Lumber, 9’ Length	$1.50	1	$1.50
2” PVC Pipe, 3” Length	$8.99	2	$17.98
1.5”X10” Round Stakes	$0.79	4	$3.16
13/64” Cable, 6’ Length	$0.99	1	$0.99
#10-32 Eye Bolt	$1.39	1	$1.39
250-lb Proof Carabiner	$5.99	1	$5.99
Gorilla Glue ©, 16oz	$13.99	1	$13.99
		Total Cost of Materials:	$62.93

Safety Considerations

Make sure before each run that the bicycle rim is securely attached to the circle of plywood and that all connections to the cable are secure.

Throw/Distribution Test

For the final design of the throw/distribution test, rain gauges were intended to be used in order to measure the amount of water/foam that fell in a certain area. The rain gauges were not delivered in time for the May 5th test day, so an alternative was needed. The final test used a grid of red plastic cups in order to collect the liquid for measurement. Each data point consisted of one cup with a roofing nail through the bottom in order to stake it to the ground, and another cup stacked inside. The top cup would collect the liquid for weighing, and after weighing and emptying, the top cup could quickly be returned to its corresponding cup on the ground, thereby maintaining the same position in the grid. This method allowed for quick, easy and repeatable measurements. The grid was laid out in 10 foot increments lengthwise, and spread out in 6 foot increments left and right of center, up to 12 feet from center. The grid was laid out as far as 120 feet from the nozzle. The amount of liquid in each cup was measured with a digital postal scale with a resolution of ±0.5 grams.

Cost Analysis

Table 4.3 provides a cost breakdown of a single round of throw/distribution tests.

Table 4.3 – Material cost for a single round of throw/distribution tests.

Material	Price Per Unit	Quantity	Cost
100 Pack of Disposable Red Cups	$5.99	1	$5.99
3-lb Digital Scale	$39.99	1	$39.99
5-lb Box of Roofing Nails	$4.99	1	$4.99
		Total Cost of Materials:	$50.97

Friction Force Measurement Apparatus

This section describes the preliminary design for the friction force measurement apparatus, which was used in our preliminary testing, as well as the final design for the friction force measurement apparatus, which was used in our final testing.

Preliminary Testing Design

This section describes the friction force measurement apparatus that was used in our preliminary testing.

Operation and Layout

Figure 4.5 shows a model of the apparatus constructed for preliminary testing. The apparatus works by the user applying a force to a spring scale attached to a pulley system to propel a sled. The bottom of the test frame was covered in foam insulation to trap water in the test surface. A two-pulley system was used to double the resolution of the system by doubling the required force to drag the sled. Figure 4.6 shows the pulley system and the connection between the weight and the pulley system and the sled platform. The user applies force by standing on the frame (helping seal the frame to the ground) and pulling on the spring scale. See Appendix E for detailed part drawings.

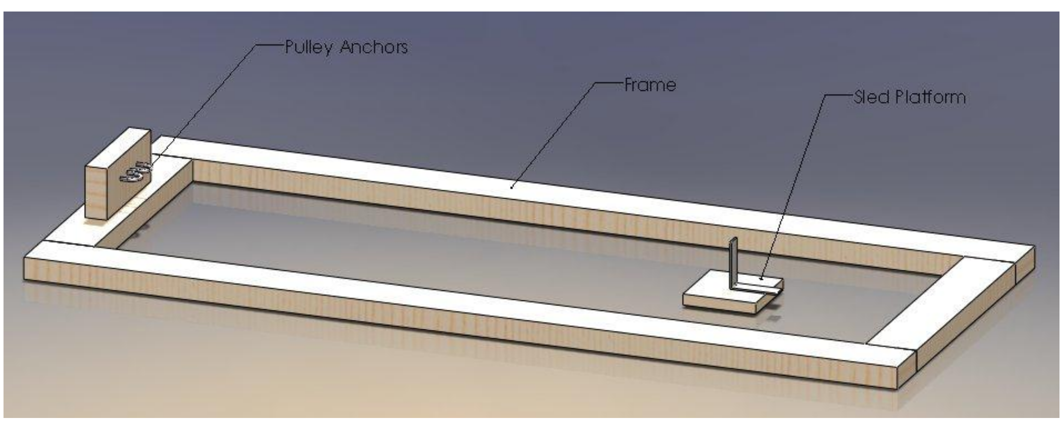


Figure 4.5 – SolidWorks model of the manufactured parts for the friction testing apparatus.

Figure 4.6 – (Left) Weight and sled platform attached to rope. (Right) Pulley assembly.

Design Analysis

Because of the simplicity of this design, no in depth analysis was required. Because the pulley doubles the force required to move the sled, the resolution of the spring scale increases from 1/2 lbf to 1/4 lbf. All purchased components were rated to at least 55 lbf working load, providing an immense safety factor for the small weight used in preliminary tests (5lb). Components were chosen for function and geometry. The sled track was chosen to be 4’ 5” long and 1’ 6” wide to accommodate larger weight sizes and give an adequate area for dynamic friction testing. The rubber test sample was chosen to be 4” by 4” for consistency with published ASTM tests. The user should use appropriate technique to apply forces to the spring scale to avoid injury. Because of the prototype nature of the design, no long-term maintenance is necessary. After using the device rinse foam concentrate off of metal parts.

Cost Analysis

Table 4.4 outlines the materials used for the construction of the preliminary design. Materials were chosen to keep costs low. The device was constructed for a total of $94.12. We did not pay for labor, as all labor was done by team members. However, Table 4.4 assumes a labor rate of $10 per hour.

Table 4.4. – Material and labor cost for a single friction forced measurement apparatus.

Material	Price Per Unit	Quantity	Cost
2X4 Dimensional Lumber, 92” Length (Pine)	$2.49	2	$4.98
1X6 Dimensional Lumber, 48” Length (Pine)	$2.85	1	$2.85

U-Bolt and Nuts	$1.79	2	$3.58
1” Wood Screws (Box)	$3.99	1	$3.99
1/4" Nylon Cord (ft)	$0.29	10	$2.90
Swivel Pulley	$5.99	2	$11.98
Rubber Sample	$1.59	3	$4.77
PVC Insulation, 1” Thick	$2.49	3	$7.47
Liquid Nails Adhesive	$4.58	2	$9.16
50-lbf Spring Scale	$29.99	1	$29.99
Fence Bracket	$0.69	6	$4.14
5X5 L-Bracket	$2.77	3	$8.31
Labor (1-Hour)	$10.00	2	$20.00
Total Cost of Materials and Labor:			$114.12

Final Testing Design

This section describes the friction force measurement apparatus that was used in our final testing.

Operation and Layout

In preliminary tests we encountered too much variation in real world surfaces to measure consistent results, had difficulty finding a flat surface to conduct wet and submerged testing on, and experienced some leakage of fluid under the frame due to surface unevenness. Thus the final design does not use the test barrier method, but instead uses a test tray. This way we have greater control over the test surfaces in order to ensure that they are uniform, and also to ensure even fluid depth for submerged friction tests.

Although static force measurements were recorded with some accuracy, the spring scale provided inaccurate measurements of dynamic friction. The large displacements caused by spring deflections and surface unevenness produced erratic velocities. By using a strain gauge based force transducer, the final design eliminates the large deflections in the system. By using a mechanically driven wench we can eliminate variations in velocity. We also manufactured a test sled out of a retired structural firefighting boot to produce a realistic test, as well as 5 test samples of various surfaces.

The friction testing apparatus uses a winch to drag a fire boot sled across various surfaces in submerged and dry conditions. Test samples screw onto the basin of the test apparatus, where they can be submerged after being properly secured. See Appendix I for operating procedures. Figure 4.7 shows a SolidWorks model of the final design. Detailed part and assembly drawings may be found in Appendix E. The design consists of a tank to submerge test samples in, complete with overflow valves and a drain, as well as a mount for the winch. The entire apparatus rests on three legs with independently adjustable

heights to facilitate leveling of the device. Figure 4.8 shows the manufactured device and various components.

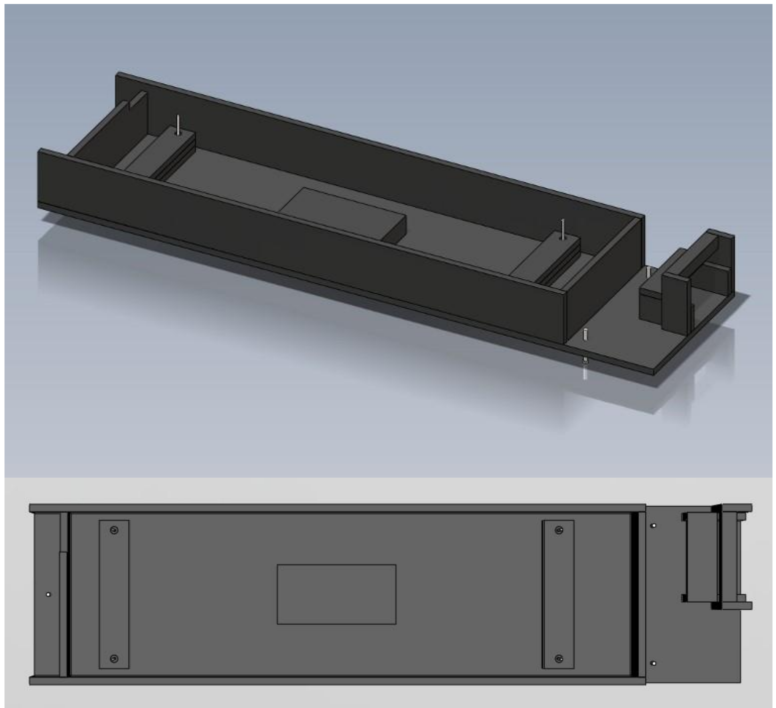


Figure 4.7 – SolidWorks model of friction testing apparatus, isometric and top views. Winch and fire boot sled are not shown in the model.

Figure 4.8 – Friction testing apparatus (top left). Winch used to drag test sled (top right). Example of a glued and painted joint (bottom left). Adjustable-height foot on the bottom of the friction force measurement apparatus (bottom right).

The user collects data using either a 50-lbf spring scale or a force transducer. We borrowed a force transducer from a colleague, and the data acquisition system from professor John Ridgely. Figure 4.9 shows the force transducer alone and attached to the winch and fire boot sled. The user may provide any data acquisition system and force transducer at the time of use.

Figure 4.9 – Force transducer (top left), strain gage on force transducer (top right), force transducer protected from foam with plastic bag (middle left), friction sled apparatus attached to force transducer (middle right), close up of force transducer attached to sled and winch during a submerged foam test on glazed ceramic tile (bottom).

We manufactured five test samples for use in the friction testing apparatus. The surfaces for the manufactured test samples can be seen in Figure 4.10. All friction test surfaces are shown in Figure 4.11.

Figure 4.10 – Manufactured test samples for friction testing. Samples are 1’x4’ mounted on a 15”x48” piece of plywood with holes drilled to attach to the friction testing apparatus.

Figure 4.11 – Test surfaces for friction testing: painted deck (top left), medium weave carpet (top center), thick weave carpet (top right), wood laminate (middle left), linoleum (middle center), polished concrete (middle right), concrete (bottom left), glazed ceramic tile (bottom center), asphalt (bottom right).

Cost Analysis

Table 4.5 outlines the materials used for the construction of the final design. Materials were chosen to keep costs low. The device was constructed for a total of $201.18. We did not pay for labor, as all labor was done by team members. However, Table 4.5 assumes a labor rate of $10 per hour.

Table 4.5. – Material and estimated labor cost for final design construction. Some materials overlap with the kink force testing apparatus and some were previously purchased.

Material	Price Per Unit	Quantity	Cost
1X6 Dimensional Lumber, 96" Length (Pine)	$3.49	2	$6.98
1X4 Dimensional Lumber, 72" Length (Pine)	$2.85	1	$2.85
1X18 Dimensional Lumber, 72" Length (Pine)	$18.99	1	$18.99
2X2 Dimensional Lumber, 72" Length (Pine)	$1.79	1	$1.79
50 lbf Spring Scale	$29.99	1	$29.99
110V 220/440 Lbf Electric Hoist	$99.99	1	$99.99
Silicone II	$3.79	2	$7.58
Liquid Nails Adhesive	$4.58	2	$9.16
1-1/4" Nails (Box)	$3.99	1	$3.99
1/2" Wood Screws (Box)	$3.99	1	$3.99
Black Rustoleum Paint	$7.99	1	$7.99
2X2 L-Bracket	$0.69	2	$1.38
2X4 L-Bracket	$0.79	2	$1.58
1/4" Bolt, 2 Washers, 2 Nuts	$1.49	4	$5.96
3/8" Bolt, Toothed/Threaded Washer	$1.49	3	$4.47
1/2" Rubber Hose, 10' Length	$3.49	1	$3.49
Labor (1-Hour)	$10.00	6	$60.00
Total Cost of Materials and Labor:			$270.18

The user is expected to provide test samples and a test sled, as well as a force transducer and data acquisition system at the time of deployment. Therefore these costs are not included in Table 4.5.

Chapter 5
Product Realization

Here are the details of how we manufactured our prototypes.

Nozzle Reaction Force Measurement Apparatus

Here are the manufacturing details for the nozzle reaction force measurement apparatus. Figure 5.1 shows the completed nozzle reaction force measurement apparatus, and the stand we constructed after our preliminary testing. Figure 5.2 shows the nozzle reaction force measurement apparatus in use during our final testing.

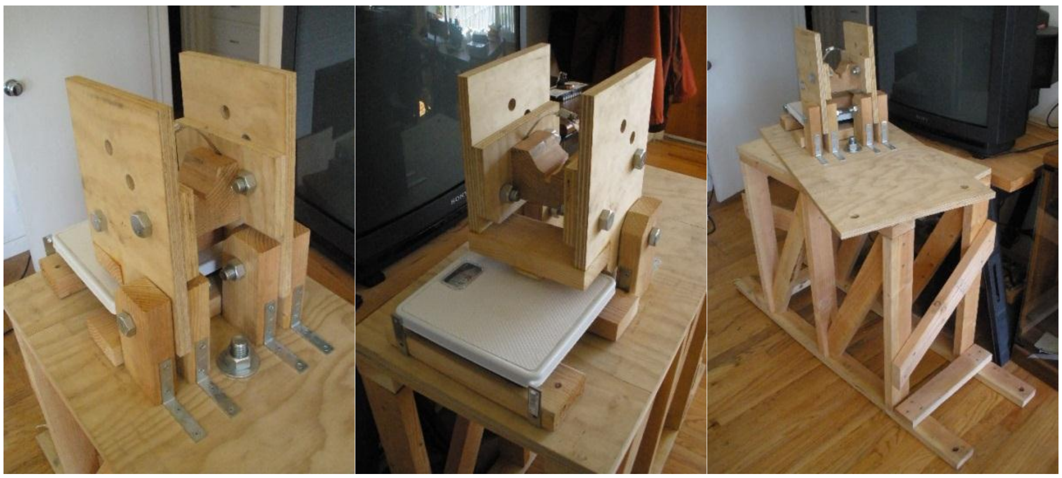


Figure 5.1 – Completed nozzle reaction force measurement apparatus installed on its stand.

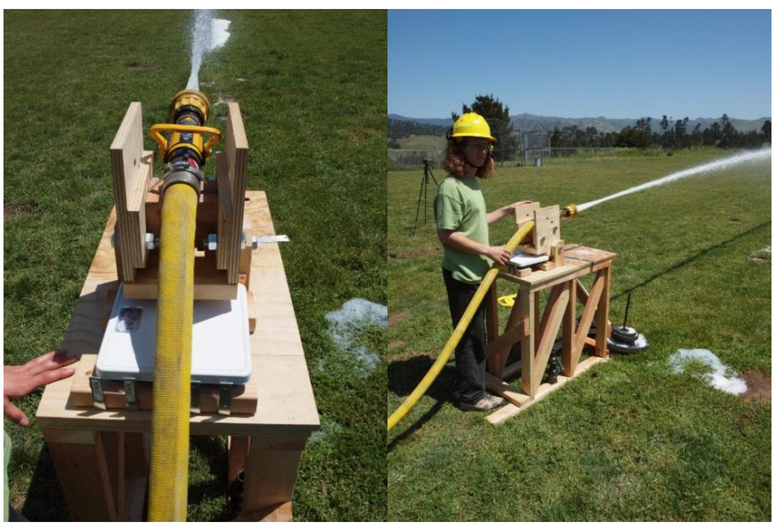


Figure 5.2 – Nozzle reaction force measurement apparatus in use during final testing.

Manufacturing Processes and Materials Employed

Manufacturing Processes

A vertical band saw was used to create the following features: 1.) the channel in the V-Holder part, 2.) the net shape of the Sliding Plate part, 3.) the net shape of the Angle Plate part. Sample features created with a vertical band saw are shown in Figure 5.3.

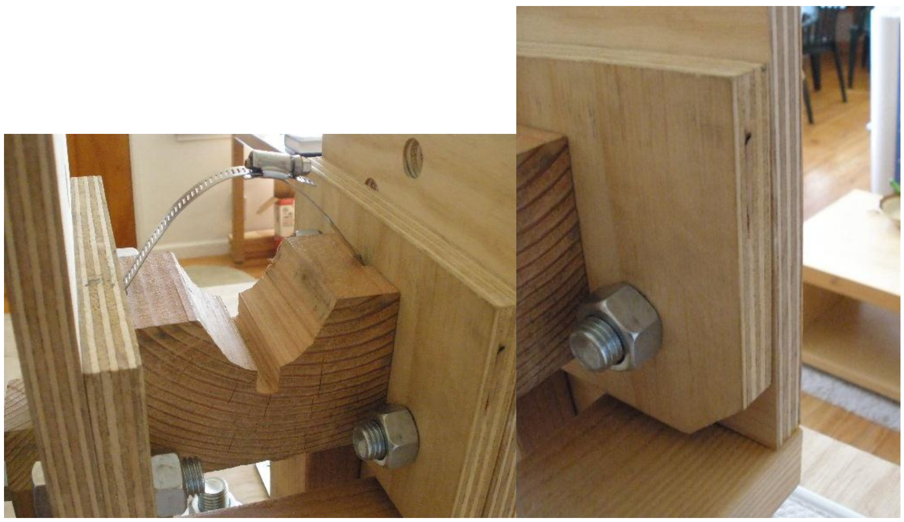


Figure 5.3 – Features created with a vertical band saw.

A drill press was used to create the following features: 1.) the holes in the Sliding Plate part, 2.) the holes in the Angle Plate part, 3.) the hole in the Base Support part. Sample features created with a drill press are shown in Figure 5.4.

Figure 5.4 – Features created with a drill press.

A handheld power drill was used to create the following features: 1.) all screw pilot holes, 2.) the stake holes in the front of the Base part.

A miter saw was used to create the following features: 1.) the net shape of the Base Support parts, 2.) the net shape of the Cross Beam part, 3.) the net shape of the V-Holder part. Sample features created with a miter saw are shown in Figure 5.5.

Figure 5.5 – Features created with a miter saw.

Materials

Weatherproof wood glue was used to join the following parts: 1.) joining the triangle to the main beam of the Cross Beam part, 2.) joining the Cross Beam part to the two Angle Plate parts. An example of the use of wood glue on the apparatus is shown in Figure 5.6.

Figure 5.6 – Weatherproof wood glue joining parts.

Dimensional lumber (2x4 douglas fir) was used for the following parts: 1.) the Cross Beam part, 2.) the Base Support part.

Dimensional lumber (4x4 douglas fir) was used for the following parts: 1.) the V-Holder part.

Plywood (23/32” thick ADX) was used for the following parts: 1.) the Sliding Plate part, 2.) the Angle Plate part, 3.) the Base part.

Differences between Design and Prototype As-Built

There are two differences between the design and the prototype as-built. The first difference is that in the prototype, the Base part is 3.75” longer and 0.5” wider than the design specified. The second difference is that in the prototype the Angle Plate parts do not have a triangle cut on the top of them; we just left the edges square instead of taking the time to make the extra cuts. These differences are minor and do not impact prototype performance.

Recommendations for Future Manufacturing

When manufacturing future prototypes, we suggest the following changes:

- Use a mill instead of a drill press to drill the holes in the Sliding Plate and Angle Plate parts. This will help to ensure that the holes all align properly when the apparatus is assembled.
- Use a mill instead of a hand drill to drill as many of the screw pilot holes as possible. This will help to ensure that when you screw parts together, they will line up properly.
- Be sure to include about 0.125” of clearance at the hinge point between the Base Support parts and the Angle Plate parts. Too little clearance causes the hinge to stick, and this causes hysteresis problems when using the apparatus to measure forces.
- Be sure to include about 1/16” of clearance for all holes where bolts will need to be inserted and removed multiple times, even at the main hinge joint. This will help prevent the hinge from sticking, and make changing angles during throw testing much faster. It also gives you extra clearance if the wood soaks up water during testing and permanently swells (which effectively shrinks your holes).
- Make an extra effort to keep the holes in the Base Support parts lined up when you assemble the Base Sub-Assembly. Do not just install the Base Supports into the Base while the hinge is assembled and assume that the holes will line up; even if you tighten the hinge bolts around the Angle Plate parts, you can still create internal stresses when you install the Base Supports, and once you release pressure from the hinge bolts, the holes will be misaligned. If you can get those Base Support holes to line up, it makes it much easier to insert and remove the hinge bolts (and you will end up having to do this more often than you think, especially when transporting the device).

Hose Kink Force Measurement Apparatus

Here are the manufacturing details for the hose kink force measurement apparatus. Figure 5.7 shows the finished hose kink force measurement apparatus. Figure 5.8 shows the hose kink force measurement apparatus in use during our final testing.

Figure 5.7 – Finished hose kink force measurement apparatus.

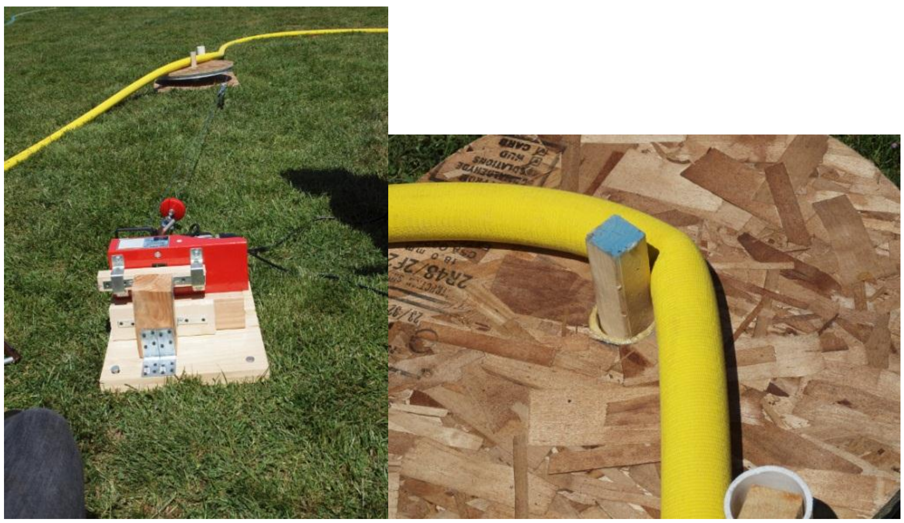


Figure 5.8 – Hose kink force measurement apparatus in use during final testing. Left image shows the winch used to actuate the apparatus.

Manufacturing Process and Materials Employed

<u>Manufacturing Processes</u>

The manufacturing of the prototype was fairly straightforward. No advanced machining or manufacturing methods were used.

- A circular saw was used to cut the base board to size.
- A jigsaw was used to cut out the circular top board.
- A hand saw was used to cut the PVC and 2 by 2 wood to length.
- A handheld power drill was used to drive screws and drill holes as necessary.

Everything was fastened together with either gorilla glue or brackets with wood screws.

Materials

- The base board and the circular board were both made of 1/2"-thick plywood.
- A 22 inch bicycle rim was used for the cable pulley.
- Dimensional lumber (2x2 pine) was used for the rotation axles.
- PVC pipe (2”) was used as the rollers around the axles.
- Gorilla Glue © was used to join the bicycle rim to the circular board and the center axle to the circular board.

Differences between Design and Prototype As-Built

The only difference that came out of manufacturing was that the center axle was not completely square on the circular board. This didn’t cause too much of a problem but it is an imperfection.

Recommendations for Future Manufacturing

For an actual manufactured prototype, I would recommend that all parts be made of metal, with thrust bearings at rotating interfaces to reduce friction. This would increase the strength, stability, and life of the device.

Stream Throw and Distribution Test Setup

There was no manufacturing involved with the throw/distribution test, apart from poking nails through the bottoms of red plastic cups. Figure 5.9 shows the stream throw and distribution test setup during our final testing.


Figure 5.9 – Stream throw and distribution test setup during final testing.

The actual test differed from the design in two slight ways: the maximum range and the resolution at critical points. The maximum range of the stream during the preliminary testing was under 100 feet, so the final test grid only extended to 100 feet. Upon seeing the stream the day of final testing, it was apparent that the grid would have to be extended to 120 feet. The stream was also much narrower during final testing than on the preliminary test day. This made the grid resolution of 6 feet inadequate at certain points in the stream. To correct for this, I added points halfway between other points where the stream was most concentrated, doubling the resolution. Both of these issues can be attributed to the wind effects during preliminary testing that were not as prevalent during final testing.

The red cups proved to be a very appropriate volume and area for collecting the fluid as it fell. For future testing, a grid with more resolution would be better, as 12 feet to the left and right was slightly too far out of range. A receptacle that is more heavy-duty than plastic disposable cups would also be a good improvement. The cups were not able to take very much lateral force without blowing over.

Friction Force Measurement Apparatus

Here are the manufacturing details for the friction force measurement apparatus.

Manufacturing Processes and Materials Employed

Manufacturing Processes

A circular saw was used to create the net shape of all wooden parts.

A hand drill was used to create the following features: 1.) attaching brackets to winch mount and base board, 2.) drilling holes for feet. 3.) drilling holes for the sample mounting bolts. 4.) drilling holes for the drainage spout.

A hand saw was used to create the overflow pour spout.

A hammer was used to attach all wooden parts after a liquid adhesive had been applied.

A paint brush was used to apply black Rustoleum matte paint to seal all wood parts from exposure to moisture.

Materials

Liquid Nails wood paneling adhesive was used to join all wooden parts.

1 1/4 inch nails were used to attach all wooden parts to the base board, attach the sides of the containment tank, and attach the support blocks inside the containment chamber. All nails were applied after the wood was covered in liquid nails on the important contact surfaces.

Silicone II was used to seal the containment tank.

Black Rustoleum matte paint was used to seal all wood parts from exposure to moisture.

Dimensional lumber (1x6 pine) was used for the containment chamber walls and middle support block.

Dimensional lumber (1x3 pine) was used for the test sample end supports.

Dimensional lumber (1x4 pine) was used for the winch mount side supports and base.

Dimensional lumber (2x2 pine) was used for the winch mount cross beam.

Plywood (1/2 inch) was used for the base board.

1/2 inch clear rubber tubing was used for the drainage spout.

Differences between Design and Prototype As-Built

The prototype as built uses a piece of plywood for the base instead of a piece of laminated pine. This required the addition of several pieces of 1x3 to increase the rigidity

of the base board. The design alteration was made because a preliminary build encountered catastrophic failure when the laminated pine delaminated due to exposure to foam and water, causing an irreparable breach in the tank.

Recommendations for Future Manufacturing

When manufacturing the device, we recommend the following changes:

- Use a chop saw for cutting pine instead of a circular saw to attain more accurate lengths and square corners.
- Seal the device with silicone that allows paint to dry on it without flaking off, or paint the device before applying silicone.
- Use a drill press to manufacture the holes for the various bolts. A hand drill produced large varieties of hole shape and quality, especially using larger bits.

Chapter 6
Testing, Data Collection, Test Results, and Design Verification

On March 2nd, 2012, we carried out a preliminary test run using our first prototype apparatuses. The purpose of this preliminary test run was to identify problems we may have overlooked, and then ensure that we address these issues in our final design.

After identifying issues in our preliminary tests, we addressed those issues, and then conducted our final tests and data collection on May 5th, 2012.

Preliminary Testing

Hose Handling Preliminary Testing

To determine what test conditions we wanted to test, we first developed a model to predict the nozzle reaction force and nozzle exit velocity based on water flow rate, compressed air flow rate, and nozzle exit diameter. The analysis utilized Bernoulli's equation, the ideal gas law for air, the assumption that the nozzles were lossless, and the assumption that the air and water were well-mixed (i.e. the mixture was just treated as a fluid with an altered density).

The results predicted by this model are given in Figures 6.1 through 6.4.

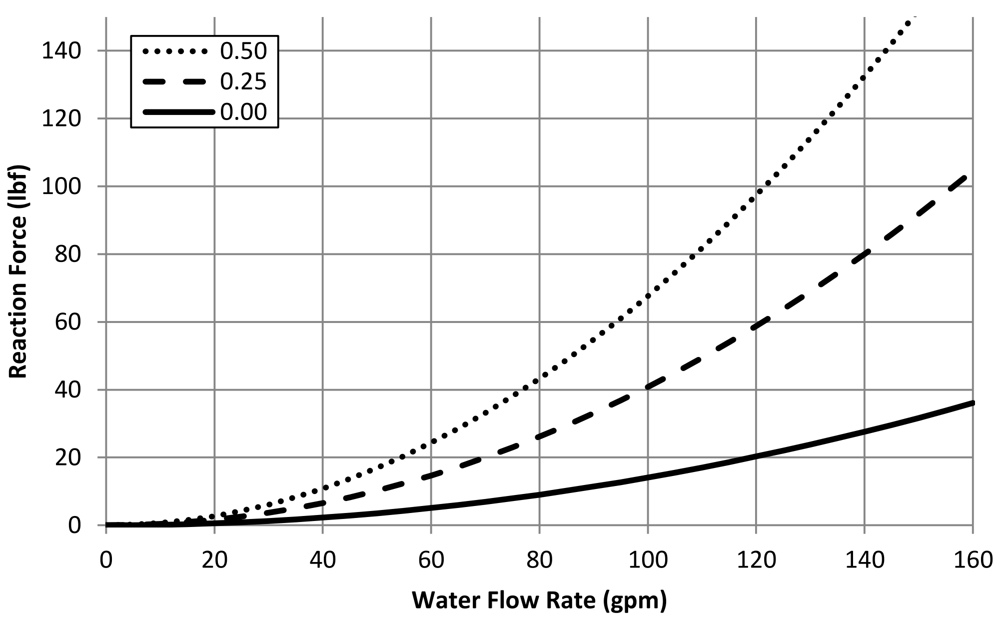


Figure 6.1 – Predicted nozzle reaction force for a nozzle with a 1-1/8" discharge diameter operating at 0.00, 0.25, and 0.50 SCFM of compressed air per gpm of water.

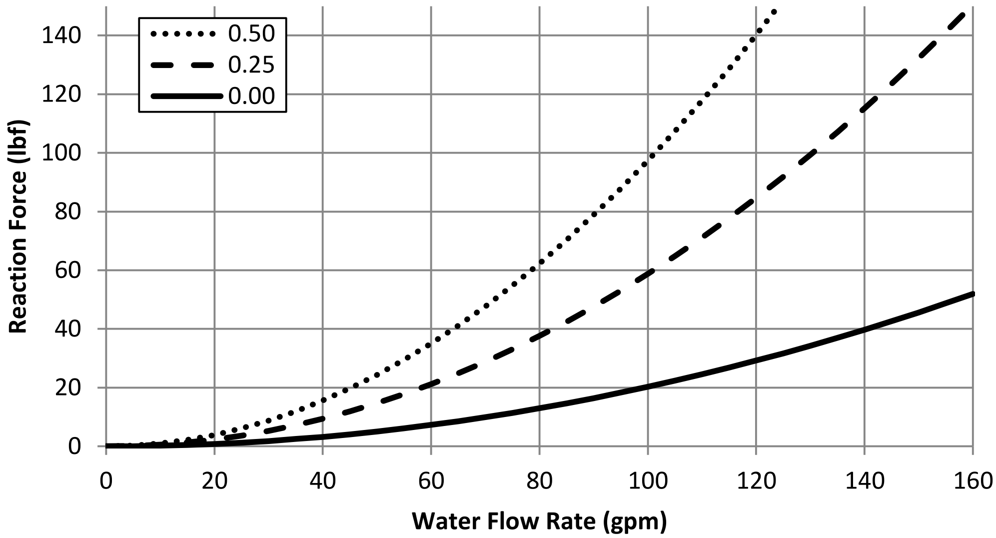


Figure 6.2 – Predicted nozzle reaction force for a nozzle with a 15/16" discharge diameter operating at 0.00, 0.25, and 0.50 SCFM of compressed air per gpm of water.

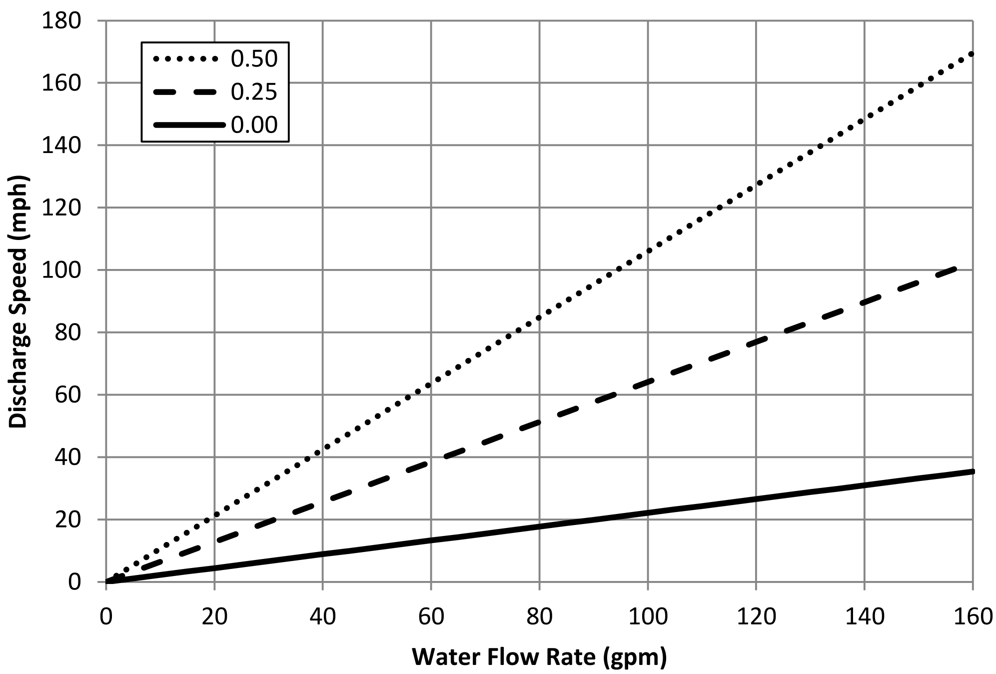


Figure 6.3 – Predicted nozzle discharge velocity for a nozzle with a 1-1/8" discharge diameter operating at 0.00, 0.25, and 0.50 SCFM of compressed air per gpm of water.

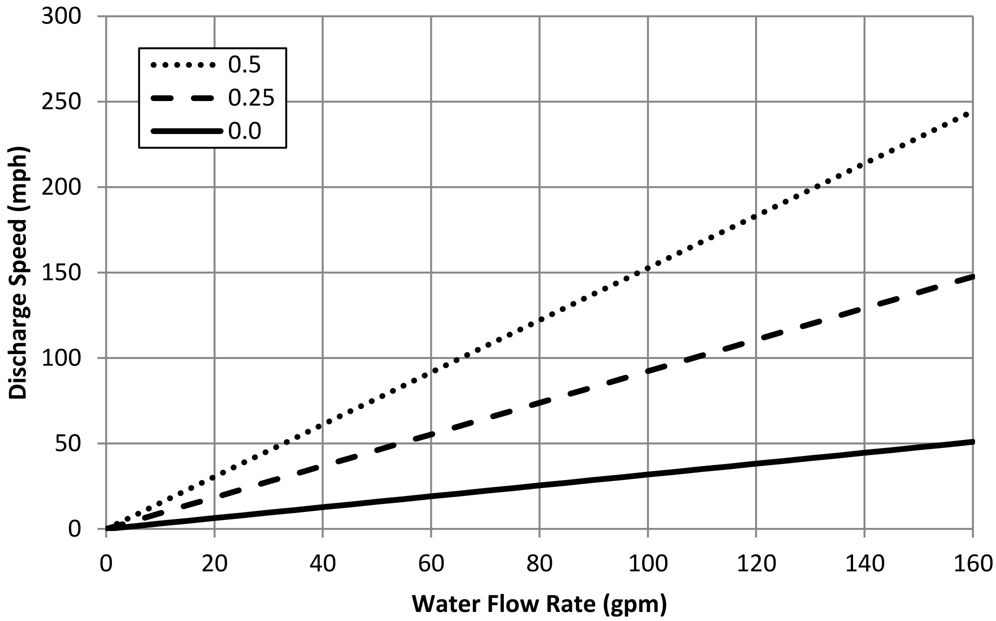


Figure 6.4 – Predicted nozzle discharge velocity for a nozzle with a 1-1/8” discharge diameter operating at 0.00, 0.25, and 0.50 SCFM of compressed air per gpm of water.

We decided that we would not test any conditions which would produce more than 150 pounds of force at the nozzle because these test conditions are unrealistic since 150 pounds is already more nozzle reaction force than three firefighters working together can handle. Therefore, nozzle reaction forces over 150 pounds would never be encountered in the field, so we had no reason to measure data in that range.

To determine our test conditions (i.e., what water and air flow rates we would take measurements at), we took the usable range of the force curve (that part that produced less than 150 pounds of nozzle reaction force), and divided it into five segments, taking data at the point at the end of each of the five segments.

The specific test itinerary we used in our preliminary field tests is given in Appendix D.

Friction Force Preliminary Testing

The preliminary friction test plan was exploratory in nature, with the main objective being to verify design concepts and narrow in on the best method of testing friction on various surfaces. Only dry and wet tests were conducted.

Preliminary Testing Issues

Hose Handling Preliminary Testing Issues

The following issues arose during our preliminary testing.

- We were unable to measure the water flow rate (that information was not available on the pumping rig we used).
- We were unable to measure the air flow rate with any confidence (the data output by the instrumentation on the pumping rig was obviously erroneous; the SCFM of air reading was always either “-30” or “0”).
- Water flow rate was difficult to control due to coarse resolution of pump discharge pressure gauge.
- Water flow rate was difficult to control due to negligible friction loss in the short length of hose that we used.
- Wind skewed the stream throw data, perhaps severely.
- Changing winds made it difficult to measure the stream distribution because it was difficult to hit the target when the wind was constantly changing.
- The CAFS equipment did not allow us to vary the air flow rate at all. It was all automatically controlled; all we could do was turn the air on and off.

The data produced from our preliminary testing was completely inconclusive. We believe this is because we were unable to measure the water flow rate, and we may not have actually varied the flow rate at all because the required pressure changes that would produce our desired flow rates in the short length of hose we used were so small that they were less than the resolution of the fire truck’s outlet pressure gage (which had 5 psi resolution). Therefore, our preliminary test data is not published in this report.

Friction Force Preliminary Testing Issues

The following issues arose during our preliminary testing.

- We could not generate a consistently submerged surface on outdoor test sites with the preliminary design.
- We were generating friction coefficients of greater than two on outdoor test sites due to the extreme softness of the test sample.
- Dynamic force measurements were impossible to read accurately with the spring scale.
- Not all surfaces were flat enough to conduct wet testing.
- We could only test a limited number of materials.

No data was gathered from preliminary testing because we were unable to attain any results that made sense or were repeatable.

Improvements Implemented After Preliminary Testing

Hose Handling Test Improvements

To address the issues we observed during preliminary testing, we performed the following actions.

- We built a frame to raise the reaction force testing apparatus up off of the ground so the nozzle was held at the height that a standing firefighter would normally hold the nozzle.
- We drilled a hole in the center of the base plate of the reaction force testing apparatus, and bolted it to the frame we had made. This bolt acted as a hinge which allowed us to yaw the entire nozzle reaction force apparatus. This allowed us to hit the targets more reliably when performing the stream distribution tests. See Figure 6.5 for a picture of this hinge bolt.
- We asked the fire department we were working with to have their air flow and water flow gages repaired and calibrated.
- We purchased an electric winch to actuate the kink force measurement apparatus in a more repeatable way. See Figure 6.6 for a picture of the electric winch actuating the kink force measurement apparatus.
- We used 400 feet of hose line in order to get decent friction losses in the hose so we could more finely control the liquid flow rate.

Figure 6.5 – Reaction force measurement apparatus yaw hinge.

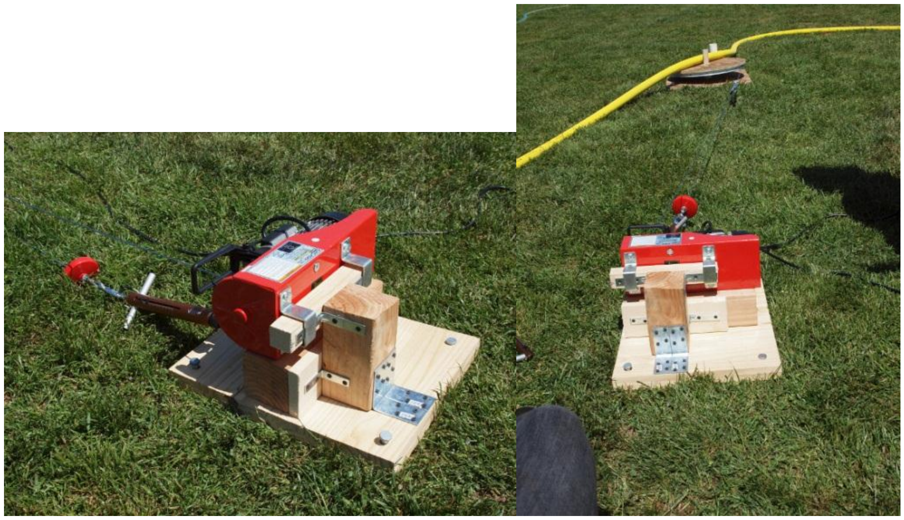


Figure 6.6 – Electric winch used to actuate the kink force measurement apparatus.

Friction Force Measurement Apparatus Improvements

To address the issues we observed during preliminary testing, we performed the following actions.

- We purchased an electric winch to perform repeatable drags for dynamic friction testing.
- We implemented a force transducer to increase the stiffness of the winch line in dynamic testing.
- We built an apparatus to conduct friction tests of manufactured test samples in.
- We manufactured test samples of a variety of materials.
- We manufactured a test sled out of an interior structural fire boot.

The friction test apparatus was redesigned entirely for final testing.

Final Testing

Hose Handling Final Testing

For our final testing plan, we stuck with the same water flow rates from our preliminary testing plan. The final testing itinerary is provided in Appendix D. Since we couldn't control the air flow rate, we just used the same water flow rates for the CAFS testing as we did for the water only testing, but we turned the CAFS on for the CAFS testing.

The results of our final tests are given in Appendix H.

Friction Force Final Testing

The friction force test plan depends on the assumption that resistance to horizontal motion is solely generated by friction, where friction is related to the normal force being applied between the test surface and test sled through a coefficient of static and dynamic friction. With the introduction of foam and water to the test surface this may not entirely be the case, however this assumption still allows for accurate comparison of reduction in traction forces. Even though friction may not be the only force resisting horizontal motion, results are reported as friction coefficients to simplify data down to the critical quantity.

The friction measurement test plan involves dragging a weighted fire boot sled across various test surfaces. This requires the manufacturing of various test surfaces of materials encountered by firefighters in interior structural firefighting. The samples were tested under the following conditions:

- Dry, static and dynamic (0.275 fps)
- Wet (water), static and dynamic (0.275 fps and 0.550 fps)
- Wet (foam solution at 0.3%), static and dynamic (0.275 fps and 0.550 fps)
- Submerged ¼ in (water), static and dynamic (0.275 fps and 0.550 fps)
- Submerged ¼ in (foam solution at 0.3%), static and dynamic (0.275 fps and 0.550 fps)

Wet tests were conducted with 16 fluid ounces of fluid spread evenly across 4 square feet of test surface. Foam solution was agitated for one minute in a 5-gallon bucket before being applied to the test surface. Static coefficients of friction were measured using a 50 lb spring scale. The maximum value was recorded. Dynamic coefficients of friction were measured using a force transducer and data acquisition system. For test surfaces of interest that could not easily be manufactured into test samples, we only conducted dry and wet static tests.

Final Testing Issues

Hose Handling Final Testing Issues

We encountered the following issues during our final testing.

- Changing winds made the stream distribution test difficult to perform, and undoubtedly skewed our data. We had to constantly adjust the nozzle yaw angle to try to keep the water aimed at the distribution test collection array.
- The air flow meter on the fire engine still didn't work, despite the fact that the station's mechanic had calibrated it and confirmed that it was working the day before our testing.
- The water flow meter on the fire engine failed during our last test phase, and the engine operator used field calculations to adjust the line pressure to try to control the water flow rate. This produced questionable water flow rates.

Despite these issues, our data from our final tests is useful and most of it is probably accurate. Again, all results, including data tables, are reported in Appendix H.

Friction Force Final Testing Issues

We encountered the following issues during our final testing.

- The force transducer would not work accurately when wet, creating a time consuming process of drying out the strain gages.
- The software required to run the data acquisition system (Hyperterminal) would crash frequently, necessitating a full system restart.
- The Minestrone board used as the DAQ had several missing screws for the input terminals of the force transducer, causing loose connections that could corrupt testing.
- The Minestrone board did not function how the user manual said it would. Sample rates for the dynamic friction tests are therefore unknown. Data was gathered across a period of approximately one second.
- Testing dynamic friction on carpet produces too much chatter of the test sled to provide useable data, so the dynamic tests on carpet were not included.
- The fire boot could not be weighted more than approximately 45 lbs without becoming unstable.
- An initial build of the final design disintegrated as exposure to water and foam solution weakened the lamination of a board used to construct the test basin. The subsequent design used a different selection of wood and sealed the wood with paint.

Despite these issues, sufficient data was gathered to produce accurate results with reasonable uncertainties. Most of the difficulties that arose were technical, and not issues with the device itself. When everything did work properly, results were obtained with a low uncertainty. The process to achieve those results, however, was extremely time consuming.

Friction Force Test Results

Raw data for friction tests can be found in Appendix H. Results of the static friction tests can be found below in Table 6.1. Dynamic friction test results can be found in Tables 6.2 and 6.3.

Table 6.1 – Experimental results from static friction tests between a weighted structural firefighting boot and various surfaces. Tests use a foam solution with 0.3% foam concentrate. Uncertainties are expressed with 95% confidence. Measurements reported in green indicate agreement between foam and water measurements, while measurements in yellow indicate distinction between foam and water measurements.

Interior Surface	Maximum Static Coefficient of Friction				
	Dry	Wet (Water)	Wet (Foam)	Submerged (Water)	Submerged (Foam)
Wood Laminate	0.52±0.04	0.59±0.04	0.51±0.06	0.69±0.06	0.52±0.09
Linoleum	0.59±0.09	0.63±0.04	0.42±0.10	0.75±0.06	0.51±0.09
Glazed Ceramic Tile	0.58±0.06	0.46±0.04	0.31±0.05	0.46±0.05	0.25±0.06
Medium Weave Carpet	0.84±0.04	0.86±0.06	0.88±0.08	0.96±0.07	0.89±0.08
Heavy Weave Carpet	1.03±0.07	1.00±0.06	0.82±0.03	0.99±0.10	0.81±0.05
Polished Concrete	0.66±0.06	0.75±0.04	0.68±0.07		
Concrete	0.93±0.05	0.84±0.08	0.84±0.05		
Asphalt	0.88±0.04	0.80±0.05	0.63±0.04		
Painted Deck	0.81±0.06	0.73±0.04	0.64±0.06		

Table 6.2 – Experimental results from dynamic friction tests between a weighted structural firefighting boot and various surfaces. Tests use a constant velocity of 0.275fps and foam solution with 0.3% foam concentrate. Uncertainties are expressed with 95% confidence. Measurements reported in green indicate agreement between foam and water measurements, while measurements in yellow indicate distinction between foam and water measurements.

Interior Surface	Dynamic Coefficient of Friction at 0.275 fps				
	Dry	Wet (Water)	Wet (Foam)	Submerged (Water)	Submerged (Foam)
Wood Laminate	0.49±0.06	0.43±0.09	0.48±0.06	0.46±0.09	0.27±0.06
Linoleum	0.44±0.02	0.56±0.03	0.29±0.05	0.53±0.13	0.24±0.02
Glazed Ceramic Tile	0.47±0.07	0.42±0.04	0.31±0.05	0.50±0.05	0.36±0.05

Table 6.3 – Experimental results from dynamic friction tests between a weighted structural firefighting boot and various surfaces. Tests use a constant velocity of 0.550fps and foam solution with 0.3% foam concentrate. Uncertainties are expressed with 95% confidence. Measurements reported in green indicate agreement between foam and water measurements, while measurements in yellow indicate distinction between foam and water measurements.

Interior Surface	Dynamic Coefficient of Friction at 0.550 fps				
	Dry	Wet (Water)	Wet (Foam)	Submerged (Water)	Submerged (Foam)
Wood Laminate		0.42±0.03	0.46±0.07	0.42±0.03	0.27±0.06
Linoleum		0.48±0.09	0.23±0.04	0.26±0.11	0.15±0.07
Glazed Ceramic Tile		0.51±0.06	0.29±0.03	0.49±0.04	0.21±0.06

Flow Separation Tests and Results

After our preliminary testing on March 2nd, 2012, we were able to perform some rudimentary CAFS flow separation tests back at the Cambria Community Services District fire station.

We brought a CAFS hose line up onto the roof of the fire station (the nozzle was about 22 feet above ground level) and ran CAFS through the line for a few seconds (120 gpm of water, 0.3% foam concentrate, CAFS on) until the flow had reached a steady state. Then we closed the nozzle valve and waited for five minutes. Then we reopened then nozzle valve to see how long it would take to reestablish normal CAFS flow. We found that normal CAFS flow was reestablished immediately. We performed this same test again, this time waiting ten minutes between closing and reopening the nozzle, and we found that, even after waiting for ten minutes, normal CAFS flow was reestablished immediately upon opening then nozzle.

The idea behind this test was to see if the CAFS bubble structure would break down while the nozzle was closed, and the air would separate from the solution. The concern behind this is that if the CAFS bubble structure breaks down, and then air floats to the top portion of the line while the solution sinks to the bottom portion of the hose line, when the fireman first opens the nozzle after this separation has occurred, the nozzle will blast air onto the fire and actually fuel the fire. Our thought was that a vertical height would help to encourage this flow separation.

Since we found that normal CAFS flow was reestablished immediately, and we didn't have the facilities available to perform more detailed flow separation tests, the flow

separation tests became a low priority item, and we did not do any more work with flow separation tests after our preliminary testing day.

Design Verification

The testing described above and the presentation of our test results in Appendix H constitutes our design verification process. A specification verification checklist which evaluates how well our final product meets or original specifications is provided in Appendix B.

Chapter 7
Conclusions and Recommendations

After our experiences on this project, here are our conclusions and recommendations to those who will continue this work.

Nozzle Reaction Force Conclusions and Recommendations

In conclusion, our results indicate that it may be the case that CAFS and water produce the same reaction forces for the same liquid flow rate. The "hump" in the data for the 1-1/8" smooth bore nozzle with CAFS seems to meet up with the water curve at higher flow rates (see Figure H.5). This may indicate that the smooth bore nozzle is experiencing some sort of different flow regime with CAFS at low liquid flow rates, and then at higher flow rates the reaction force with CAFS and water are the same. The 15/16" combination nozzle may not have experienced this flow regime (see Figure H.6) because the complex geometry of combination nozzles produces a much more turbulent flow at the nozzle outlet than smooth bore nozzles.

We recommend first that the existing reaction force measurement apparatus be recalibrated. The new calibration curve should then be applied to the existing data from our final tests (conducted on May 5th, 2012) to produce new plots. The reasoning behind this is because the first data point for the 1-1/8" smooth bore nozzle flowing water indicates a negative reaction force, and this does not make any sense at all.

Secondly, we recommend that the same testing procedure be performed again, perhaps with a newly manufactured prototype of the force measurement apparatus. It would be useful to see if the results we measured during our May 5th tests are repeatable, especially that odd hump in the 1-1/8" nozzle data with CAFS. If that "hump" is indeed repeatable, it may warrant further investigation as to why that hump occurs.

Hose Kinking Force Conclusions and Recommendations

From the testing conducted, it appears that the flow rate of the hose changes the force necessary to kink the hose substantially. When the hose is flowing, it appears that the CAFS requires a larger force to kink than the water, but while the hose is charged, the water requires the larger force. This makes sense, since the air in the hose is compressible, while the water is not. The flowing test shows the opposite result, and I suspect it is because the two tests were conducted at the same water flow rate. This means that the CAFS had the same amount of water flowing plus the air, giving the hose a larger total flow rate. This would cause the hose to be more resistant to kinking, which is what the data shows.

We recommend that the kink apparatus be remade with more precise components. This would reduce any friction losses associated with the kinking action, giving a more accurate reading. The test method could also be improved. In order to get a pure kink measurement, someone would have to move the hose along with the rotation in order to eliminate the drag of the hose on the ground.

Stream Throw and Distribution Conclusions and Recommendations

As one would expect, the CAFS is much more susceptible to wind resistance. The air pockets within the stream lower the density of the fluid, and therefore increase the drag. This is reflected in the maximum throw distances. Although the CAFS went farther, its trend was not the same as the water's. The CAFS maximum throw was at 22.5 degrees, while the water's throw increased with the angle. The CAFS left the nozzle with a higher velocity, but that velocity quickly diminished. The distribution also shows that the CAFS is more susceptible to wind. The spread of the CAFS is in general more spread out horizontally than the water. Its distance is also halted quicker.

Recommendations for the distribution test would include a tighter grid, more data points, and a windless environment. The grid we used was probably too spread out to give a thorough evaluation of how the stream hit the ground. Also, the amount of data points we used (around 50) were not sufficient to give a depiction of the distribution with adequate resolution. I would recommend having about 150-200 data points with a maximum distance of 3 feet from each other.

Friction Force Conclusions and Recommendations

Friction Force Conclusions

Each test surface behaves differently under exposure to foam and water. Through examination of the collected data we have compiled the following observations:

- 9 out of the 26 test pairings indicate an agreement between the measurements of static or dynamic friction coefficients for foam and water covered surfaces. Out of these nine test pairings, only three indicated foam covered surfaces as having a higher average friction coefficient when compared to water on the same surface.
- 17 of the 26 test pairings indicate that foam solution creates a distinctly slipperier surface compared to water.
- In general, the faster the dynamic movement across foam covered surfaces, the lower the dynamic friction coefficients become. Water covered surfaces do not exhibit this trend.
- The introduction of water to a surface increases the average static coefficient of friction when compared to the dry values for 4 of the test surfaces. Although the measurements are within uncertainty of each other, three of these surfaces are extremely smooth (polished concrete, linoleum, wood laminate).
- Highly deformable surfaces (carpet) can potentially produce friction coefficients of greater than 1.
- The magnitude of uncertainties was generally low, however cases of high uncertainty can be attributed either to a high amount of surface variation or error produced by the data acquisition system used in dynamic testing.

The observations we made indicate that foam creates a significantly slipperier surface on interior structural surfaces encountered in structural firefighting. Smooth surfaces such as linoleum, tile, and wood laminate pose the greatest slip hazard with foam. Deformable surfaces such as carpet pose less slip hazard. The main danger of foam solution seems to be the propensity to decrease the friction coefficient as velocity increases, indicating a slip on foam would be harder to recover from than a slip on water.

Friction Force Recommendations

Data collection could be improved by acquiring a more reliable data acquisition system. This would decrease the time required to run tests. Waterproofing the force transducer would also help decrease testing time by reducing the downtime required to dry the force transducer.

The measurements taken are about as accurate as they can get with the current test sled. In order to increase the repeatability and thus decrease the uncertainty associated with statistical error, a new design iteration of the test sled could be created that has a lower center of gravity distributed over the center of the fire boot. Increasing the resolution of data acquisition would not decrease uncertainty significantly. The majority of uncertainty comes from statistical variation in measurements.

Tests could include various concentrations of foam in the foam solution. This would indicate how much more dangerous a dry foam could be compared to a wet foam when it comes to creating slip hazards. Tests could also be run with various increasing weights applied to the test sled to determine the effect pressure has on the friction coefficients.

A variety of test surfaces have been investigated. If the cost was justified by the need, test samples could be manufactured using concrete and asphalt to give dynamic and submerged friction coefficients. Also, roofing material could be investigated, again if the cost justified the need.

Appendix A
Customer Requirements Survey

This appendix contains the completed customer requirements surveys that we provided to our sponsor, along with the instructions that went with each customer requirements survey. We used the results of these customer requirements surveys to develop our formal engineering specifications.

Proposed Requirements for All Test Results

The following are potential customer requirements that apply to all or most of the test results that our apparatuses will produce. Please rate the importance of each customer requirement for each individual test result.

Use "H" for high importance, "M" for moderate importance, "L" for low importance, and leave the space blank for "no importance" or "not applicable."

When a customer requirement is equally important for all test results, indicate the level of importance in the "All Test Results" column, and leave the other five columns blank.

	↓PRODUCTS↓					
	All Test Results	Reaction Force Results	Kink Force Results	Stream Throw Results	Stream Distribution Results	Surface Friction Results
↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓IMPORTANCE↓					
General						
Testing is cheap to conduct	M					
Results are accurate	H					
Result uncertainty is as low as possible (uncertainty can be quantified)	H					
Intellectual Property						
Test results are confidential	L					

↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓IMPORTANCE↓	↓PRODUCTS↓ All Test Results	Reaction Force Results	Kink Force Results	Stream Throw Results	Stream Distribution Results	Surface Friction Results
Usability							
Tests are fully-repeatable based on supplied information	H						
Data is easy to archive and store	M						
Data is reported in black and white (no color) so it's easier to print and photocopy	L						
Data analysis is done in Microsoft Excel, not MATLAB (since more people have Excel, more people will be able to open the analysis files)	H						
Results available in electronic form	H						
Results available in print form	L						
Data collection/analysis tools available in electronic form	H						
Data collection/analysis tools include user's manual and full documentation	H						
Coverage							
Covers different nozzle models	L						
Covers smooth-bore nozzles	H						
Covers fog nozzles	H						
Covers fog nozzles on straight-stream setting	H						
Covers different fog nozzle settings (from full fog to straight-stream)	L						
Covers nozzles at full-open ball valve setting	H						
Covers nozzles at different ball valve settings (from fully-closed to fully-open)	L						
Covers different hose sizes	M						
Covers different hose construction/materials	M						
Covers unusual/rarely-encountered operating conditions	L						
Covers conditions that are not extreme (low flow rates, low forces, et cetera)	L						

	↓PRODUCTS↓					
	All Test Results	Reaction Force Results	Kink Force Results	Stream Throw Results	Stream Distribution Results	Surface Friction Results
↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓IMPORTANCE↓					
Covers master streams	L					
Covers agitated hose streams (spinning teeth on nozzle)	L					
Covers non-agitated hose streams (no spinning teeth on nozzle)	L					
Features						
Data captures time history	L					
Data captures transient effects, not just steady state	M					
Repeat runs performed to test repeatability	H					
Empirical equations developed from data	M					
Develop fast equations for use by pump engineers in the field	L					
Includes "go/no-go" statement on CAFS versus water	L					
Gives uncertainty bands at confidence intervals	H					
Analysis includes probability density functions and other advanced statistical analysis	M					
Data captures noise level (i.e., high-frequency fluctuations)	M					
Data includes photographs of a few sample test	H					
Data includes photographs of ALL tests performed	H					
Data includes video/audio recording of a few sample tests	H					
Data includes video/audio recording of ALL tests performed	L					

Proposed Requirements for All Apparatuses

The following are potential customer requirements that apply to all or most of the physical apparatuses that we will design. Please rate the importance of each customer requirement for each individual apparatus.

Use "H" for high importance, "M" for moderate importance, "L" for low importance, and leave the space blank for "no importance" or "not applicable."

When a customer requirement is equally important for all apparatuses, indicate the level of importance in the "All Apparatuses" column, and leave the other five columns blank.

↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓PRODUCTS↓ All Apparatuses	Reaction Force Tester	Kink Force Tester	Stream Throw Tester	Stream Distribution Tester	Surface Friction Tester
	↓IMPORTANCE↓					
General						
Light-weight	L					
Reliable	H					
Long product life	M					
Low noise level	L					
Operates in low-temperature environments	L					
Products are colored fire truck red	L					
Use						
Easy setup and takedown	M					
Easy transportation	M					
Easy data collection	M					
Automated data collection	L					
Requires minimal crew to take data	L					
User does not get wet/dirty when using	M					
Features						
Interfaces with threaded hose couplings	H					
Interfaces with Storz hose couplings	L					
Interfaces with different coupling sizes	M					
Accepts different nozzle models	M					
Able to measure fixed cannons (e.g. master streams)	L					
Includes calibration features	H					
Includes user's manual and full product documentation	H					
Does not need to be fixed to the ground (staked, bolted, or otherwise)	L					
Actuated automatically (only human interaction is reading the data)	L					
Can be completely disassembled to replace individual parts	M					

	↓PRODUCTS↓					
	All Apparatuses	Reaction Force Tester	Kink Force Tester	Stream Throw Tester	Stream Distribution Tester	Surface Friction Tester
↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓IMPORTANCE↓					
Requires no electricity	M					
Requires no external power supply (electrical or otherwise)	M					
Product is remote-controlled	L					
Easy to use in low lighting/at night	L					
Does not use readings from the fire truck at all	L					
Calibrates readings from the fire truck before trusting them	H					
Multiple ways to measure the same thing (allows us to check instruments against each other)	L					
Users						
Can be used by firemen	L					
Can be used by handicapped	L					
Can be used by deaf people	L					
Efficiency/Economy						
Cheap to produce	M					
Low water/CAFS resource usage	H					
Cheap to run tests	M					
Low maintenance cost	H					
Cheap disposal at end of product life	M					
Environmental						
Recyclable at end of product life	M					
Product does not contain hazardous materials	H					
Business						
Product details are confidential	L					
Possibility for mass production	M					
Possibility for retail sale	L					
Possibility for marketing campaigns	L					

↓POTENTIAL CUSTOMER REQUIREMENTS↓	All Apparatuses	Reaction Force Tester	Kink Force Tester	Stream Throw Tester	Stream Distribution Tester	Surface Friction Tester
	↓IMPORTANCE↓					
Product is aesthetically pleasing	L					
Product has a cool name	L					
Safety						
Product is child-safe	L					

Proposed Requirements for Specific Test Results

The following are potential customer requirements that apply to specific test results only. Please rate the importance of each customer requirement.

Use "H" for high importance, "M" for moderate importance, "L" for low importance, and leave the space blank for "no importance."

↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓ IMPORTANCE
Kink Force Data	
Covers kink force while line is charged but not flowing fluid	H
Covers kink force while line is flowing fluid	H
Covers kink force at different positions along the length of the hose line	L
Stream Distribution Data	
Covers distribution at different points along the length of the stream	L
Reports total area of effect	H
Reports distribution of fluid delivery rate over the area of effect	H
Reports percentage of fluid that reached the target	L

↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓ IMPORTANCE
Data indicates the shape of the stream's cross section	M
Stream Throw Data	
Covers different angles of fire (i.e., the angle that the nozzle is tilted at)	M
Data indicates distance to the "centroid of fluid delivery"	H
Data indicates horizontal travel distance	H
Data indicates vertical travel distance	L
Data plots the entire trajectory of the stream in two dimensions	L
Reports the velocity of the fluid at different points along the length of the stream	L
Reports travel of farthest drop	L
Nozzle Reaction Data	
Reports the angle at which the nozzle reaction force is applied (i.e., we check to see if the reaction force is not parallel with the axis of the nozzle)	H
Surface Friction Data	
Covers many surfaces materials	H
Reports friction between dry surfaces	H
Reports friction between wetted surfaces	H
Reports friction between completely submerged surfaces	H
Reports friction between surfaces with fluid flowing over them	L
Reports static friction coefficient	H
Reports variation of static friction coefficient as a function of applied normal pressure	H
Reports kinetic friction coefficient	H
Reports variation of kinetic friction coefficient as a function of applied normal pressure	H

Proposed Requirements for Specific Apparatuses

The following are potential customer requirements that apply to specific apparatuses only. Please rate the importance of each customer requirement.

Use "H" for high importance, "M" for moderate importance, "L" for low importance, and leave the space blank for "no importance."

↓POTENTIAL CUSTOMER REQUIREMENTS↓	↓ IMPORTANCE
Kink Force Tester	
Kink force tester reproduces how a kink actually occurs in the field	L
Reproduces different ways that a kink develops	H
Reports force as a function of "percentage kinked"	L
Stream Distribution Tester	
Distribution tester eliminates the effects of wind	H
Stream Throw Tester	
Throw tester eliminates the effect of wind	H
Fluid is projected from nozzles at different heights	L

Appendix B
Engineering Specifications and Specification Verification Checklist

Formal Engineering Specifications

The engineering specifications are listed in the "Specification" column.

The "Risk" column indicates which engineering specifications we believe will be most difficult to achieve. "L" indicates that we anticipate the specification is low risk (i.e. it will definitely be easy to achieve). "M" indicates medium risk and "H" indicates high risk.

The "Compliance" column indicates how the engineering specification will be met. "A" indicates that we will attempt to meet the specification through "analysis." "T" indicates the specification will be met through "testing." "I" indicates that the specification will be met through "inspection."

Specification	Risk	Compliance
Specifications Pertaining to All Test Results		
Uncertainty is quantified	L	I
Tests are fully repeatable based on supplied information	L	I
All data analysis tools are Microsoft Excel files	L	I
All results are available in electronic form	L	I
Data analysis tools include user's manual and full documentation	L	I
Data includes repeat runs to test repeatability	L	I
Results include empirical equations developed from data	L	I
Results report uncertainty bands at confidence intervals	M	I
Results include photographs documenting each type of test	L	I
Results include video/audio recording documenting each type of test	L	I
Includes data on smooth bore nozzles fully-opened	L	I
Includes data on fog nozzles fully-opened in straight-stream setting	L	I
Results include data for the following operating conditions: Water flow rate: 80gpm to 160gpm Foam concentration: 0.0% to 0.5% (these are percent volume) Air flow rate: 0SCFM/gpm to 1.5SCFM/gpm	L	I

Specifications Pertaining to All Apparatuses		
Predicted service life of 500 hours of testing	M	A
Designed with a safety factor on yielding of 2.0	L	I
Each apparatus weighs under 75 lbf	M	AT
Each apparatus fits in the bed of a Ford F150 and does not protrude above the roof of the cab	M	AT
Each apparatus can be set up by one person in under 10 minutes	M	T
Each apparatus can be taken down by one person in under 10 minutes	M	T
A single datum can be recorded by one person in under 1 minute	M	T
Accommodates the following hose sizes: 1”, 1.5”, 1.75”, 2”, 2.5”	L	I
Apparatus accommodates the following couplings: 1.5” threaded, 2.5” threaded	L	I
Accommodates different nozzle models	L	I
Device can be calibrated without using extra tools/instruments	M	I
Each apparatus includes user’s manual and full product documentation	L	I
Calibrate readings from the fire truck before trusting them	H	I
Apparatus does not contain any hazardous materials	L	I
Specifications Pertaining to Kink Apparatus and Test Results		
Covers the following hose sizes: 1.5”, 1.75”, 2”, 2.5”	L	I
Covers the following hose constructions: Rubber-lined double jacket interior hand line	L	I
Covers fluid flowing and fluid not flowing in the hose	L	I
Covers two ways that a kink develops: hose pulls 180 degrees around a small square, and hose loop pulls straight into a kink	L	I
Specifications Pertaining to Stream Distribution Apparatus and Test Results		
Reports total area of effect at the target location	L	I
Reports distribution of fluid delivery rate over the area of effect at the target location	L	I
Testing performed on a day when it’s not windy outside	M	I

Specifications Pertaining to Stream Throw Apparatus and Test Results		
Results indicate distance to the "centroid of fluid delivery"	L	I
Results indicate horizontal travel distance	L	I
Testing performed on a day when it's not windy outside	M	I
Specifications Pertaining to Nozzle Reaction Apparatus and Test Results		
Reports the angle at which the nozzle reaction force is applied (i.e., we check to see if the reaction force is not parallel to the axis of the nozzle)	M	I
Specifications Pertaining to Surface Friction Apparatus and Test Results		
Results cover the following bottom surface materials: concrete, asphalt, wood deck material, plastic deck material, carpet, hardwood flooring, tile, linoleum, shingles, tar paper roofing, charred wood deck material, charred plastic deck material, charred carpet, charred hardwood, and charred linoleum.	L	I
Results cover the following top surface materials: rubber boot material sample	L	I
Results cover surfaces submerged in the following fluids: water/foam concentrations from 0.0% to 0.5% (these are percent volume)	L	I
Results cover dry surfaces	L	I
Results report static friction coefficient	L	I
Results report variation in static friction coefficient as a function of applied normal pressure	L	I
Results report kinetic friction coefficient	L	I
Results report variation in kinetic friction coefficient as a function of applied normal pressure	L	I
Specifications Pertaining to Flow Separation Test Results		
Results cover fluid settling and separation times from 1 minute to 10 minutes	L	I
Results cover a single vertical section of hose who's height ranges from 20 feet to 60 feet	L	I

Specification Verification Checklist

The engineering specifications are listed in the "specification" column. How well our final product met each specification is indicated by the checked box to the right of each specification.

↓ Specification ↓	Specification Met?			
	Poorly	Acceptably	Well	Excellently
Specifications Pertaining to All Test Results				
Uncertainty is quantified				x
Tests are fully repeatable based on supplied information				x
All data analysis tools are Microsoft Excel files				x
All results are available in electronic form				x
Data analysis tools include user's manual and full documentation	x			
Data includes repeat runs to test repeatability	x			
Results include empirical equations developed from data	x			
Results report uncertainty bands at confidence intervals			x	
Results include photographs documenting each type of test				x
Results include video/audio recording documenting each type of test				x
Includes data on smooth bore nozzles fully-opened				x
Includes data on fog nozzles fully-opened in straight-stream setting				x
Results include data for the following operating conditions: Water flow rate: 80gpm to 160gpm Foam concentration: 0.0% to 0.5% (these are percent volume) Air flow rate: 0SCFM/gpm to 1.5SCFM/gpm			x	
Specifications Pertaining to All Apparatuses				
Predicted service life of 500 hours of testing			x	
Designed with a safety factor on yielding of 2.0				x
Each apparatus weighs under 75 lbf			x	
Each apparatus fits in the bed of a Ford F150 and does not protrude above the roof of the cab				x
Each apparatus can be set up by one person in under 10 minutes				x
Each apparatus can be taken down by one person in under 10 minutes				x
A single datum can be recorded by one person in under 1 minute				x

Accommodates the following hose sizes: 1”, 1.5”, 1.75”, 2”, 2.5”				x
Apparatus accommodates the following couplings: 1.5” threaded, 2.5” threaded				x
Accommodates different nozzle models				x
Device can be calibrated without using extra tools/instruments	x			
Each apparatus includes user’s manual and full product documentation	x			
Calibrate readings from the fire truck before trusting them		x		
Apparatus does not contain any hazardous materials				x
Specifications Pertaining to Kink Apparatus and Test Results				
Covers the following hose sizes: 1.5”, 1.75”, 2”, 2.5”	x			
Covers the following hose constructions: Rubber-lined double jacket interior hand line				x
Covers fluid flowing and fluid not flowing in the hose				x
Covers two ways that a kink develops: hose pulls 180 degrees around a small square, and hose loop pulls straight into a kink	x			
Specifications Pertaining to Stream Distribution Apparatus and Test Results				
Reports total area of effect at the target location	x			
Reports distribution of fluid delivery rate over the area of effect at the target location				x
Testing performed on a day when it’s not windy outside		x		
Specifications Pertaining to Stream Throw Apparatus and Test Results				
Results indicate distance to the “centroid of fluid delivery”		x		
Results indicate horizontal travel distance				x
Testing performed on a day when it’s not windy outside		x		
Specifications Pertaining to Nozzle Reaction Apparatus and Test Results				
Reports the angle at which the nozzle reaction force is applied (i.e., we check to see if the reaction force is not parallel to the axis of the nozzle)	x			

Specifications Pertaining to Surface Friction Apparatus and Test Results				
Results cover the following bottom surface materials: concrete, asphalt, wood deck material, plastic deck material, carpet, hardwood flooring, tile, linoleum, shingles, tar paper roofing, charred wood deck material, charred plastic deck material, charred carpet, charred hardwood, and charred linoleum.		x		
Results cover the following top surface materials: rubber boot material sample				x
Results cover surfaces submerged in the following fluids: water/foam concentrations from 0.0% to 0.5% (these are percent volume)				x
Results cover dry surfaces				x
Results report static friction coefficient				x
Results report variation in static friction coefficient as a function of applied normal pressure	x			
Results report kinetic friction coefficient				x
Results report variation in kinetic friction coefficient as a function of applied normal pressure	x			
Specifications Pertaining to Flow Separation Test Results				
Results cover fluid settling and separation times from 1 minute to 10 minutes		x		
Results cover a single vertical section of hose who's height ranges from 20 feet to 60 feet		x		

Appendix C
Friction Test Decision Matrices

The following are decision matrices that we used for comparing friction testing concept alternatives.

Table C.1 – This decision matrix compares the various apparatuses required by published ASTM surface friction test methods to design requirements for the surface friction test. This matrix ignores design requirements involving the surface to surface interface as each machine would have to be modified to test on the variety of surfaces required. Such design factors are independent of the actual measuring device and will be covered in Table C.2.

Design Requirement	General																					Device-Specific						Totals	
	Reliable	Long Life	Easy Setup and Takedown	Easily Transportable	Easy Data Collection	User Stays Clean and Dry	Interfaces with Threaded Hose Couplings	Interfaces with Different Coupling Sizes	Accepts Different Nozzle Models	Includes Calibration features	Allows for Replacement of Individual Parts	Requires No Electricity	Requires no External Power	Cheap to Produce	Cheap to Run Tests	Cheap to maintain	Cheap to Dispose of At End of Life	Low Water and CAFS Resource Usage	Product Does Not Contain Hazardous Material	Recyclable at End of Life	Possibility of Mass Production	Covers Many surface materials	Reports Friction Between Dry Surfaces	Reports Friction between Wet Surfaces	Reports friction between submerged surfaces	Reports Static Coefficient of Friction	Reports Kinetic Coefficient of Friction	Un-weighted	Weighted
Weight	2	1	1	1	1	1	2	1	1	2	1	1	1	1	1	2	1	2	2	1	1	2	2	2	2	2	2	Totals	
Procedure and Apparatus																													
James Machine	3	3	1	0	3	3	x	x	x	3	2	2	2	1	2	2	2	3	3	2	1	x	x	x	x	3	3	44	62
Horizontal-Pull Dynamometer	3	3	2	3	3	3	x	x	x	3	2	1	2	2	2	2	2	3	3	2	2	x	x	x	x	3	2	48	65
Spring Scale Apparatus	1	2	3	3	1	3	x	x	x	0	1	3	3	3	2	2	2	3	3	2	2	x	x	x	x	2	0	40	49
NIST-Brungraber Machine	3	3	2	2	3	3	x	x	x	3	2	1	2	1	2	2	2	3	3	2	1	x	x	x	x	3	0	43	58
Horizontal-Pull Slipmeter	3	3	2	3	3	3	x	x	x	3	2	1	2	2	2	2	2	3	3	2	2	x	x	x	x	3	2	48	65

Table C.2 – Decision matrix for securing and submerging the test surface.

Design Requirement	General																					Device-Specific						Totals	
	Reliable	Long Life	Easy Setup and Takedown	Easily Transportable	Easy Data Collection	User Stays Clean and Dry	Interfaces with Threaded Hose Couplings	Interfaces with Different Coupling Sizes	Accepts Different Nozzle Models	Includes Calibration features	Allows for Replacement of Individual Parts	Requires No Electricity	Requires no External Power	Cheap to Produce	Cheap to Run Tests	Cheap to maintain	Cheap to Dispose of At End of Life	Low Water and CAFS Resource Usage	Product Does Not Contain Hazardous Material	Recyclable at End of Life	Possibility of Mass Production	Covers Many surface materials	Reports Friction Between Dry Surfaces	Reports Friction between Wet Surfaces	Reports friction between submerged surfaces	Reports Static Coefficient of Friction	Reports Kinetic Coefficient of Friction	Un-weighted	Weighted
Weight	2	1	1	1	1	1	2	1	1	2	1	1	1	1	1	2	1	2	2	1	1	2	2	2	2	2	2	Totals	
Design: Design 1	1	2	3	3	1	1	x	x	x	0	2	x	x	3	2	2	2	1	2	2	2	3	3	3	1	x	x	39	55
Design: Design 2	3	2	1	2	3	3	x	x	x	3	2	x	x	2	1	2	2	3	2	2	2	2	3	3	3	x	x	46	70
Design: Design 3	2	2	2	2	2	3	x	x	x	3	2	x	x	2	3	2	2	3	2	2	2	3	3	3	3	x	x	48	72

Appendix D
Testing Itineraries

Testing Itinerary for Preliminary Tests

The following is the testing itinerary that we followed during our preliminary tests, which were performed on March 2nd 2012.

Arrive at Cambria CSD
Collect equipment at test site (same field we were at last time)
EQUIPMENT:
Pumping rig
1-3/4" hose with 1-1/2" couplings
1-1/8" and 15/16" nozzles
Reaction force testing apparatus
Kink force testing apparatus
Distribution force testing apparatus
Throw testing apparatus
Flip last length of hose around using double female adapter and double male adapter
EQUIPMENT REQUIRED:
1-1/2" Double male adapter
1-1/2" Double female swivel adapter
Set up pumping rig
Test pumping rig operation to see how we control the SCFM of air
Set up test apparatuses
TEST APPARATUSES:
Set up reaction force measurement apparatus
Set up kink force measurement apparatus
Set up stream distribution measurement apparatus
Set up stream throw measurement apparatus
Set up 1-1/8" tip smooth bore nozzle
NOTE: IF PUMPING EQUIPMENT CANNOT PRODUCE THE DESIRED CONDITIONS, MAKE NOTE OF THAT AND MOVE ON TO NEXT TEST CONDITION
NOTE: WHEN POSSIBLE, ANALYZE DATA AS WE TAKE IT
PHASE I
Measure reaction force and kinking force at 0.00 SCFM/gpm

CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
0.00 SCFM of air per gpm of water
0.00% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 65 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 95 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 130 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 160 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure stream throw and distribution at 0.00 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
0.00 SCFM of air per gpm of water
0.00% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal

PHASE II
Measure reaction force and kinking force at 0.25 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
0.25 SCFM of air per gpm of water
0.30% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 65 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 95 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 130 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 160 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure stream throw and distribution at 0.25 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
0.25 SCFM of air per gpm of water
0.30% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal

Measure distribution at 45.0° above horizontal
PHASE III
Measure reaction force and kinking force at 0.50 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
0.50 SCFM of air per gpm of water
0.30% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 55 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 85 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 110 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure reaction force at 140 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same pump discharge pressure
Measure stream throw and distribution at 0.50 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
0.50 SCFM of air per gpm of water
0.30% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal

Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal
Set up 15/16" tip combo nozzle
PHASE IV
Measure reaction force at 0.00 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
0.00 SCFM of air per gpm of water
0.00% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure reaction force at 65 gpm of water
Measure reaction force at 95 gpm of water
Measure reaction force at 130 gpm of water
Measure reaction force at 160 gpm of water
Measure stream throw and distribution at 0.00 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
0.00 SCFM of air per gpm of water
0.00% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal
PHASE V
Measure reaction force at 0.25 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
0.25 SCFM of air per gpm of water
0.30% Foam concentrate

SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure reaction force at 65 gpm of water
Measure reaction force at 95 gpm of water
Measure reaction force at 130 gpm of water
Measure reaction force at 160 gpm of water
Measure stream throw and distribution at 0.25 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
0.25 SCFM of air per gpm of water
0.30% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal
PHASE VI
Measure reaction force at 0.50 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
0.50 SCFM of air per gpm of water
0.30% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 25 gpm of water
Measure reaction force at 50 gpm of water
Measure reaction force at 70 gpm of water
Measure reaction force at 95 gpm of water
Measure reaction force at 120 gpm of water
Measure stream throw and distribution at 0.50 SCFM/gpm
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
0.50 SCFM of air per gpm of water
0.30% Foam concentrate
SPECIFIC TESTS:

Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal
Take down and stow test apparatuses
TEST APPARATUSES:
Take down reaction force measurement apparatus
Take down kink force measurement apparatus
Take down stream distribution measurement apparatus
Take down stream throw measurement apparatus
Take down pumping rig and equipment
Return to Cambria CSD
Test flow separation
GENERAL SETUP:
Set up pumping rig with 1-3/4" hose with 1-1/2" couplings and a 15/16" tip combo nozzle
Charge line with conditions to produce 120 gpm of water, 0.30% foam concentrate, and 60 SCFM of air
Shut off flow at the nozzle, and leave line charged (aka, leave the pumping rig as is)
Elevate nozzle up to 20 foot height (on top of fire station)
SPECIFIC TESTS:
Wait for 5 minutes
Open nozzle and measure the time it takes to re-establish normal flow pattern
Shut off flow at the nozzle, and leave line charged (aka, leave the pumping rig as is)
Wait for 10 minutes
Open nozzle and time the time it takes to re-establish normal flow pattern
Take down pumping rig
Cal Poly collects a sample of the foam concentrate for later friction testing
Clean up

Testing Itinerary for Final Tests

The following is the testing itinerary that we followed during our final tests, which were performed on May 5th 2012.

Arrive at Cambria CSD
Collect equipment at test site (same field we were at last time)
EQUIPMENT REQUIRED:
Water Tender 57
1-3/4" hose with 1-1/2" couplings
1-1/8" smooth bore nozzle
15/16" combination nozzle
Reaction force testing apparatus
Kink force testing apparatus
Distribution measurement apparatus
Throw measurement apparatus
Flip last length of hose around using double female adapter and double male adapter
EQUIPMENT REQUIRED:
1-1/2" Double male adapter
1-1/2" Double female swivel adapter
Set up pumping rig (USE ENOUGH HOSE TO GET FRICTION LOSSES!)
Test pumping rig gauges (qualitative test)
Set up test apparatuses
TEST APPARATUSES:
Set up reaction force measurement apparatus
Set up kink force measurement apparatus
Set up stream distribution measurement apparatus
Set up stream throw measurement apparatus
Set up the 15/16" combination nozzle
NOTE: IF PUMPING EQUIPMENT CANNOT PRODUCE THE DESIRED CONDITIONS, MAKE NOTE OF THAT AND MOVE ON TO NEXT TEST CONDITION
NOTE: WHEN POSSIBLE, ANALYZE DATA AS WE TAKE IT
PHASE I - Stream Throw and Distribution - 15/16" Nozzle - CAFS
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
CAFS ON
0.30% Foam concentrate
SPECIFIC TESTS:

Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal
Take a picture of the field to show how much foam remains on the ground
PHASE II - Stream Throw and Distribution - 15/16" Nozzle - Water Only
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
CAFS OFF
0.00% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal
Set up 1-1/8" tip smooth bore nozzle
PHASE III - Stream Throw and Distribution - 1-1/8" Nozzle - CAFS
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
CAFS ON
0.30% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal

Take a picture of the field to show how much foam remains on the ground
PHASE IV - Stream Throw and Distribution - 1-1/8" Nozzle - Water Only
CONSTANT TEST CONDITIONS (THESE DO NOT CHANGE)
120 gpm of water
CAFS OFF
0.00% Foam concentrate
SPECIFIC TESTS:
Measure throw at 0.0° above horizontal
Measure distribution at 0.0° above horizontal
Measure throw at 22.5° above horizontal
Measure distribution at 22.5° above horizontal
Measure throw at 45.0° above horizontal
Measure distribution at 45.0° above horizontal
FOR STATIC KINK TEST, CLOSE VALVE BEFORE RECIRCULATING TO STORE STATIC PRESSURE IN THE LINE
PHASE V - Reaction and Kinking Forces - 1-1/8" Nozzle - CAFS
CONTSANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
CAFS ON
0.30% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 65 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 95 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 130 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 160 gpm of water

Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
PHASE VI - Reaction and Kinking Forces - 1-1/8" Nozzle - Water Only
CONTSANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
CAFS OFF
0.00% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 65 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 95 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 130 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 160 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Set up the 15/16" combination nozzle
PHASE VII - Reaction and Kinking Forces - 15/16" Nozzle - CAFS
CONTSANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
CAFS ON
0.30% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 65 gpm of water

Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 95 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 130 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 160 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
PHASE VIII - Reaction and Kinking Forces -15/16" Nozzle - Water Only
CONTSANT TEST CONDITIONS (THESE DO NOT CHANGE):
Angled 0.0° above horizontal
CAFS OFF
0.00% Foam concentrate
SPECIFIC TESTS:
Measure reaction force at 30 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 65 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 95 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 130 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Measure reaction force at 160 gpm of water
Measure kinking force while fluid is flowing
Shut off nozzle and measure kinking force at the same static pressure
Take down and stow test apparatuses
TEST APPARATUSES:
Take down reaction force measurement apparatus

Take down kink force measurement apparatus
Take down stream distribution measurement apparatus
Take down stream throw measurement apparatus
Set up transverse force test
Get good pictures of the transverse force test
Take down pumping rig and equipment
Return to Cambria CSD
Cal Poly collects a sample of the foam concentrate for later friction testing
Clean up

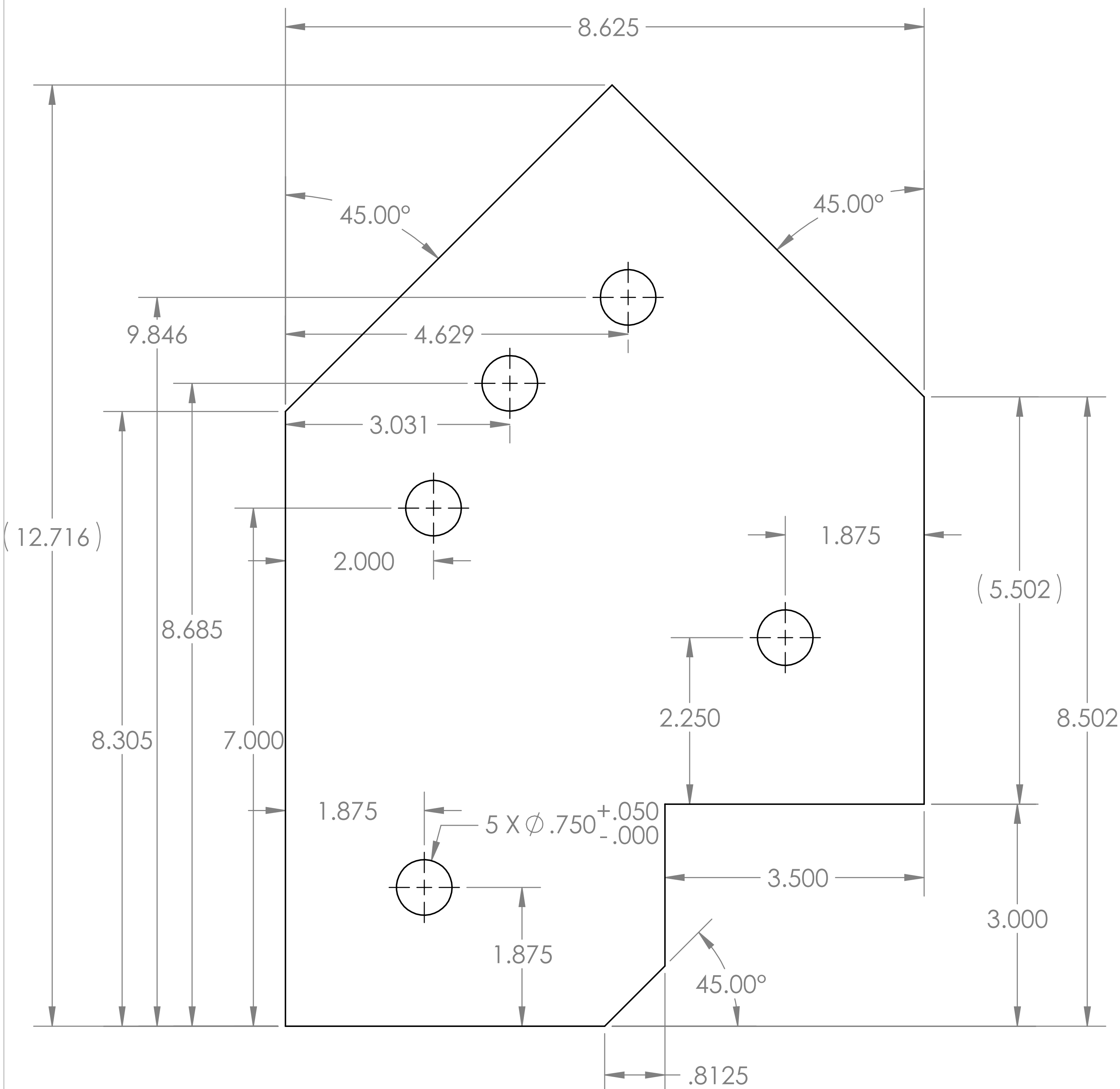
Appendix E
Detail Drawing Package

The following pages contain our dimensioned drawings for the following apparatuses:

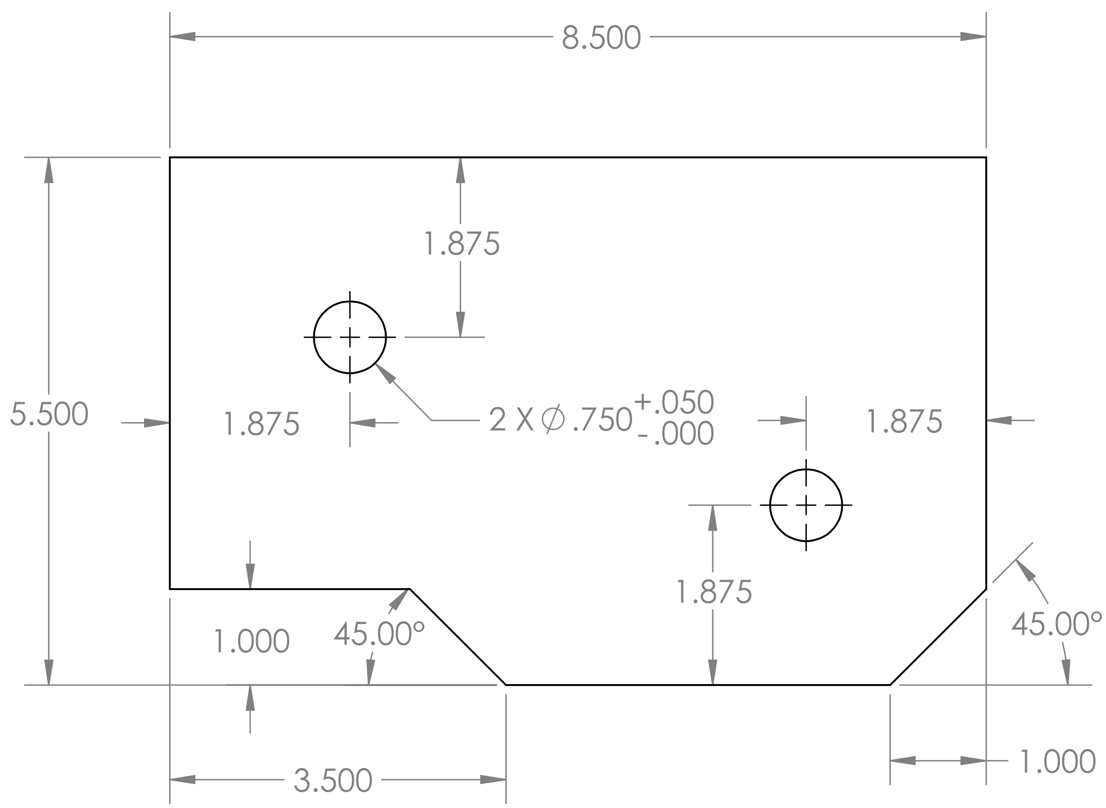
- Reaction force measurement apparatus
- Hose kink force measurement apparatus
- Friction force measurement apparatus

Reaction Force Measurement Apparatus Detail Drawings

The following pages contain our detail drawings for the reaction force measurement apparatus.



				NAME	DATE	
RAC001		DIMENSIONS ARE IN INCHES DEFAULT TOLERANCE ±0.030"	DRAWN	LAPOLLA	25 FEB 12	
			CHECKED			
			ENG APPR.			ANGLE PLATE
			MFG APPR.			
		MATERIAL: 0.75" THICK ADX PLYWOOD	Q.A.			
		FINISH	COMMENTS:			
NEXT ASSY	USED ON					SIZE A · DWG. NO. RAA001 · REV. 1
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:2 · WEIGHT: · SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
DEFAULT TOLERANCE ±0.030"

	NAME	DATE
DRAWN	LAPOLLA	25 FEB 12
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL:
0.75" THICK ADX PLYWOOD

FINISH

NEXT ASSY | USED ON

APPLICATION

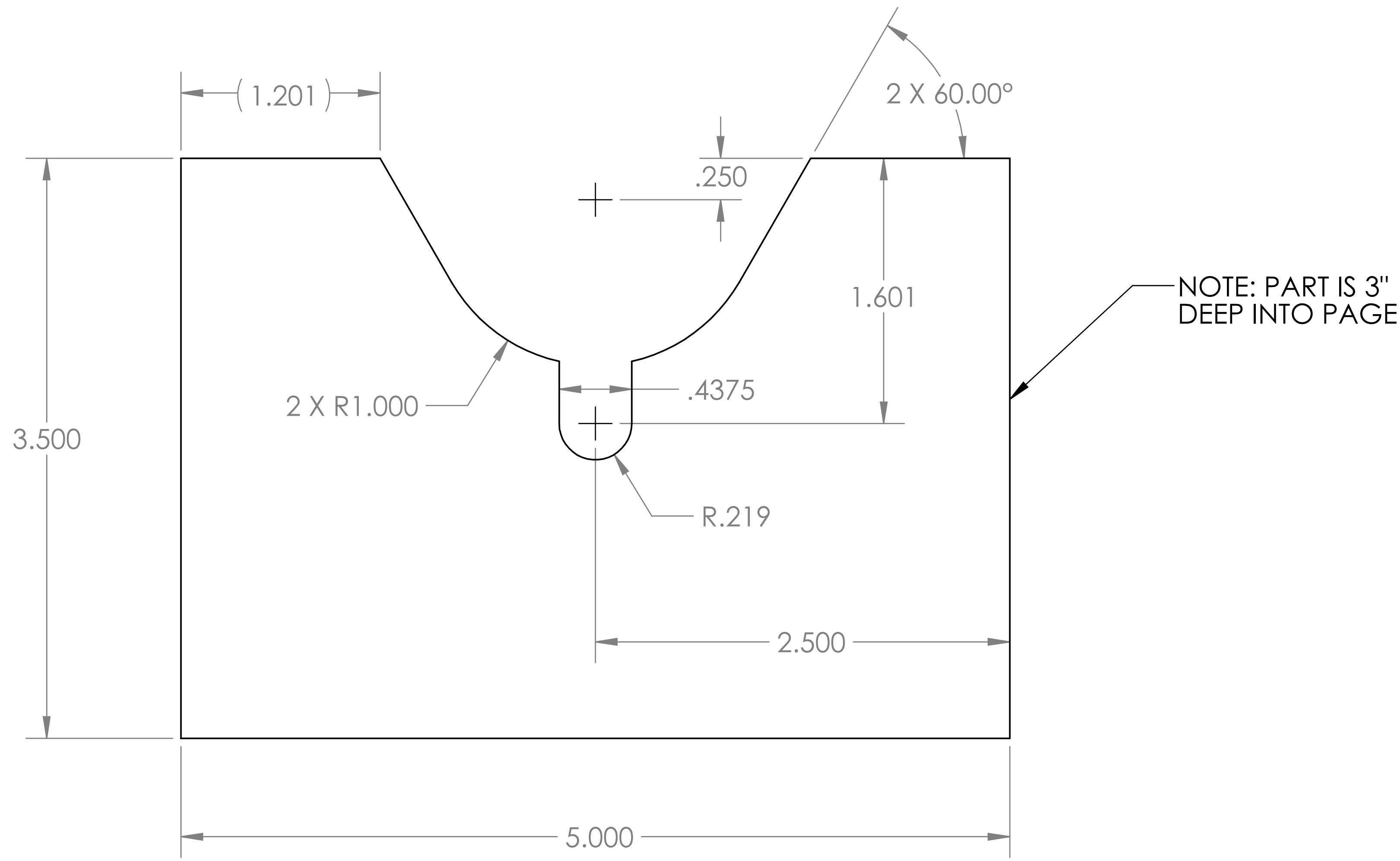
DO NOT SCALE DRAWING

TITLE:

SLIDING PLATE

SIZE A | DWG. NO. RAA002 | REV 1

SCALE: 1:2 | WEIGHT: | SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES DEFAULT TOLERANCE ±0.030"	DRAWN	LAPOLLA	25 FEB 12
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL: 4X6 DIMENSIONAL LUMBER (FIR)	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

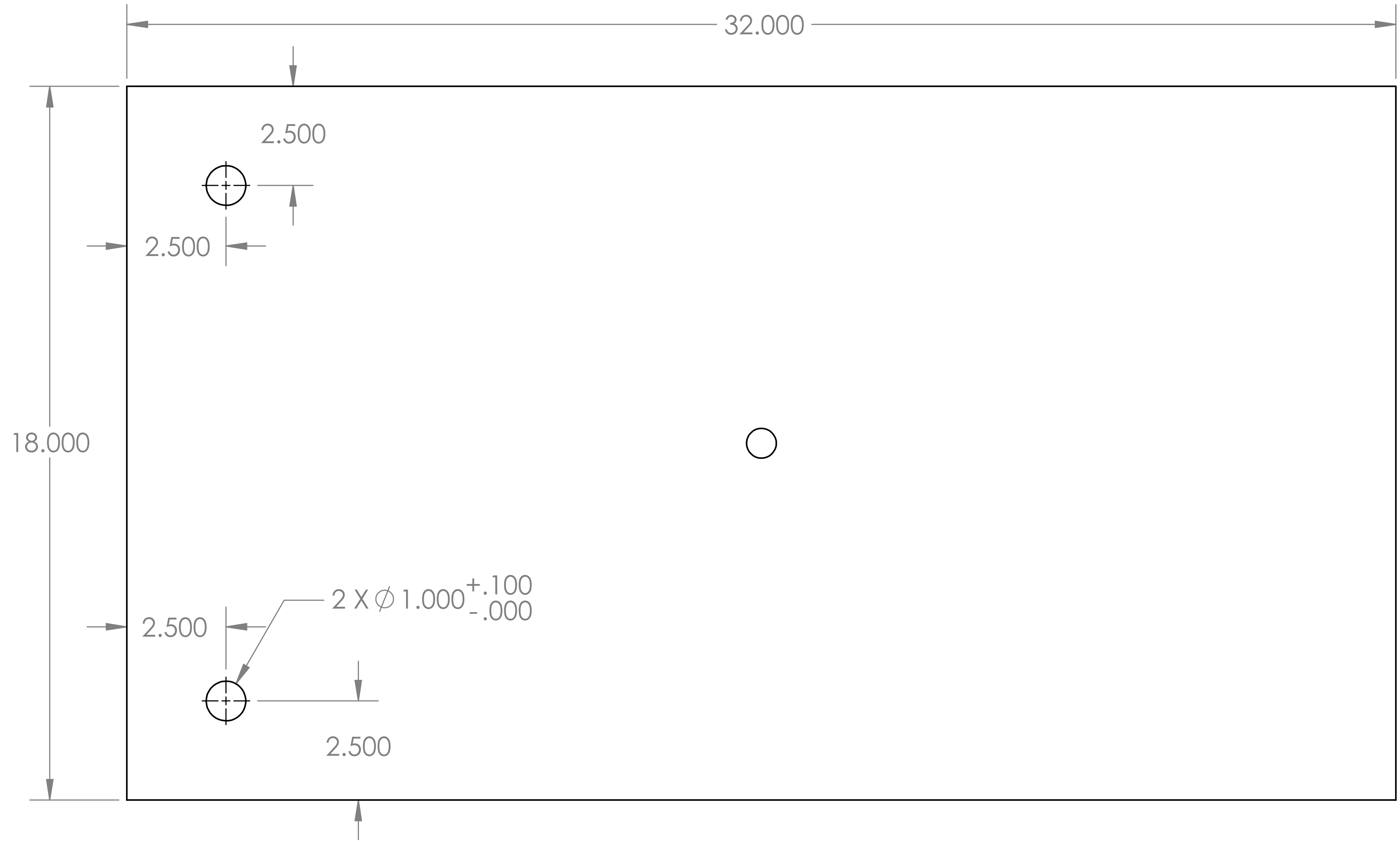
NEXT ASSY	USED ON
APPLICATION	

TITLE:

V HOLDER

SIZE	DWG. NO.	REV
A	RAA003	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



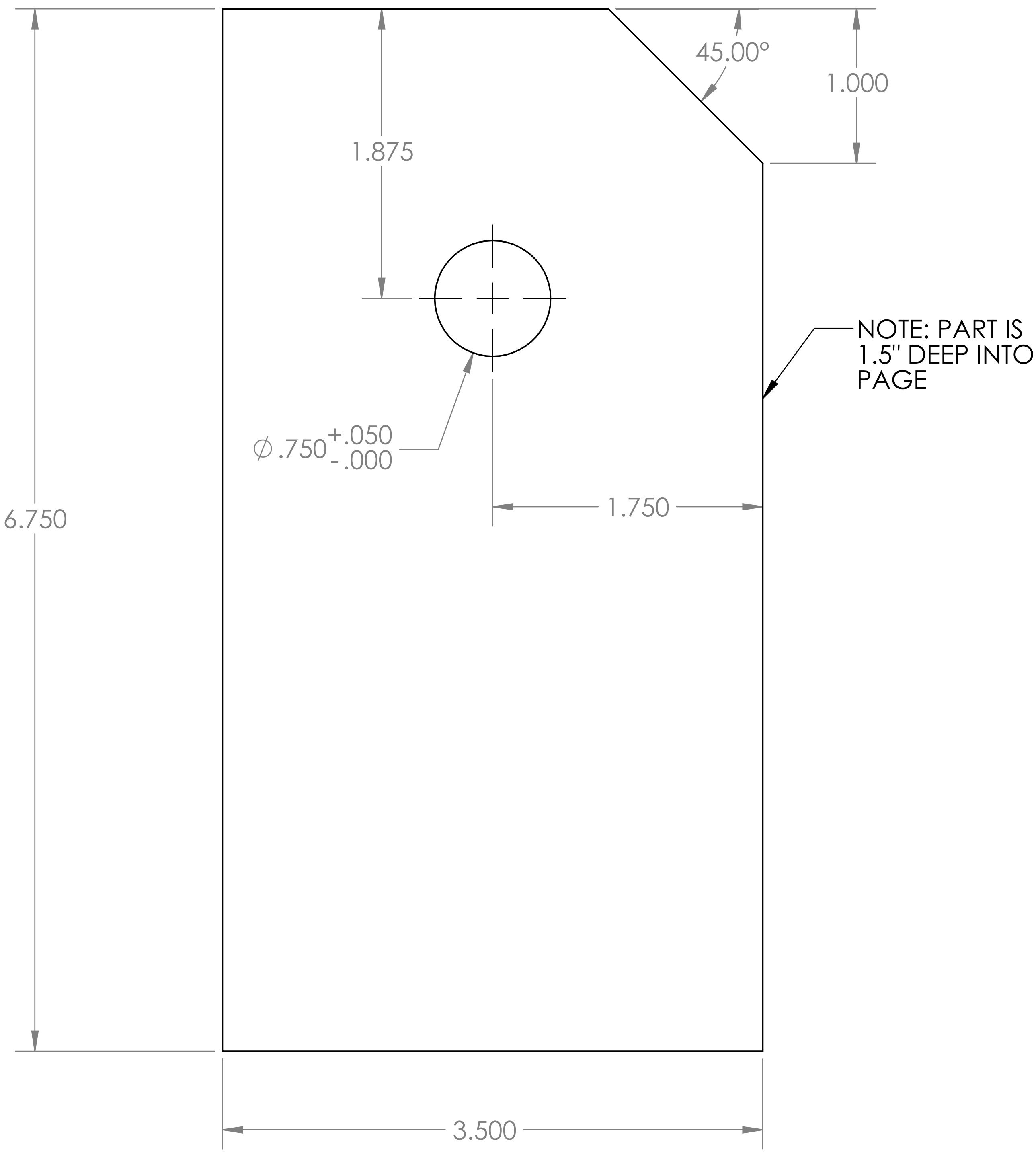
UNLESS OTHERWISE SPECIFIED:		
DIMENSIONS ARE IN INCHES DEFAULT TOLERANCE ±0.030"		
MATERIAL: 0.75" THICK ADX PLYWOOD		
FINISH		
NEXT ASSY	USED ON	
APPLICATION		DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	LAPOLLA	7 MAR 12
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE:

BASE

SIZE	DWG. NO.	REV
A	RAA004	1
SCALE: 1:4	WEIGHT:	SHEET 1 OF 1



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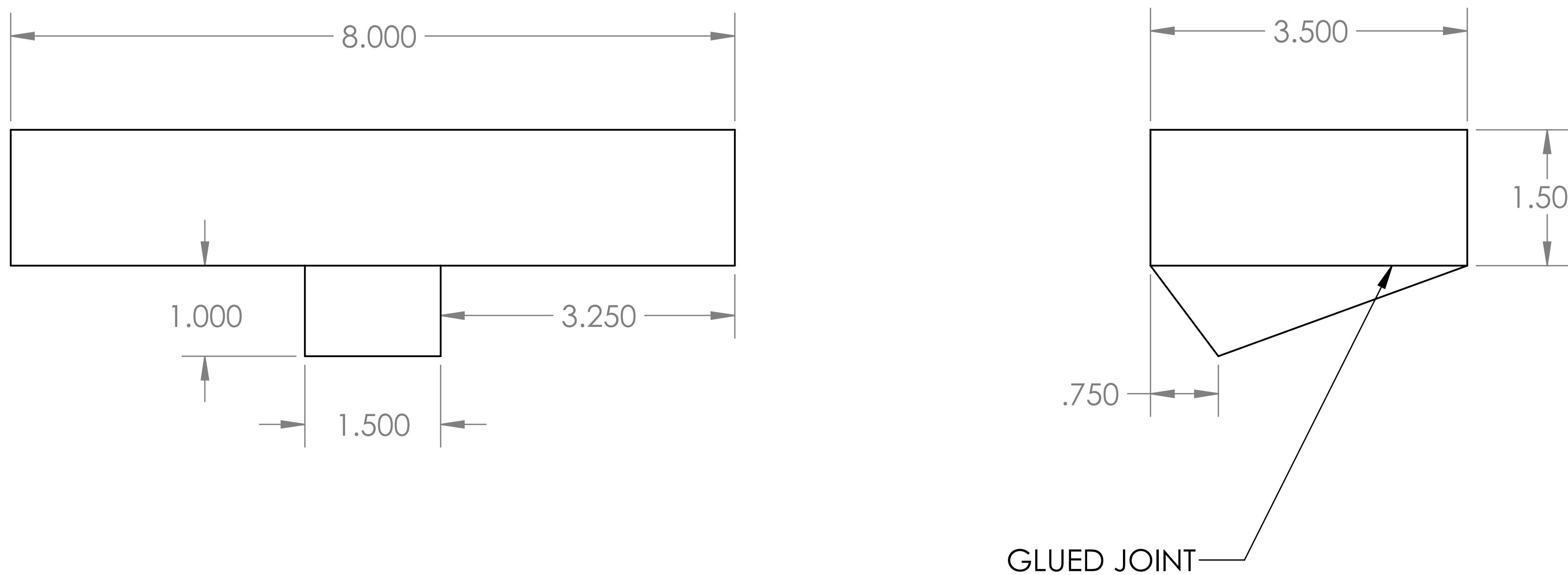
			DRAWN	LAPOLLA	7 MAR 12	
			CHECKED			
			ENG APPR.			BASE SUPPORT
			MFG APPR.			
		MATERIAL: 2X4 DIMENSIONAL LUMBRER (FIR)	Q.A.			
			COMMENTS:			
NEXT ASSY	USED ON	FINISH				SIZE A / DWG. NO. RAA005 / REV. 1
APPLICATION		DO NOT SCALE DRAWING				SCALE:1:1 / WEIGHT: / SHEET 1 OF 1

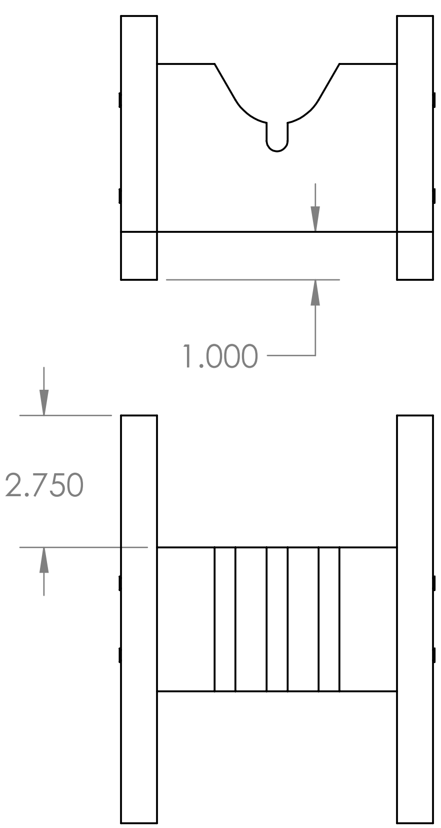


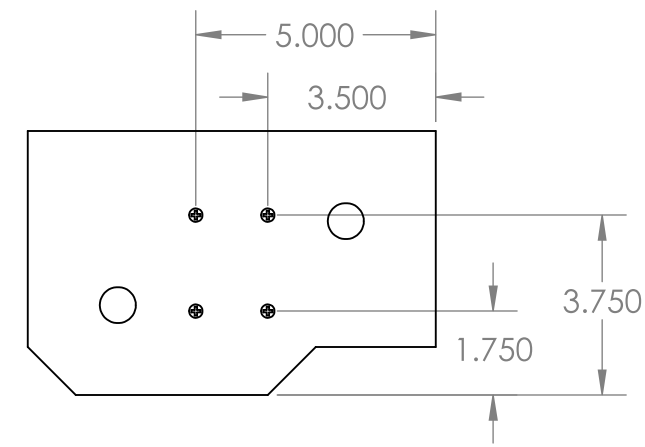
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
DIMENSIONS ARE IN INCHES DEFAULT TOLERANCE ±0.030"	DRAWN	LAPOLLA	25 FEB 12	TITLE:
	CHECKED			CROSSBEAM
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL: 2X4 DIMENSIONAL LUMBER (FIR)	COMMENTS:			SIZE A DWG. NO. RAB001 REV
FINISH				
DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	RAA003	V HOLDER	1
2	RAA002	SLIDING PLATE	2
3	(PURCHASED)	#8X2" COUNTERSINK HEAD SHEET METAL SCREW	8
4	(PURCHASED)	4-3/32" TO 6" STAINLESS STEEL SCREW TYPE HOSE CLAMP (OMITTED IN DRAWING)	1





DRILL FULL-DEPTH 7/64" PILOT HOLES FOR ALL SCREWS
COUNTERSINK TO GET SCREW HEADS FLUSH WITH SURFACE

INSTALL SCREW-TYPE HOSE CLAMP AROUND THE V HOLDER BEFORE SCREWING THE ASSEMBLY TOGETHER. THE HOSE CLAM SHOULD FIT VERTICALLY BETWEEN THE SCREWS. THE HOLE IN THE HOSE CLAM SHOULD ALIGN WITH THE CHANNEL IN THE TOP OF THE V HOLDER.

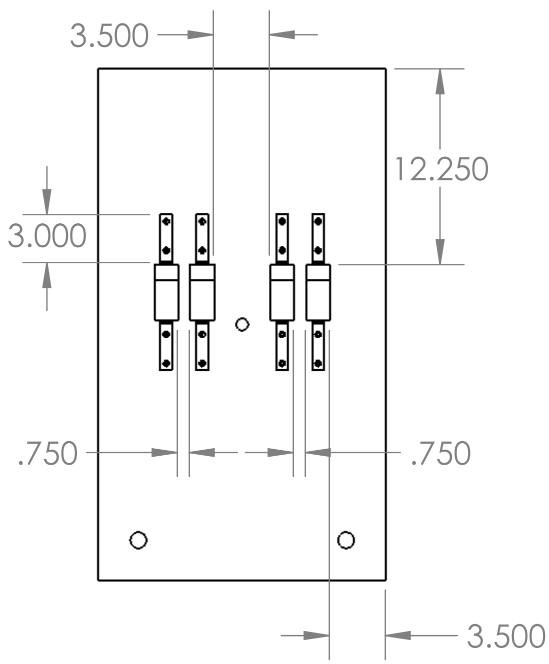
CUT A SHALLOW CHANNEL IN THE V HOLDER AS NECESSARY TO ACCOMODATE THE SCREW-TYPE HOSE CLAMP.

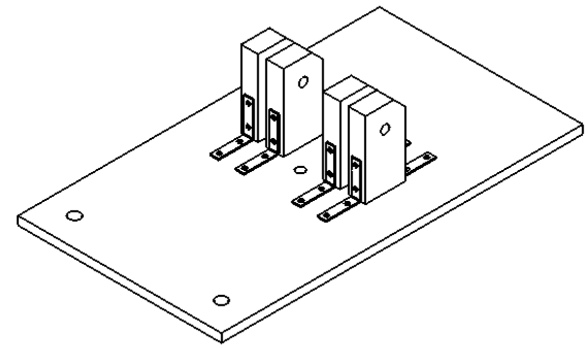
UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
DIMENSIONS ARE IN INCHES DEFAULT TOLERANCE ±0.030"	DRAWN	LAPOLLA	7 MAR 12	TITLE:	
	CHECKED			HOLDER SUB.	
	ENG APPR.				
	MFG APPR.				
	Q.A.				
MATERIAL:	COMMENTS:			SIZE A	DWG. NO. RAB002	REV 1
FINISH				SCALE: 1:4	WEIGHT:	SHEET 1 OF 1
DO NOT SCALE DRAWING					

RAA001 | NEXT ASSY | USED ON
APPLICATION

5 4 3 2 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	RAA004	BASE	1
2	RAA005	BASE SUPPORT	4
3	(PURCHASED)	3" L-BRACKET (STEEL)	8
4	(PURCHASED)	#10X1.5" COUNTERSINK HEAD SHEET METAL SCREW	16
5	(PURCHASED)	#10X0.75" COUNTERSINK HEAD SHEET METAL SCREW	16





USE THE 1.5"-LONG SCREWS TO SCREW INTO THE BASE SUPPORTS
USE THE 0.75"-LONG SCREWS TO SCREW INTO THE BASE

DRILL FULL-DEPTH 1/8" PILOT HOLES FOR ALL SCREWS

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES DEFAULT TOLERANCE ±0.030"	DRAWN	LAPOLLA	7 MAR 12
	CHECKED		
	ENG APPR.		
	MFG APPR.		
	Q.A.		
MATERIAL:	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

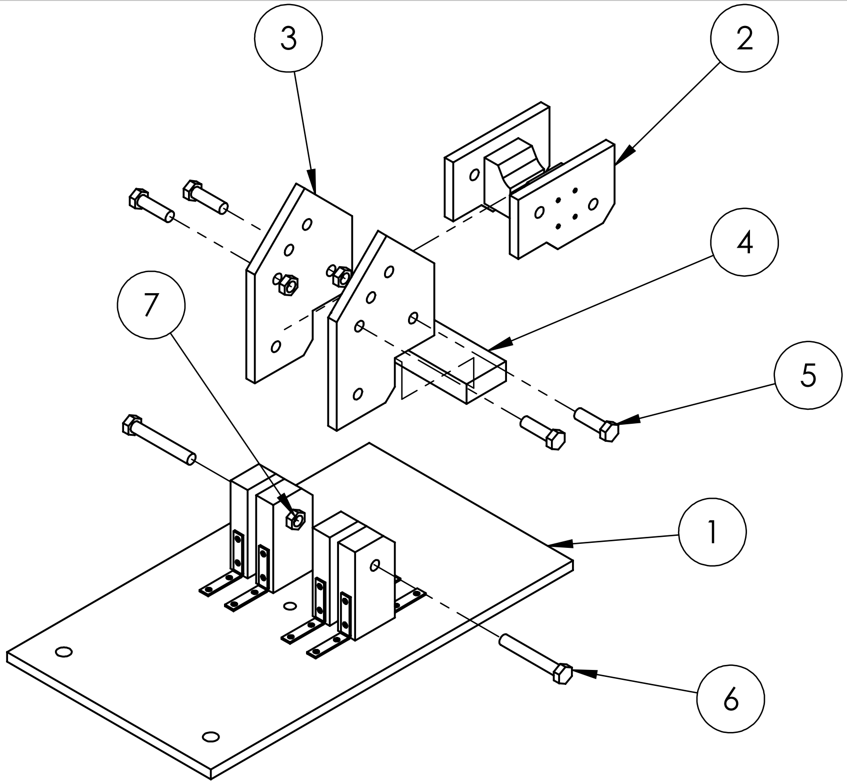
RAA001	
NEXT ASSY	USED ON
APPLICATION	

TITLE:

BASE SUB.

SIZE	DWG. NO.	REV
A	RAB003	1
SCALE: 1:12	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



NOTE: CROSS BEAM IS ATTACHED TO THE ANGLE PLATES BY WOOD GLUE

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	RAB003	BASE SUB-ASSEMBLY	1
2	RAB002	HOLDER SUB-ASSEMBLY	1
3	RAA001	ANGLE PLATE	2
4	RAB001	CROSS BEAM	1
5	(PURCHASED)	0.75"X2.5" HEX HEAD BOLT, COARSE	4
6	(PURCHASED)	0.75"X5" HEX HEAD BOLT, COARSE	2
7	(PURCHASED)	0.75" HEX NUT, COARSE	6

UNLESS OTHERWISE SPECIFIED:

	NAME	DATE
DRAWN	LAPOLLA	7 MAR 12
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MATERIAL:

FINISH

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

TITLE:

MAIN ASSY.

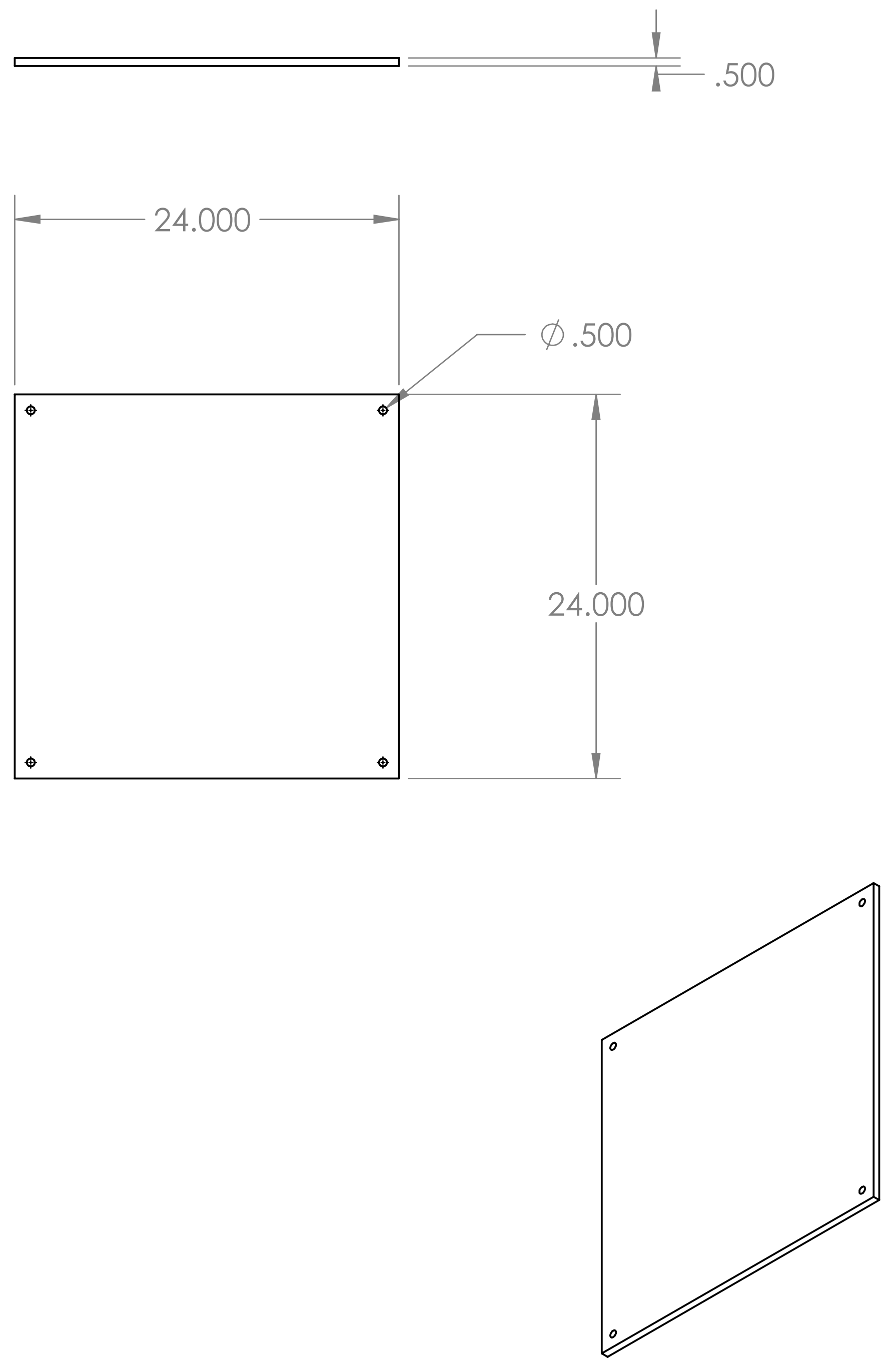
SIZE A | DWG. NO. RAC001 | REV 1

SCALE: 1:12 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1

Hose Kink Force Measurement Apparatus Detail Drawings

The following pages contain our detail drawings for the hose kink force measurement apparatus.



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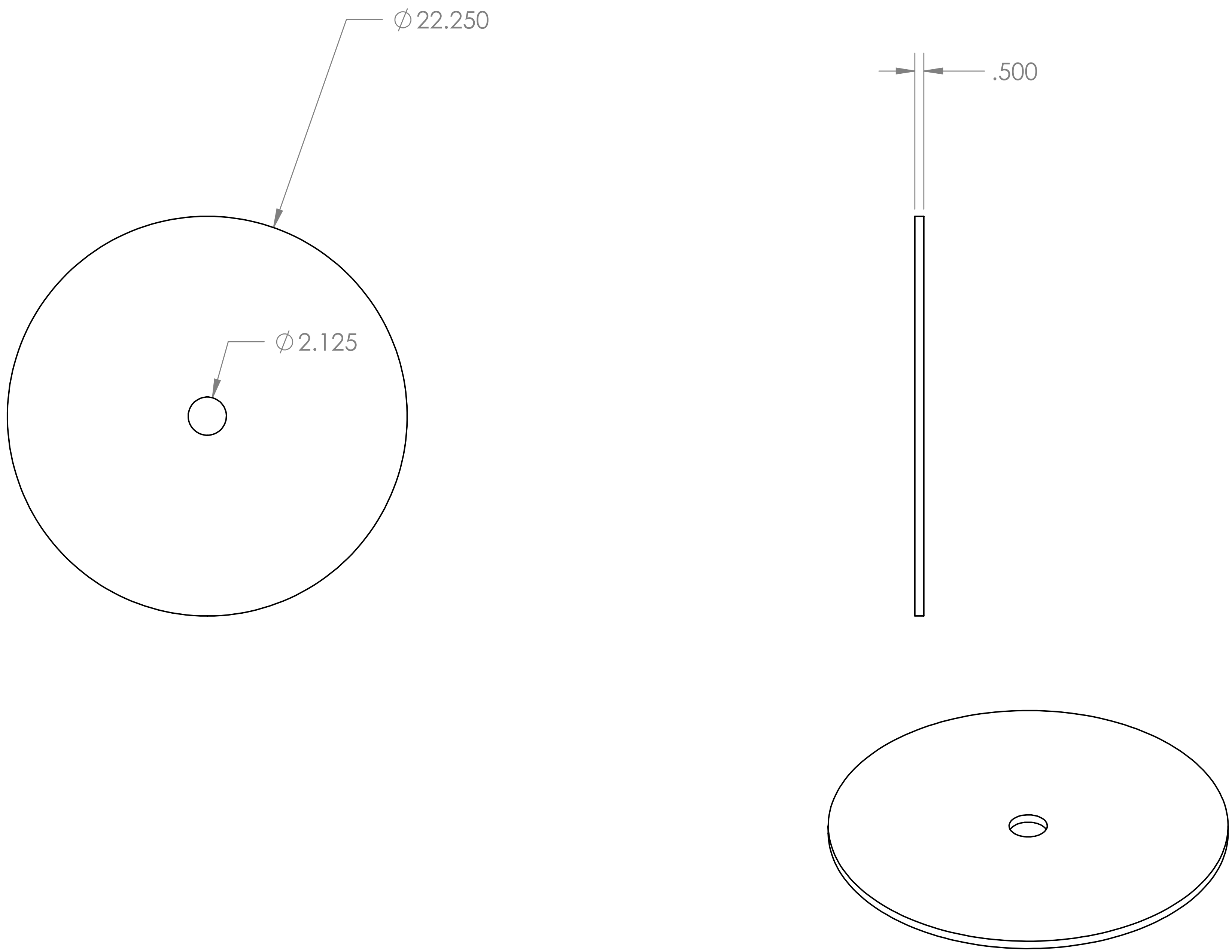
24.000
⌀.500
24.000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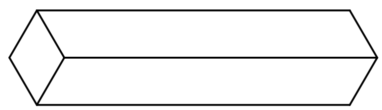

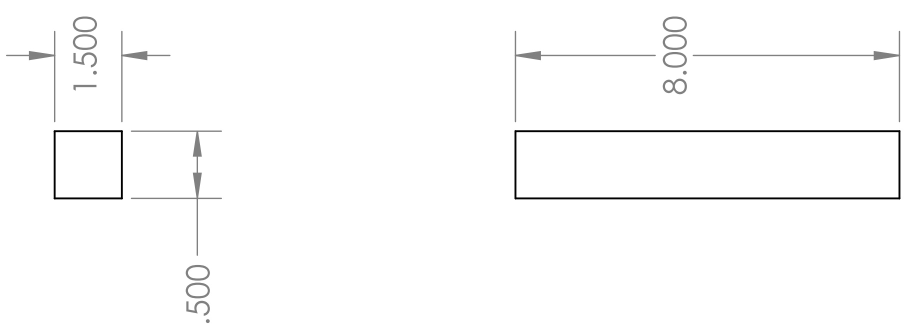
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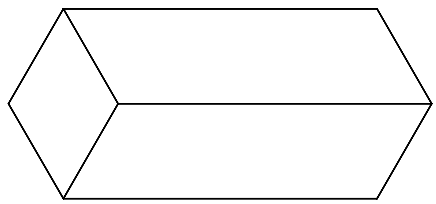
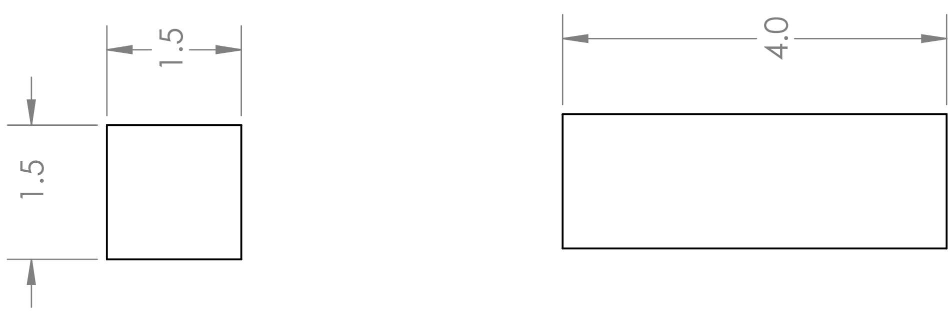
8.000
1.500

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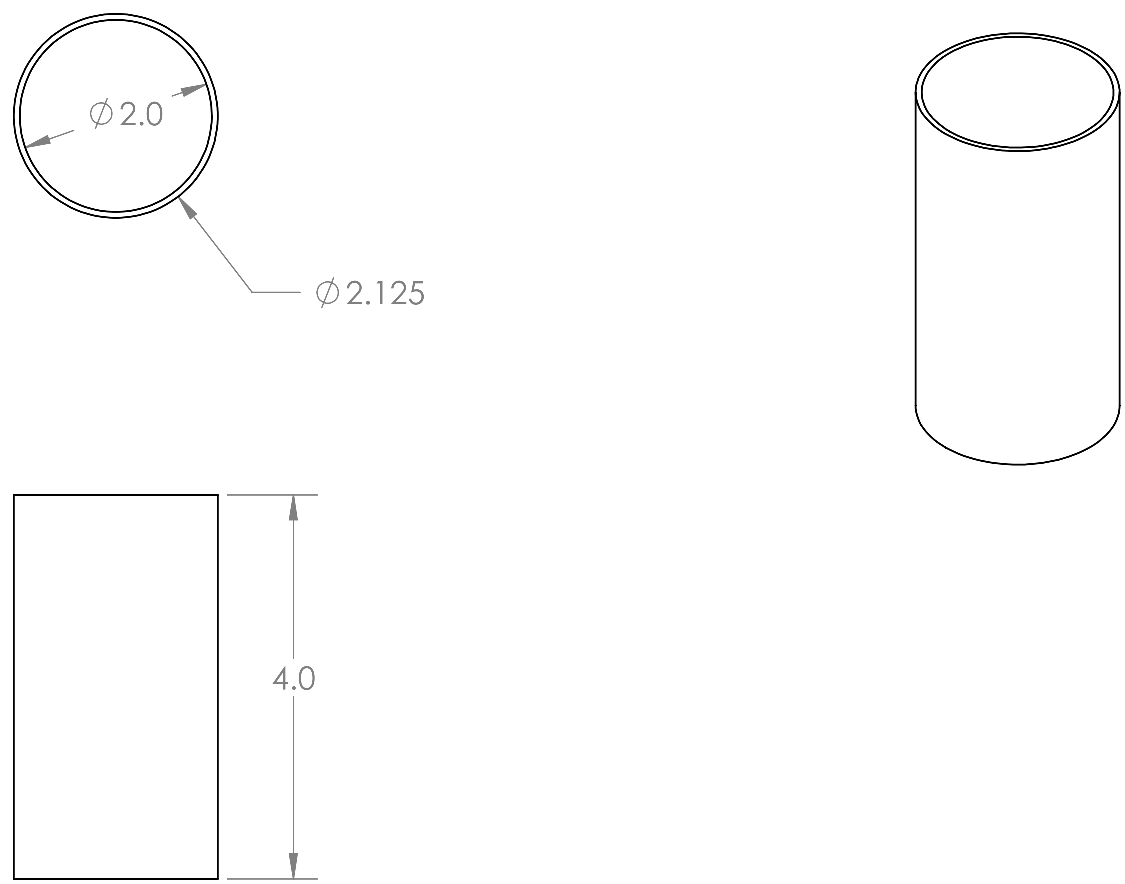
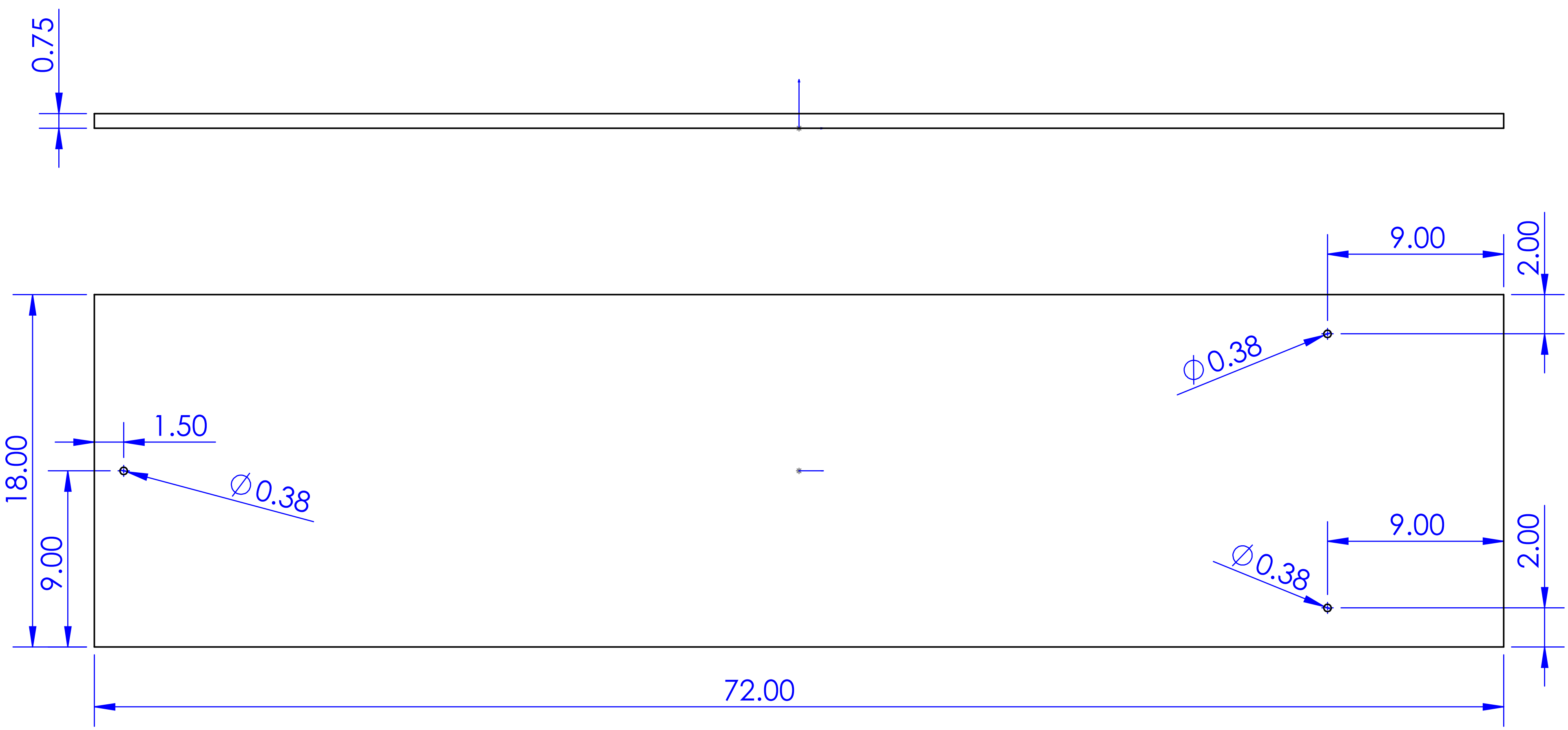
4.0



⌀2.0
⌀2.125
4.0

Friction Force Measurement Apparatus Detail Drawings

The following pages contain our detail drawings for the friction force measurement apparatus.



CAFS Senior Project		Part #: F001
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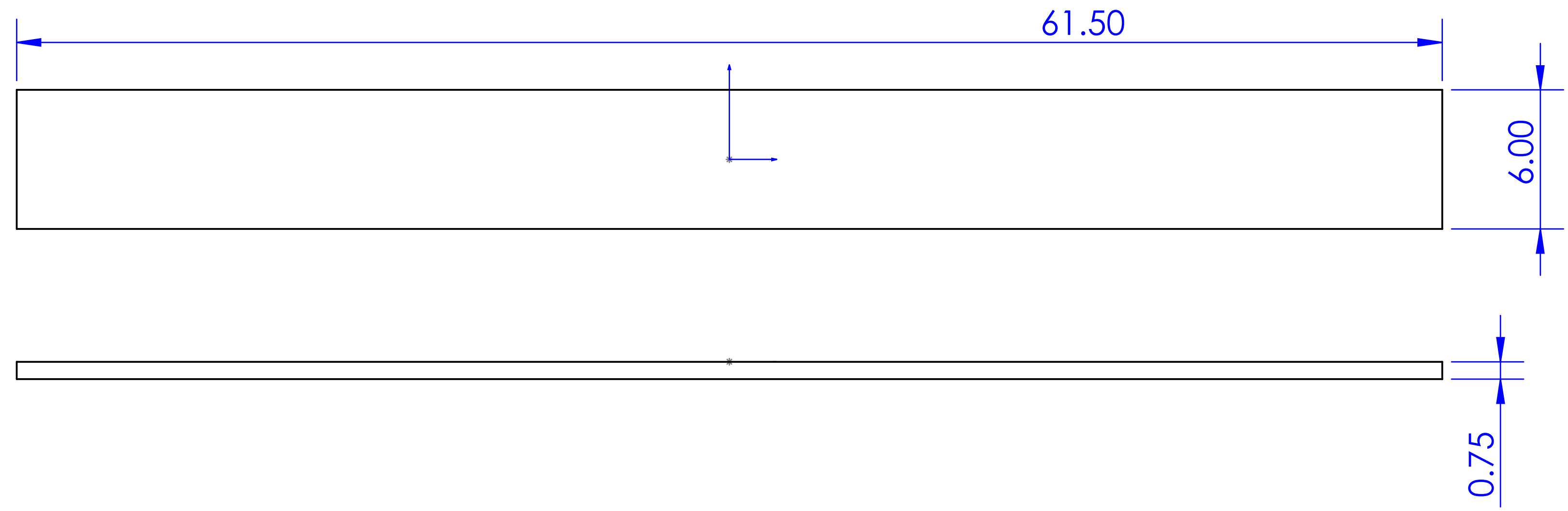
DATE: 3/6/12	DRAWN BY: A. Morano	

Mechanical Engineering CAL POLY

5 4 3 2 1



CAFS Senior Project			Part: F002
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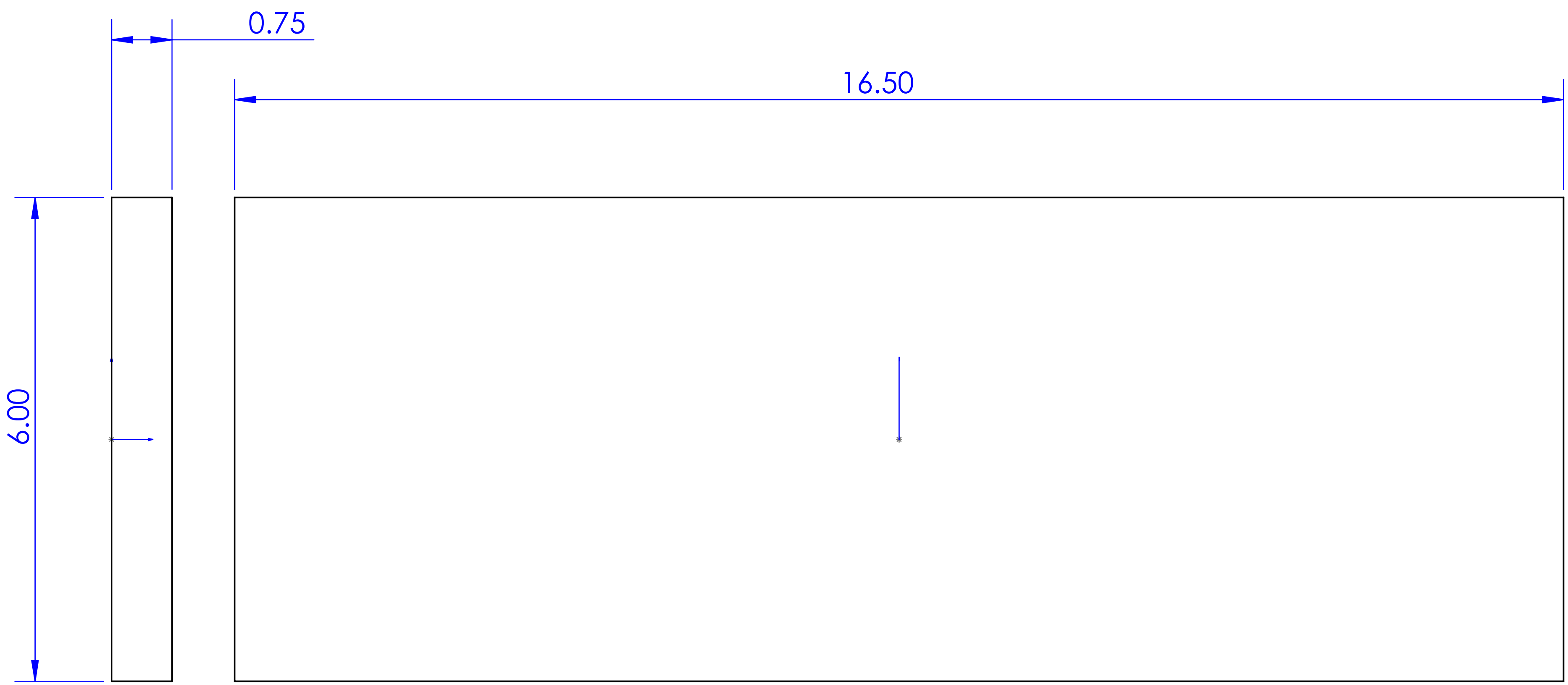
DATE: 3/6/12	DRAWN BY: A. Morano		

Mechanical Engineering CAL POLY

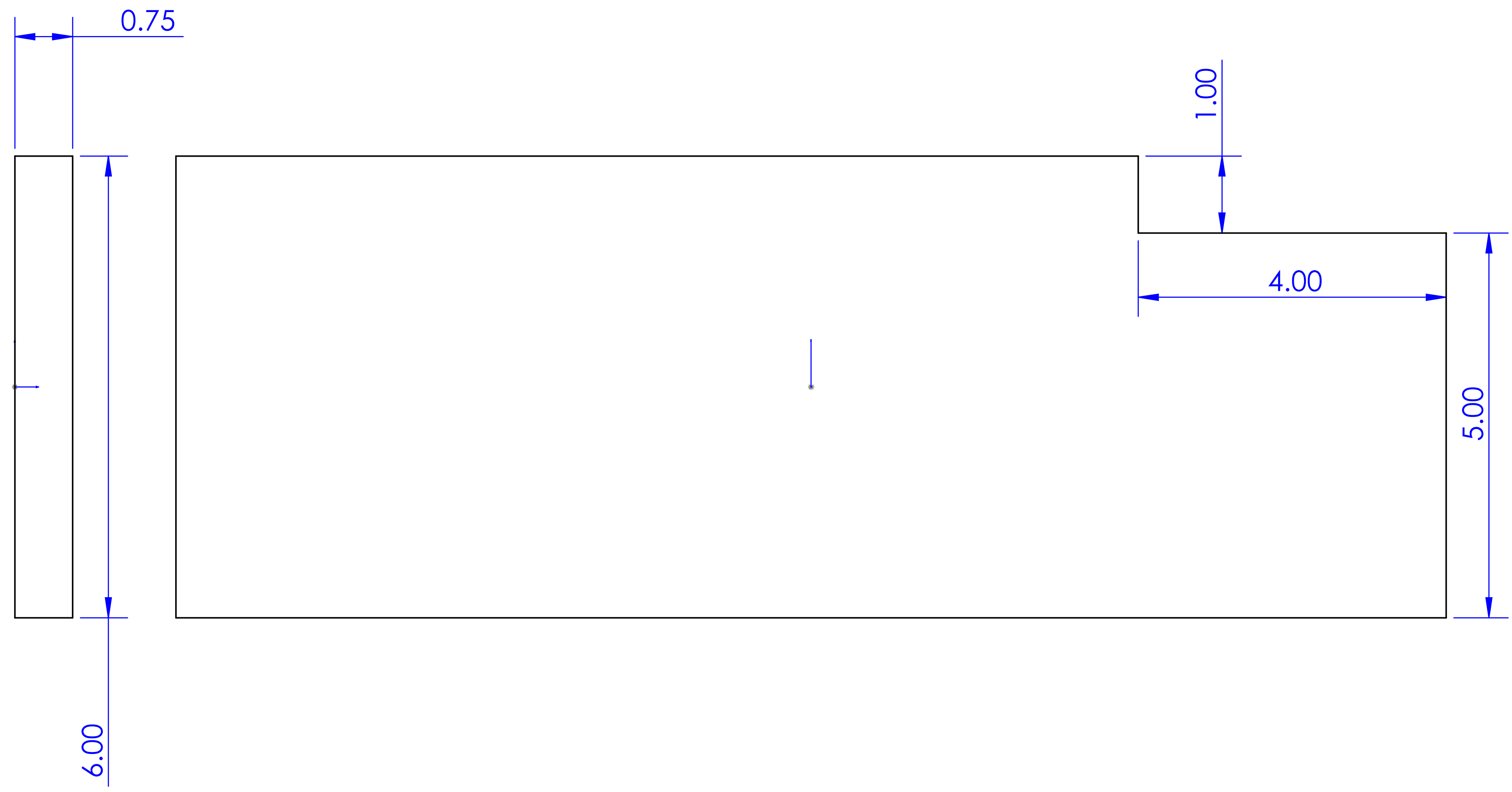
5 4 3 2 1



Mechanical Engineering CAL POLY

CAFS Senior Project		Part: F003
SCALE: 1:2	UNITS: INCHES	MATERIAL: Pine
DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1



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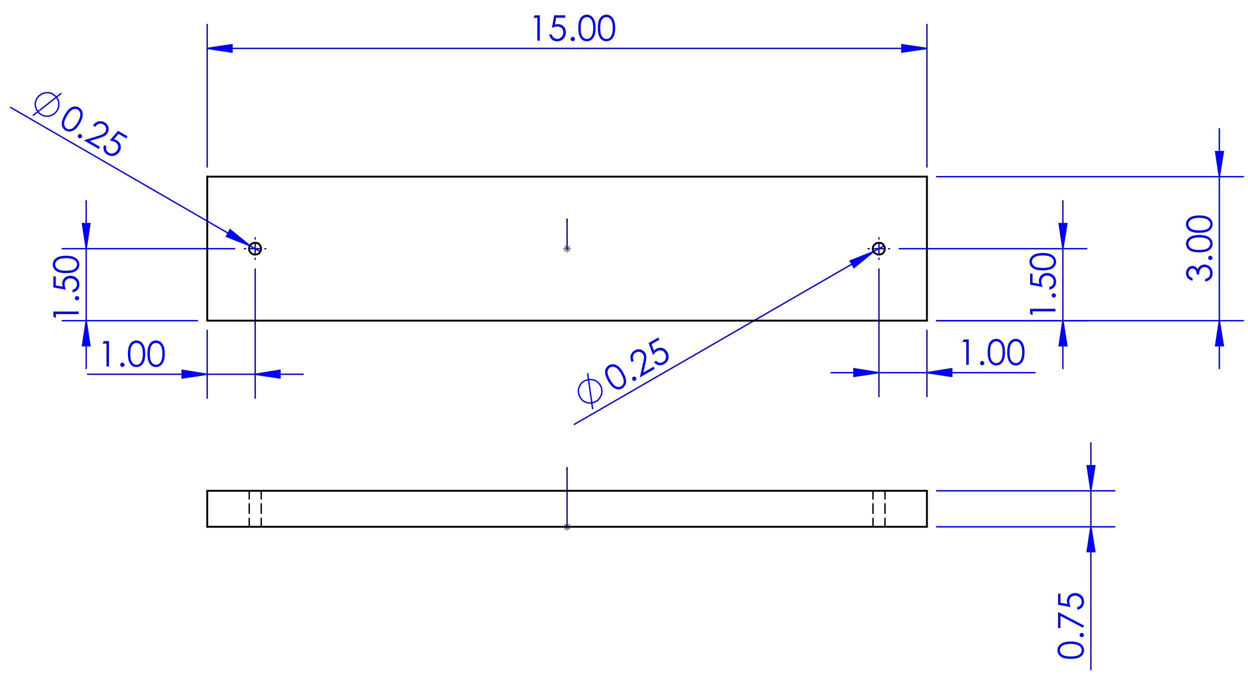
DATE: 3/6/12	DRAWN BY: A. Morano	

Mechanical Engineering CAL POLY



Mechanical Engineering CAL POLY	CAFS Senior Project		Part: F005
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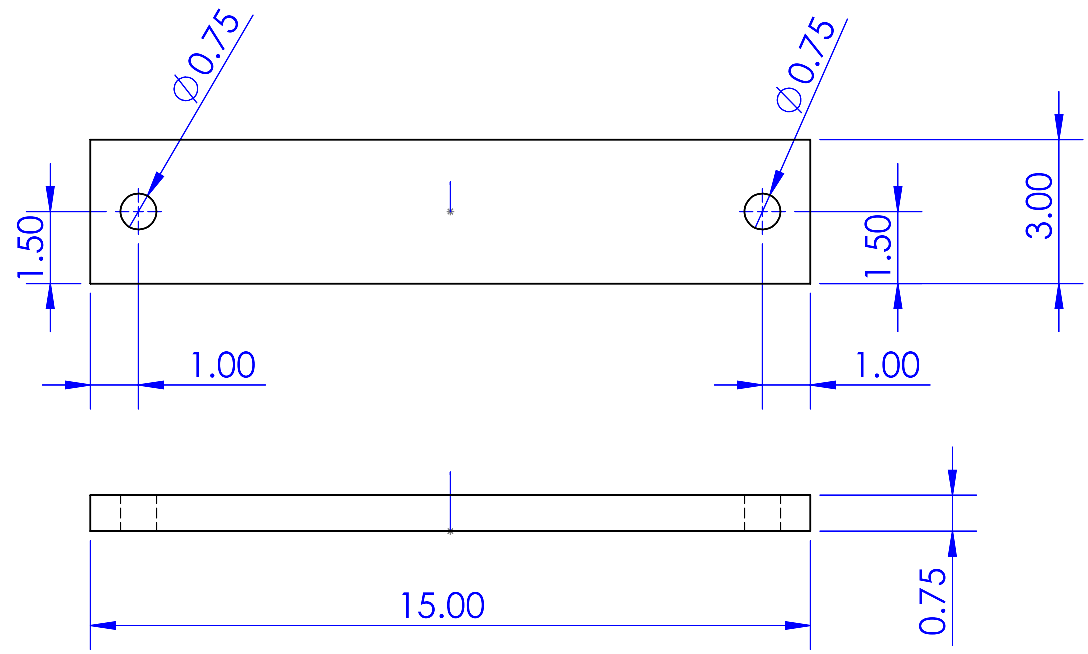
	DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1



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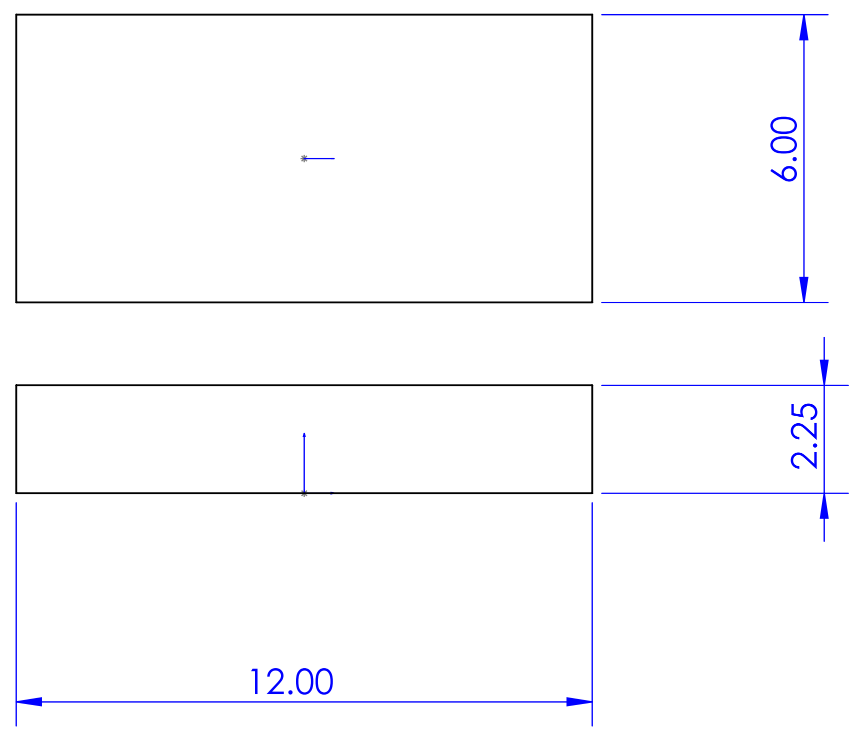
DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1



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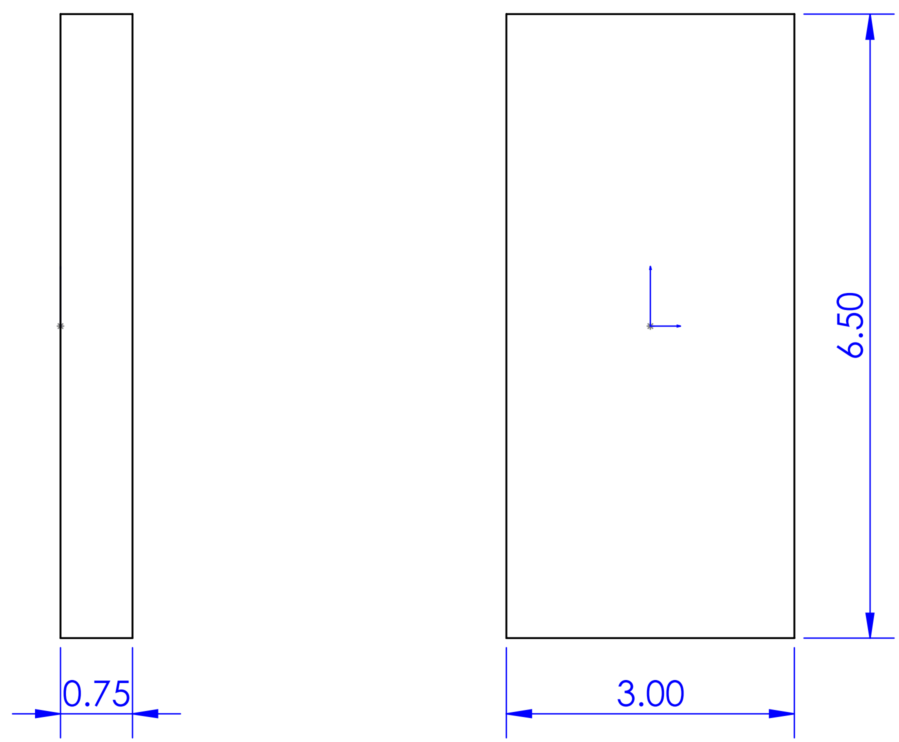
DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1



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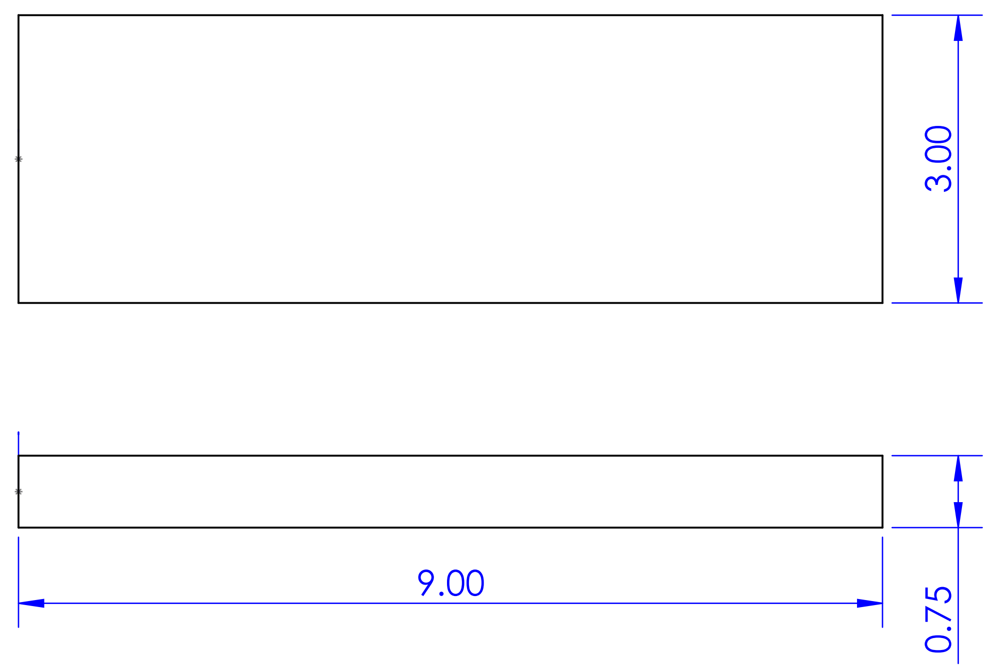
DATE: 3/6/12	DRAWN BY: A. Morano	

Mechanical Engineering CAL POLY

5 4 3 2 1



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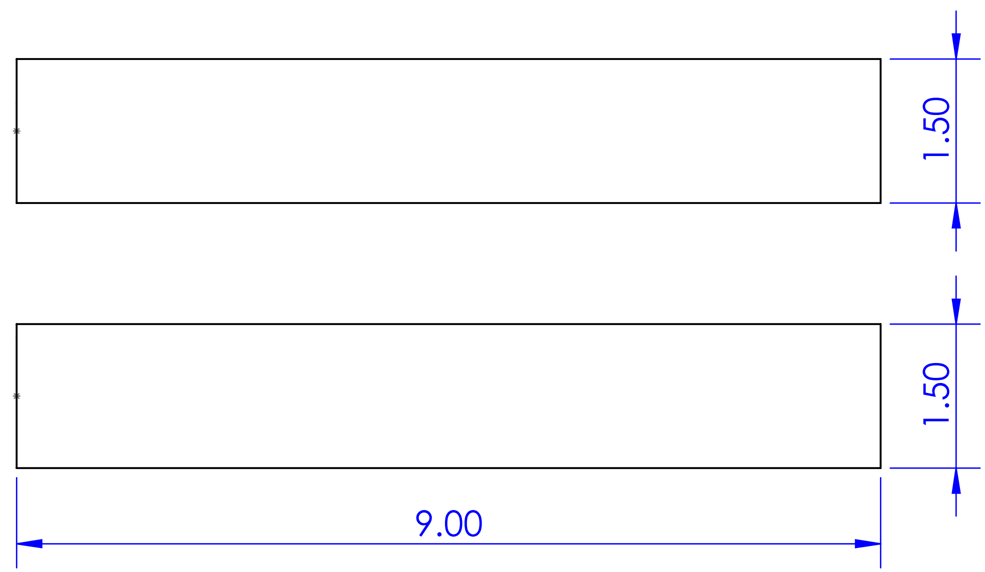
DATE: 3/6/12	DRAWN BY: A. Morano	

Mechanical Engineering CAL POLY

5 4 3 2 1



Mechanical Engineering CAL POLY

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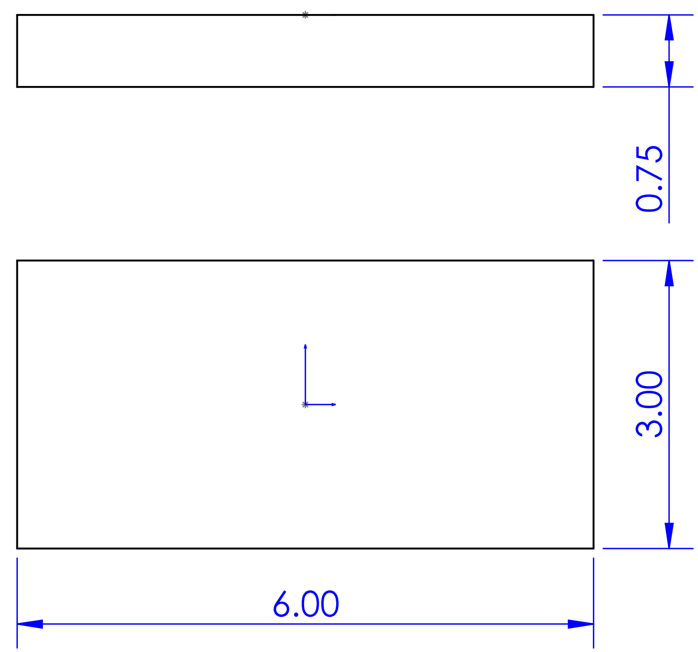
DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1



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Mechanical Engineering CAL POLY

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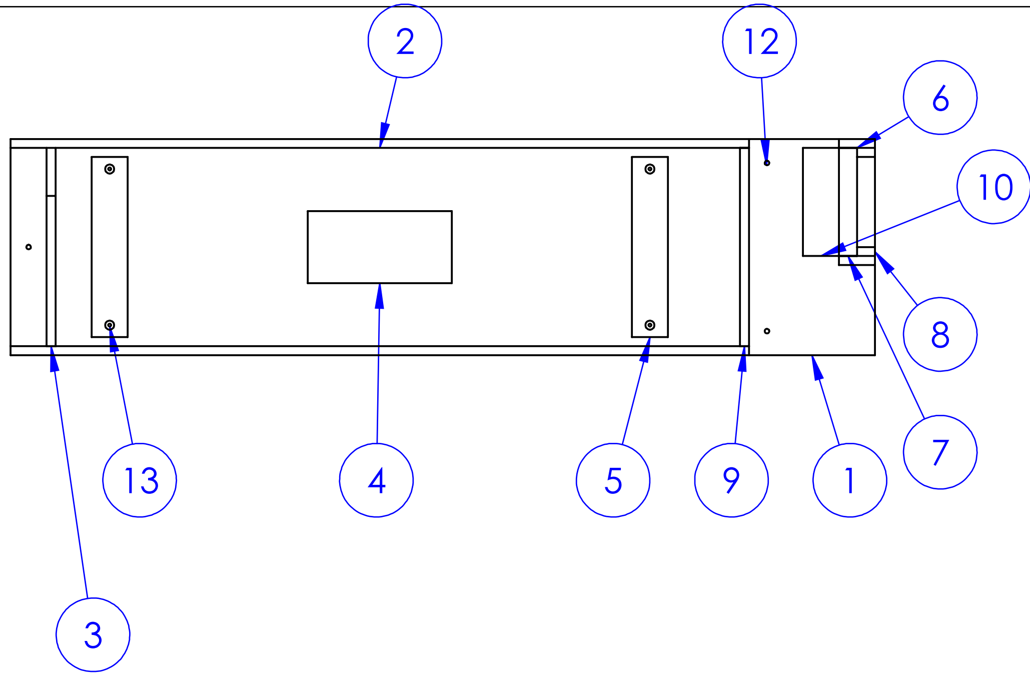
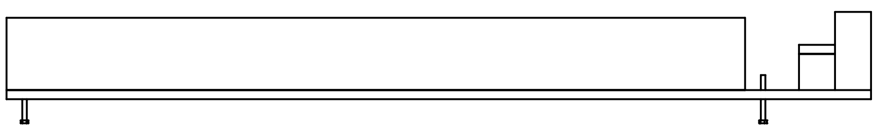
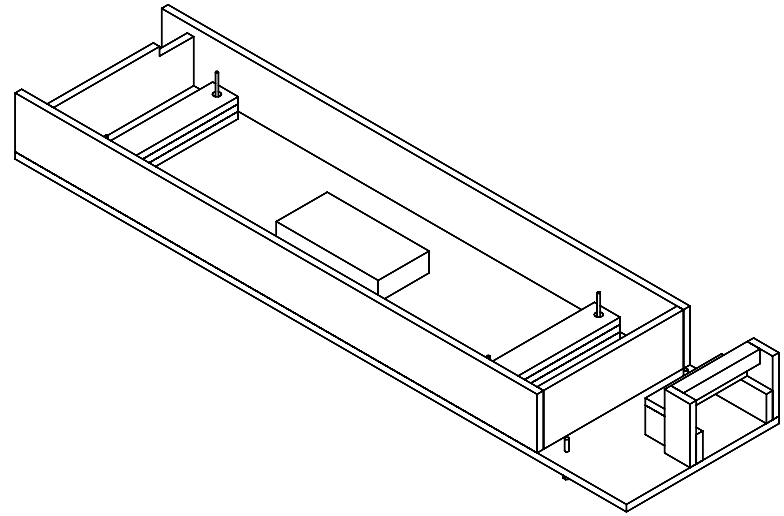




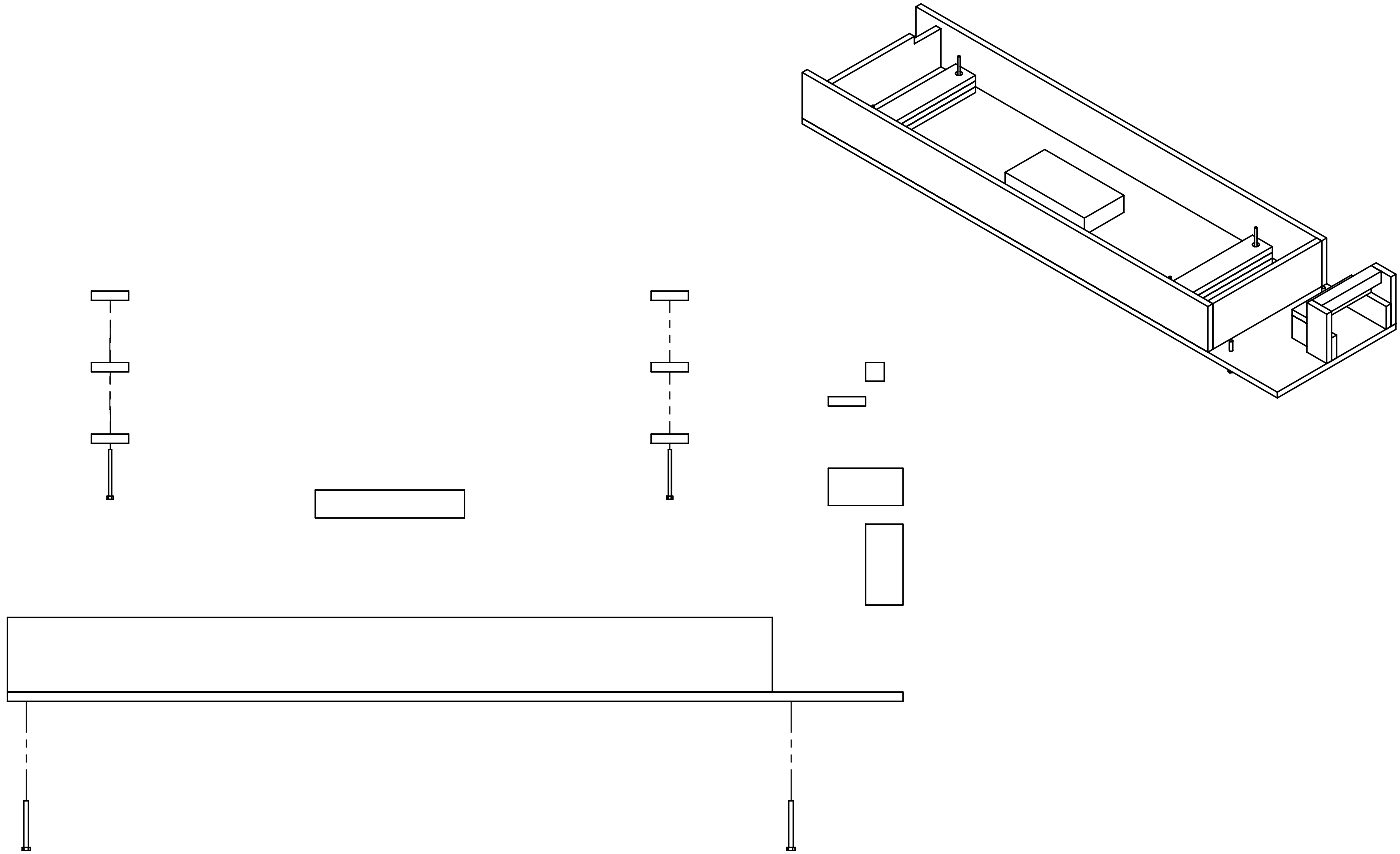


ITEM NO.	PART	PART NUMBER	QTY.
1	Base Board	F001	1
2	Side Board	F002	2
3	End Board Spillway	F004	1
4	Support Middle	F005	1
5	Support End TopBottom	F006	4
6	Winch Base	F008	2
7	Winch Cross	F010	1
8	Winch Side	F011	2
9	End Board	F003	1
10	Winch Base Flat	F009	1
11	Support End Middle	F007	2
12	3 8 in. Bolt	-	3
13	0.25 in. Bolt	-	4

Mechanical Engineering CAL POLY

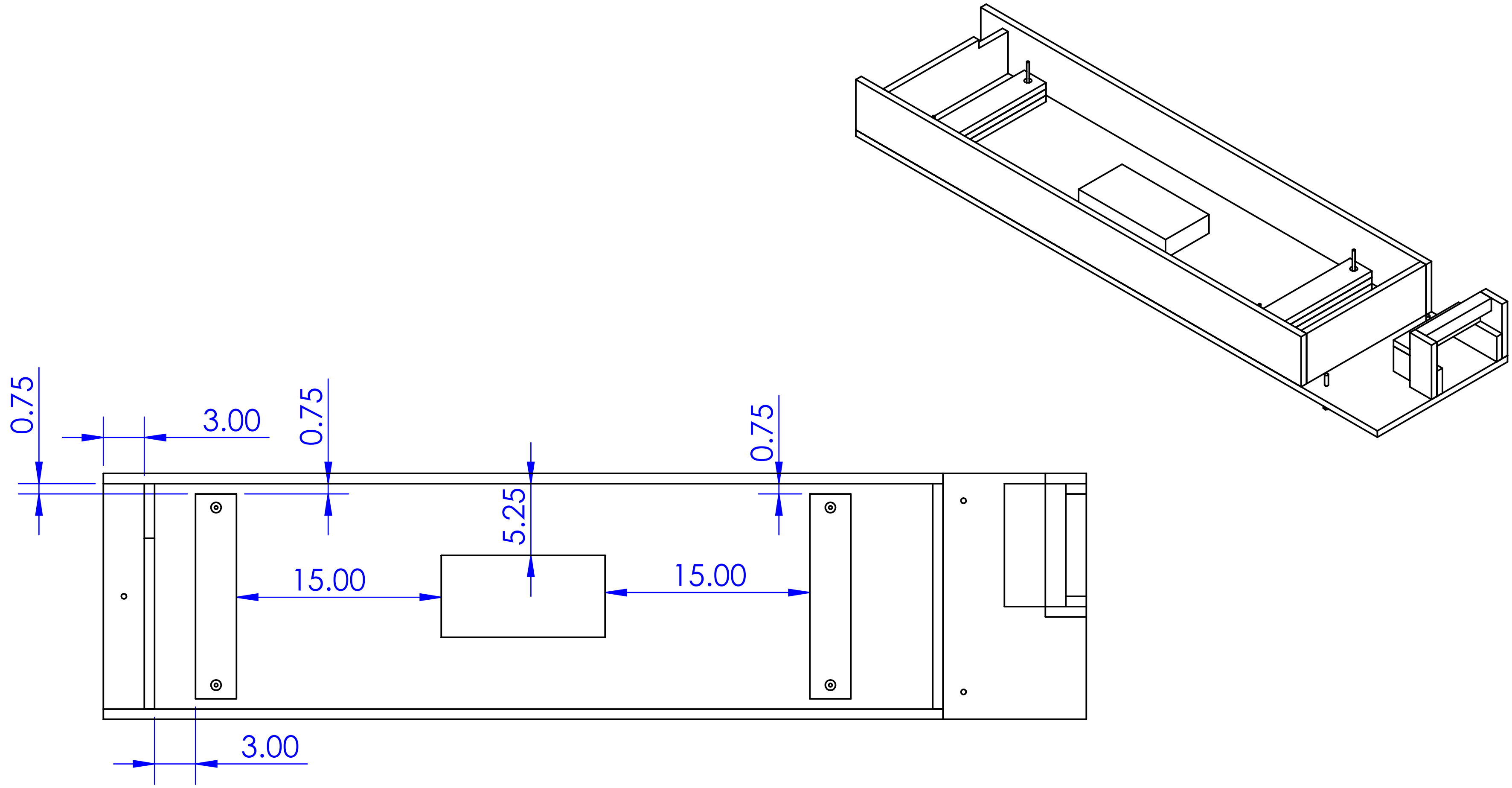
CAFS Senior Project		Part: F101
SCALE: 1:16	UNITS: INCHES	MATERIAL:
DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1



CAFS Senior Project		Part: F101
SCALE: 1:16	UNITS: INCHES	MATERIAL:
DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1



Mechanical Engineering CAL POLY

CAFS Senior Project		Part: F101
SCALE: 1:12	UNITS: INCHES	MATERIAL:
DATE: 3/6/12	DRAWN BY: A. Morano	

5 4 3 2 1

Appendix F
Detailed Supporting Analysis

Reaction Force Measurement Apparatus Detailed Analysis

To analyze the forces experienced by the reaction force testing apparatus, we performed a static analysis of each individual rigid body part on paper (this analysis is provided in Justin LaPolla's Senior Project Logbook on pages 102 to 110), and then entered the equations into a MATLAB script to determine safety factors at probable points of failure, given different design variables.

Below is the full MATLAB analysis script for the reaction force measurement apparatus.

```
clc;

% ===============================  COUPLING  ================================

% First we'll start by assessing the forces transmitted through the rocker
% lugs.

% This is shown on Page 102 of the Logbook Volume 1 under the heading
% "COUPLING". This section refers to the analysis carried out on Pages 91
% and 92 of the Logbook Volume 1.

% Independent parameters in the diagram on Page 91 are as follows.
w = 3.0/16.0; % [in]
h = 1.0/4.0 + 1.0/32.0; % [in]
L = 1.0/2.0 + 1.0/16.0; % [in]
F = 150.0; % [lbf]

% Now we'll look at the stress at points along the root of the rocker lug,
% and see where we get the maximum Von Mises stress.

% First initialize some variables we will need
MisesStressMax = 0.0; % [lbf/in^2]
% Now check the stress state at 100 points along the length of the root
for n = 0:1:99
    % Compute x from n
    x = n*L/99; % [in]
    % Compute normal stress due to bending at x
    NormalStress = 6*F*h*(L - 2*x)/(w*L^3); % [lbf/in^2]
    % Compute shear stress due to shear at x
    ShearStress = 6*F*x*(L - x)/(w*L^3); % [lbf/in^2]
    % Compute Von Mises stress at x
    MisesStress = sqrt(NormalStress^2 + 3*ShearStress^2); % [lbf/in^2]
    % Store maximum encountered Von Mises stress
    if(MisesStress > MisesStressMax)
        MisesStressMax = MisesStress; % [lbf/in^2]
        xMax = x; % [in]
    end
end

% ROCKER LUG FAILURE TEST

% Now we'll compute a safety factor. We know our rocker lugs are probably
% made out of 6061-T6 aluminum, so we'll use it's yield strength as our
% allowable strength.
```

```
S_allowable = 14000.0; % [lbf/in^2]
% NOTE: 14000 psi is estimated fatigue strength for 500 million cycles of
% completely reversed stress, according to the Aluminum Association, Inc.
S_actual = MisesStressMax; % [lbf/in^2]
SF_y = S_allowable/S_actual; % [-]

% Now we'll flag a warning if our safety factor is too low.
if (SF_y < 3.0)
    str = sprintf('WARNING: Rocker lug safety factor is %4.2f', SF_y);
    disp(str);
end

% Now we'll clear variables that we don't need any more.
clear;

% ==================  V-HOLDER/SLIDING PLATE JOINT  =======================

% Now we'll look at the force transfered through the screws that secure the
% V-Holder part to the Sliding Plate part.

% The statics for this analysis are diagramed on Page 103 of the Logbook
% Volume 1.

% First we'll enter the independent parameters in the first diagram on Page
% 103.
R = 150.0/2.0; % [lbf]
e = 1.750; % [in]
a = 1.500; % [in]
b = 2.000; % [in]

% Now time for some dependent variables
d = sqrt(a^2 + b^2)/2; % [in]
sineTheta = b/(2*d); % [-]
cosineTheta = a/(2*d); % [-]

% Now we find the total shear force on each screw
TopLeft_h = R/4.0 + (R*e/4.0/d)*cosineTheta; % [lbf]
TopLeft_v = -1.0*(R*e/4.0/d)*sineTheta; % [lbf]
TopLeft = sqrt(TopLeft_h^2 + TopLeft_v^2); % [lbf]

TopRight_h = R/4.0 + (R*e/4.0/d)*cosineTheta; % [lbf]
TopRight_v = (R*e/4.0/d)*sineTheta; % [lbf]
TopRight = sqrt(TopRight_h^2 + TopRight_v^2); % [lbf]

BottomLeft_h = R/4.0 - (R*e/4.0/d)*cosineTheta; % [lbf]
BottomLeft_v = -1.0*(R*e/4.0/d)*sineTheta; % [lbf]
BottomLeft = sqrt(BottomLeft_h^2 + BottomLeft_v^2); % [lbf]

BottomRight_h = R/4.0 - (R*e/4.0/d)*cosineTheta; % [lbf]
BottomRight_v = (R*e/4.0/d)*sineTheta; % [lbf]
BottomRight = sqrt(BottomRight_h^2 + BottomRight_v^2); % [lbf]

% WOOD SHEAR FAILURE TEST

% Now that we know the shear force on each screw, we will use data from the
% American Wood Council to determine the allowable shear force on each
% screw, and then figure a safety factor.
Shear_allowable = 87.0; % [lbf]
% NOTE: 87 lbf is the allowable shear force on a single 8-gauge (0.164"
% root diameter) wood screw engaged in 1/2" of spruce/pine/fir wood.
Shear_actual = [TopLeft TopRight BottomLeft BottomRight]; % [lbf]
SF = zeros(1,4); % [-]
for n = 1:1:4
```

```
    SF(n) = Shear_allowable/Shear_actual(n); % [-]
end
SF_min = min(SF); % [-]

% Now we'll flag a warning if our safety factor is too low on one of the
% screws.
if (SF_min < 3.0)
    str = sprintf('WARNING: V-Holder/Sliding Plate screw joint SF is %4.2f',
SF_min);
    disp(str);
end

% Now we'll clear variables that we don't need any more.
clear;

% ==================  SLIDING PLATE BOLT CONNECTIONS  ======================

% Now we'll look at the stresses on the bolts that fix the Sliding Plate to
% the Angle Plate. The statics of this problem are detailed on Pages 103
% and 104 of the Logbook Volume 1.

% First we'll enter the independent parameters in the first diagram on Page
% 103.
R = 150.0/2.0; % [lbf]
e = 1.750; % [in]
a = 4.750; % [in]
b = 1.750; % [in]

% Now time for some dependent variables
d = sqrt(a^2 + b^2)/2; % [in]
sineTheta = b/(2*d); % [-]
cosineTheta = a/(2*d); % [-]

% Now we find the total shear force on each bolt
TopLeft_h = R/2.0 + (R*e/2.0/d)*cosineTheta; % [lbf]
TopLeft_v = -1.0*(R*e/2.0/d)*sineTheta; % [lbf]
TopLeft = sqrt(TopLeft_h^2 + TopLeft_v^2); % [lbf]

BottomRight_h = R/2.0 - (R*e/2.0/d)*cosineTheta; % [lbf]
BottomRight_v = (R*e/2.0/d)*sineTheta; % [lbf]
BottomRight = sqrt(BottomRight_h^2 + BottomRight_v^2); % [lbf]

% BEARING STRESS FAILURE TEST

% Now that we know the shear force on each bolt, we'll compare the shear
% force to the allowable bearing stress load for spruce/pine/fir to see if
% we will get a failure due to bearing stress.
Stress_allowable = 665.0; % [lbf/in^2]
% NOTE: the source of this value is outlined on Page 102 of the Logbook
% Volume 1.
Stress_actual = [(TopLeft/0.75/0.75) (BottomRight/0.75/0.75)]; % [lbf/in^2]
SF = zeros(1,2); % [-]
for n = 1:1:2
    SF(n) = Stress_allowable/Stress_actual(n); % [-]
end
SF_min = min(SF); % [-]

% Now we'll flag a warning if our safety factor is too low on one of the
% bolts.
if (SF_min < 3.0)
    str = sprintf('WARNING: Sliding Plate/Angle Plate bolt joint bearing stress SF
is %4.2f', SF_min);
    disp(str);
```

```
end

% Now we'll clear variables we no longer need
clear Stress_allowable Stress_actual SF n SF_min str;

% WOOD TENSILE STRESS FAILURE TEST

% Now we'll see if our wood will break due to the load transfered through
% the bolt. Our design includes at least two diameters of material around
% all bolts, so we'll use 4D*t (where t is the thickness of the wood) as
% our effective area that the bolt force is distributed over.
Stress_allowable = 100.0; % [lbf/in^2]
% NOTE: 100 psi was the smallest tensile strength I could find for
% spruce/pine/fir loaded in tension parallel to the grain.
Stress_actual = [(TopLeft/(4*0.75*0.75)) (BottomRight/(4*0.75*0.75))]; %
[lbf/in^2]
SF = zeros(1,2); % [-]
for n = 1:1:2
    SF(n) = Stress_allowable/Stress_actual(n); % [-]
end
SF_min = min(SF); % [-]

% Now we'll flag a warning if our safety factor is too low on one of the
% bolts.
if (SF_min < 3.0)
    str = sprintf('WARNING: Sliding Plate/Angle Plate bolt joint tensile stress SF
is %4.2f', SF_min);
    disp(str);
end

% Now we'll clear variables we no longer need
clear;

% ==================  ANGLE PLATE HINGE CONNECTION  =======================

% Now we'll look at the stresses on the Angle Plate hinge bolt. This
% analysis will also give us some force vectors that we will use for
% analysis of other joints, most notably the force at the hinge (named
% force A), and the force on the scale (F).

% The static analysis of this problem is diagramed on Page 104 of the
% Logbook Volume 1.

% We'll start by defining the independent variables shown in the diagram
% on Page 104.
R = 150.0/2.0; % [lbf]
theta = [0.0 22.5 45.0]; % [degrees]
e = [6.000 7.609 8.459]; % [in]
L = 6.000; % [in]

% Now we'll compute the forces, as outlined on Page 104 of the Logbook
% Volume 1. Notice that we do this three times, once for each angle that
% the nozzle can operate at.
F = zeros(1,3); % [lbf]
A_h = zeros(1,3); % [lbf]
A_v = zeros(1,3); % [lbf]
A = zeros(1,3); % [lbf]
for n = 1:1:3
    F(n) = e(n)/L*R; % [lbf]
    A_h(n) = -R*cosd(theta(n)); % [lbf]
    A_v(n) = R*(sind(theta(n)) - e(n)/L); % [lbf]
    A(n) = sqrt(A_h(n)^2 + A_v(n)^2); % [lbf]
end
```

```
% BEARING STRESS FAILURE TEST

% Now we'll test the bearing stress at the hinge to make sure the wood can
% handle the stress.
Stress_allowable = 665.0; % [lbf/in^2]
% NOTE: the source of this value is outlined on Page 102 of the Logbook
% Volume 1.
Stress_actual = A/(0.75*0.75); % [lbf/in^2]
SF = zeros(1,3); % [-]
for n = 1:1:3
    SF(n) = Stress_allowable/Stress_actual(n); % [-]
end
SF_min = min(SF); % [-]

% Now we'll flag a warning if our safety factor is too low on one of the
% angles.
if (SF_min < 3.0)
    str = sprintf('WARNING: Angle Plate hinge bolt joint bearing stress SF is
%4.2f', SF_min);
    disp(str);
end

% Now we'll clear variables we no longer need
clear SF SF_min Stress_actual Stress_allowable;

% WOOD TENSILE STRESS FAILURE TEST

% Now we'll see if our wood will fail in the tension at that hinge. All of
% our hinge holes are designed with at least two diameters of wood to the
% nearest edge, so the area that the force is distributed over is at least
% 4D*t (where t is the thickness of the wood).
Stress_allowable = 100.0; % [lbf/in^2]
% NOTE: 100 psi was the smallest tensile strength I could find for
% spruce/pine/fir loaded in tension parallel to the grain.
Stress_actual = A/(4*0.75*0.75); % [lbf/in^2]
SF = zeros(1,3); % [-]
for n = 1:1:3
    SF(n) = Stress_allowable/Stress_actual(n); % [-]
end
SF_min = min(SF); % [-]

% Now we'll flag a warning if our safety factor is too low on one of the
% angles.
if (SF_min < 3.0)
    str = sprintf('WARNING: Angle Plate hinge bolt joint tensile stress SF is
%4.2f', SF_min);
    disp(str);
end

% Now we'll clear variables we no longer need
clear SF SF_min Stress_actual Stress_allowable n str e L R;

% =========================  SCALE REQUIREMENTS  ==========================

% Just real quick, let's see how much force our scale will be experiencing.
F_max = 2*max(F);
str = sprintf('NOTE: Scale must handle %.2f pounds of force.', F_max);
disp(str);
clear F_max str;

% ==============================  CROSSBEAM  ===============================
```

```
% Now we'll look at the Crossbeam support that transfers the force to the
% weight scale. The statics for this problem are outlined on Page 105 of
% the Logbook Volume 1.

% First we'll define the independent parameters shown in the diagram.
e = 1.000; % [in]
w = 1.5; % [in]

% Note that F retains it's value from our last section. This F is actually
% equal to half of the force transferred to the weight scale, but that's
% just fine because our analysis only concerns one of two symmetric joints
% that support the Crossbeam.

% Now let's compute the forces in the screws that support the Crossbeam.
Left = max(abs(F/2 - F*e/w)); % [lbf]
Right = max(abs(F/2 + F*e/w)); % [lbf]

% WOOD SHEAR FAILURE TEST

% Now we'll check to see if our screws will fail due to the shear forces
% they will encounter.
Shear_allowable = 87.0; % [lbf]
% NOTE: 87 lbf is the allowable shear force on a single 8-gauge (0.164"
% root diameter) wood screw engaged in 1/2" of spruce/pine/fir wood.
Shear_actual = [Left Right]; % [lbf]
SF = zeros(1,2); % [-]
for n = 1:1:2
    SF(n) = Shear_allowable/Shear_actual(n); % [-]
end
SF_min = min(SF);

% Now we'll flag a warning if our safety factor is too low on one of the
% angles.
if (SF_min < 3.0)
    str = sprintf('WARNING: Crossbeam screw shear force SF is %4.2f', SF_min);
    disp(str);
end

% Now we'll clear variables we no longer need
clear Left Right Shear_allowable Shear_actual SF n SF_min str e w;

% When I ran this for my first design, it came up with a minimum safety
% factor of 0.71. So, I altered the design. The new design has no screws,
% and therefore this analysis does not apply to the new design. This is
% noted in the Logbook Volume 1 on Page 107. The new design is briefly
% outlined on that page as well.

% ===============  HINGE SUPPORTS THAT PROTRUDE FROM BASE  ================

% Now we'll look at the 2-by-4 hinge supports that protrude from the base
% plate.  The statics of this problem are diagramed on Pages 104 and 105 of
% the Logbook Volume 1.

% First we'll define the independent parameters specified in the diagram.
% Notice that the force A is 1/2 of it's value that we used in the Angle
% Plate analysis above (Logbook Volume 1 Page 104) because there are two
% hinge supports per Angle Plate.
A = A/2; % [lbf]
A_h = A_h/2; % [lbf]
A_v = A_v/2; % [lbf]
w = 3.5; % [in]
h_2 = 2.0; % [in]
h_1 = 0.5; % [in]
```

```
h_A = 4.875; % [in]
L = h_A - h_1 - h_2/2; % [in]
% NOTE: L is the distance from the fastener group centroid to Point A.

% Now we'll establish a few of the dependent parameters.
d = sqrt(w^2 + h_2^2)/2; % [in]
sineTheta = h_2/(2*d); % [degrees]
cosineTheta = w/(2*d); % [degrees]

% Now it's time to compute the forces experienced by each screw. Notice
% that I am using the sign conventions given in the diagram.
TopLeft_h = max(-1.0*A_h/4.0 + (-1.0*A_h*L/4.0/d)*cosineTheta); % [lbf]
TopLeft_v = max((-1.0)*(-1.0)*A_v/4.0 - (-1.0*A_h*L/4.0/d)*sineTheta); % [lbf]
TopLeft = sqrt(TopLeft_h^2 + TopLeft_v^2); % [lbf]

TopRight_h = max(-1.0*A_h/4.0 + (-1.0*A_h*L/4.0/d)*cosineTheta); % [lbf]
TopRight_v = max((-1.0)*(-1.0)*A_v/4.0 + (-1.0*A_h*L/4.0/d)*sineTheta); % [lbf]
TopRight = sqrt(TopRight_h^2 + TopRight_v^2); % [lbf]

BottomLeft_h = max(-1.0*A_h/4.0 - (-1.0*A_h*L/4.0/d)*cosineTheta); % [lbf]
BottomLeft_v = max((-1.0)*(-1.0)*A_v/4.0 - (-1.0*A_h*L/4.0/d)*sineTheta); % [lbf]
BottomLeft = sqrt(BottomLeft_h^2 + BottomLeft_v^2); % [lbf]

BottomRight_h = max(-1.0*A_h/4.0 - (-1.0*A_h*L/4.0/d)*cosineTheta); % [lbf]
BottomRight_v = max((-1.0)*(-1.0)*A_v/4.0 + (-1.0*A_h*L/4.0/d)*sineTheta); % [lbf]
BottomRight = sqrt(BottomRight_h^2 + BottomRight_v^2); % [lbf]

% WOOD SHEAR FAILURE TEST

% The following is not truly valid because all of the horizontal forces in
% these screws are pulling the screws out, not shearing them. But, I have
% no way to model that combined load state (shearing and pulling) so I'll
% go ahead and just use the combined vector and pretend that the screw is
% in pure shear. Honestly, that's the best I can do right now.
Shear_allowable = 87.0; % [lbf]
% NOTE: 87 lbf is the allowable shear force on a single 8-gauge (0.164"
% root diameter) wood screw engaged in 1/2" of spruce/pine/fir wood.
Shear_actual = [TopLeft TopRight BottomLeft BottomRight]; % [lbf]
SF = zeros(1,4); % [-]
for n = 1:1:4
    SF(n) = Shear_allowable/Shear_actual(n); % [-]
end
SF_min = min(SF);

% Now we'll flag a warning if our safety factor is too low on one of the
% angles.
if (SF_min < 3.0)
    str = sprintf('WARNING: Vertical hinge support screw shear force SF is %4.2f',
SF_min);
    disp(str);
end

% Now we'll clear variables that we no longer need.
clear BottomLeft BottomLeft_h BottomLeft_v BottomRight BottomRight_h ...
    BottomRight_v L SF SF_min Shear_actual Shear_allowable TopLeft ...
    TopLeft_h TopLeft_v TopRight TopRight_h TopRight_v cosineTheta d ...
    h_1 h_2 h_A n sineTheta w;

% ==================  SCREWS IN L-BRACKETS IN BASE  =======================

% In the last section, we took a look at the screws that are embedded in
% the two-by-fours protruding from the base. Now we'll take a look at the
% screws on those same L-brackets that are screwed into the base plate.
```

```matlab
% The statics for this section are diagramed on Pages 106 and 107 of the
% Logbook Volume 1.

% First, let's establish the independent variables shown in the diagram.
d_1 = 3.5/2.0 + 0.5; % [in]
d_2 = d_1 + 2.0; % [in]
L = 4.875; % [in]

% Notice that we can use the same values for the A vector as we did in the
% last section.

% Now we'll compute the forces applied to the screws.
FarLeft_v = max((-1.0)*(-1.0)*A_v/4 - (-1.0)*(A_h*L*d_2)/(2*(d_1^2 + d_2^2))); %
[lbf]
FarLeft_h = max((-1.0)*A_h/4); % [lbf]
FarLeft = sqrt(FarLeft_v^2 + FarLeft_h^2); % [lbf]

NearLeft_v = max((-1.0)*(-1.0)*A_v/4 - (-1.0)*(A_h*L*d_1)/(2*(d_1^2 + d_2^2))); %
[lbf]
NearLeft_h = max((-1.0)*A_h/4); % [lbf]
NearLeft = sqrt(NearLeft_v^2 + NearLeft_h^2); % [lbf]

NearRight_v = max((-1.0)*(-1.0)*A_v/4 + (-1.0)*(A_h*L*d_1)/(2*(d_1^2 + d_2^2))); %
[lbf]
NearRight_h = max((-1.0)*A_h/4); % [lbf]
NearRight = sqrt(NearRight_v^2 + NearRight_h^2); % [lbf]

FarRight_v = max((-1.0)*(-1.0)*A_v/4 + (-1.0)*(A_h*L*d_2)/(2*(d_1^2 + d_2^2))); %
[lbf]
FarRight_h = max((-1.0)*A_h/4); % [lbf]
FarRight = sqrt(FarRight_v^2 + FarRight_h^2); % [lbf]

% WOOD SHEAR FAILURE TEST

% The following is not truly valid because all of the vertical forces in
% these screws are pulling the screws out, not shearing them. But, I have
% no way to model that combined load state (shearing and pulling) so I'll
% go ahead and just use the combined vector and pretend that the screw is
% in pure shear. Honestly, that's the best I can do right now.
Shear_allowable = 87.0; % [lbf]
% NOTE: 87 lbf is the allowable shear force on a single 8-gauge (0.164"
% root diameter) wood screw engaged in 1/2" of spruce/pine/fir wood.
Shear_actual = [FarLeft NearLeft NearRight FarRight]; % [lbf]
SF = zeros(1,4); % [-]
for n = 1:1:4
    SF(n) = Shear_allowable/Shear_actual(n); % [-]
end
SF_min = min(SF);

% Now we'll flag a warning if our safety factor is too low on one of the
% angles.
if (SF_min < 3.0)
    str = sprintf('WARNING: Base horizontal bracket screw shear force SF is
%4.2f', SF_min);
    disp(str);
end

% Now we'll clear all the variables we don't need any more.
clear;

% ========================  STAKE SUPPORTS IN BASE========================

% Lastly, we need to make sure our base will not lift off of the ground!
```

```
% The static analysis is diagramed on Page 106 of the Logbook Volume 1.

% We're only going to test the case when the nozzle is angled at 0 degrees
% from horizontal, because this is the case that has the most tendency to
% lift the base from the ground.

% First, we'll establish the independent variables given on Page 106 of
% Logbook Volume 1.
L = 29.5; % [in]
e = 10.875; % [in]
R = 150.0/2.0; % [lbf]
% Notice that we cut R in half because there are two stakes, and they each
% take half of the force.

% Now we'll compute the forces that the stakes must provide.
O_v = R*e/L; % [lbf]
O_h = R; % [lbf]

% Now we'll display these results.
str = sprintf('NOTE: The stakes in the ground must take %.2f pounds of shear force
each.', O_h);
disp(str);
str = sprintf('NOTE: The front of the base plate must have %.2f pounds of downward
force so it doesn''t lift.', 2*O_v);
disp(str);

% Now we'll clear the variables we no longer need.
clear;
```

Appendix G
Project Schedule

This project schedule provides a full record of our activities during this project.

Task Name	Start	Finish
Develop general equations	Wed 1/4/12	Thu 1/12/12
Product Specification	**Tue 1/17/12**	**Mon 2/6/12**
Brainstorm and select customers for use in QFD	Tue 1/17/12	Thu 1/19/12
Brainstorm and select suggested customer requirements	Thu 1/19/12	Sat 1/21/12
Suggested customer requirements delivered to customer for evaluation	Sat 1/21/12	Sat 1/21/12
Completed customer requirements evaluation worksheets received from customer	Mon 1/23/12	Mon 1/23/12
QFD to develop quantitative product specifications	Mon 1/23/12	Mon 1/30/12
First Project Proposal Document submitted to customer for approval	Mon 1/30/12	Mon 1/30/12
Project Proposal Document approved by customer	Mon 2/6/12	Mon 2/6/12
Concept Design	**Mon 1/23/12**	**Mon 2/13/12**
Brainstorm concepts	Mon 1/23/12	Mon 2/6/12
Evaluate concepts against product specifications	Mon 1/30/12	Mon 2/6/12
First Conceptual Design Report submitted to customer for approval	Mon 2/6/12	Mon 2/6/12
Conceptual Design Report approved by customer	Mon 2/13/12	Mon 2/13/12
Preliminary Testing	**Mon 2/6/12**	**Fri 3/2/12**
Design first prototype	Mon 2/6/12	Mon 2/13/12
Build first prototype	Mon 2/6/12	Fri 3/2/12
Preliminary Testing	Fri 3/2/12	Fri 3/2/12
Project Update Report delivered to customer	Mon 3/26/12	Mon 3/26/12
Final Testing	**Mon 3/5/12**	**Sat 5/5/12**
Address preliminary testing issues	Mon 3/5/12	Fri 4/27/12
Make improvements to prototypes	Mon 3/26/12	Sun 4/29/12
Final Testing	Sat 5/5/12	Sat 5/5/12
Senior Project Completion	**Mon 5/7/12**	**Mon 6/4/12**
Data analysis and presentation	Mon 5/7/12	Fri 5/25/12
Prepare for Senior Project Design Expo	Sat 5/26/12	Thu 5/31/12

Senior Project Design Expo	Thu 5/31/12	Thu 5/31/12
Work on Final Project Report	Sat 5/26/12	Mon 6/4/12
Final Project Report Submitted	Mon 6/4/12	Mon 6/4/12

Appendix H
Test Results

This appendix contains our test results from our final testing performed on May 5th, 2012. All of these tests, except the friction tests, were performed on May 5th, 2012 at Santa Lucia Middle School in Cambria, California. The fire engine used to perform these tests was Water Tender 57 from Cambria Community Services District fire department.

Nozzle Reaction Force Test Results

This section contains the test results from our nozzle reaction force tests.

Tabulated Data

This section provides tabulated data for the nozzle reaction force test results. The data provided in these tables are NOT the raw data. This is the final data after applying the calibration curve we measured for the nozzle reaction force measurement apparatus.

Table H.1 – Tabulated nozzle reaction force and propagated reaction force uncertainty data for 1-1/8" smooth bore nozzle with CAFS on.

CAFS ON		
1-1/8" Smooth Bore Nozzle		
0.3% Foam Concentration		
70°F Fluid Temperature		
Lever Arm	L_1, (in)	6.75
Lever Arm Uncertainty (Estimated)	U_{L1}, (in)	0.50
Solution Flow Rate	Nozzle Reaction Force	Reaction Force Uncertainty
Q, (gpm)	R, (lbf)	U_R, (lbf)
30	16.24	4.32
66	28.81	4.60
95	30.91	4.67
130	22.52	4.44
157	31.95	4.70

Table H.2 – Tabulated nozzle reaction force and propagated reaction force uncertainty data for 1-1/8” smooth bore nozzle with CAFS off.

CAFS OFF		
1-1/8” Smooth Bore Nozzle		
0.0% Foam Concentration		
70°F Fluid Temperature		
Lever Arm	L_1, (in)	6.75
Lever Arm Uncertainty (Estimated)	U_{L1}, (in)	0.5
Solution Flow Rate	Nozzle Reaction Force	Reaction Force Uncertainty
Q, (gpm)	R, (lbf)	U_R, (lbf)
30	-6.81	4.38
65	-0.53	4.29
95	9.95	4.26
130	21.48	4.42
160	38.24	4.93

Table H.3 – Tabulated nozzle reaction force and propagated reaction force uncertainty data for 15/16” combination nozzle on straight stream setting with CAFS on.

CAFS ON		
15/16” Combination Nozzle		
0.3% Foam Concentration		
70°F Fluid Temperature		
Lever Arm	L_1, (in)	6.75
Lever Arm Uncertainty (Estimated)	U_{L1}, (in)	0.5
Solution Flow Rate	Nozzle Reaction Force	Reaction Force Uncertainty
Q, (gpm)	R, (lbf)	U_R, (lbf)
28	3.66	4.26
63	24.62	4.49
96	41.38	5.06
130	55.00	5.71
160	74.91	6.85

Table H.4 – Tabulated nozzle reaction force and propagated reaction force uncertainty data for 15/16" combination nozzle on straight stream setting with CAFS off.

CAFS OFF		
15/16" Combination Nozzle		
0.0% Foam Concentration		
70°F Fluid Temperature		
Lever Arm	L_1, (in)	6.75
Lever Arm Uncertainty (Estimated)	U_{L1}, (in)	0.5
Solution Flow Rate	Nozzle Reaction Force	Reaction Force Uncertainty
Q, (gpm)	R, (lbf)	U_R, (lbf)
29	4.71	4.26
68	27.76	4.57
95	38.24	4.93
133	57.10	5.82
160	83.29	7.37

Plots Showing Uncertainties

This section shows plots of the nozzle reaction force data along with the uncertainties in the data.

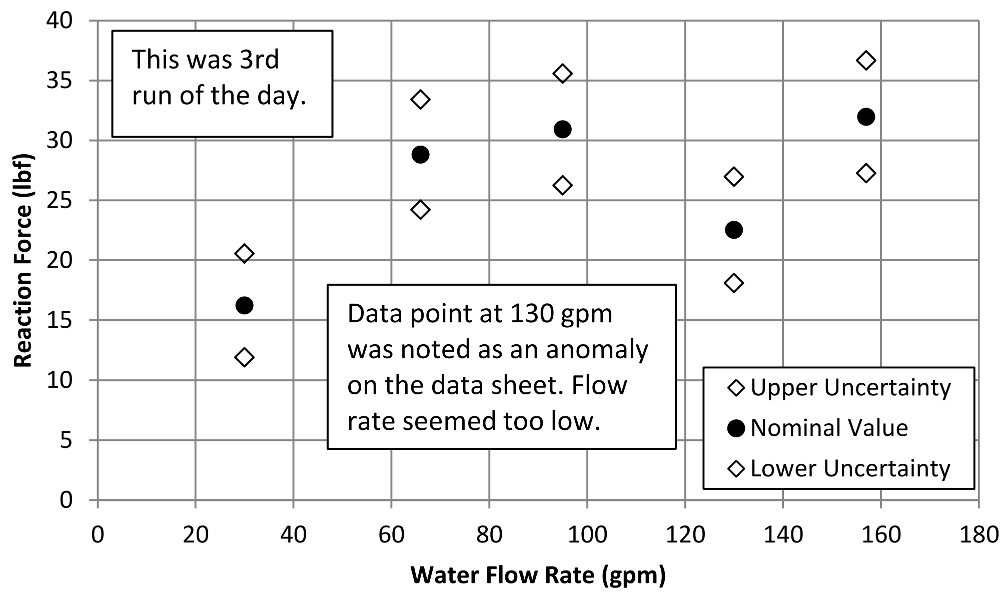


Figure H.1 – Nozzle reaction force for 1-1/8" smooth bore nozzle flowing CAFS.

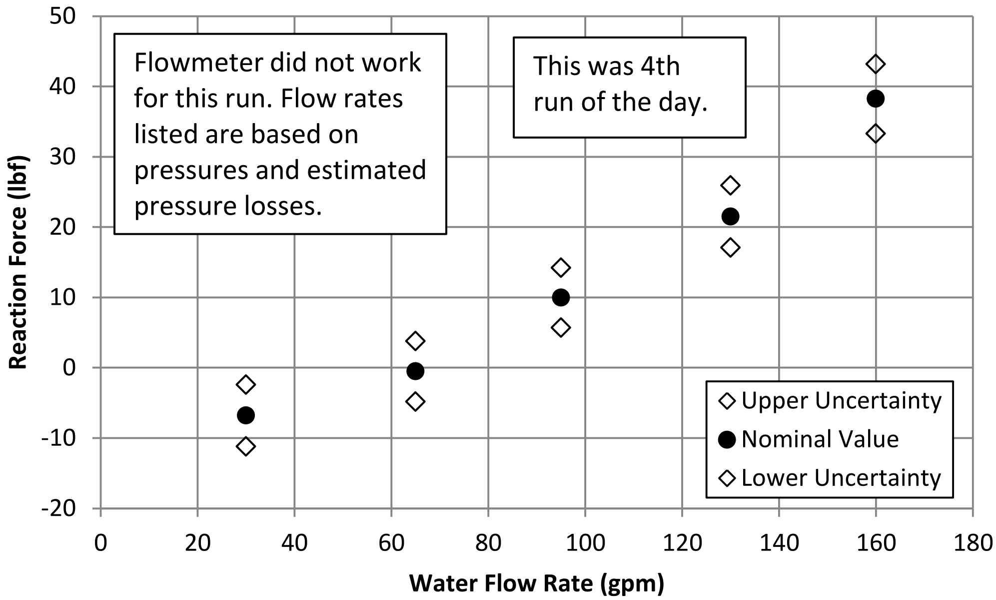


Figure H.2 – Nozzle reaction force for 1-1/8" smooth bore nozzle flowing water.

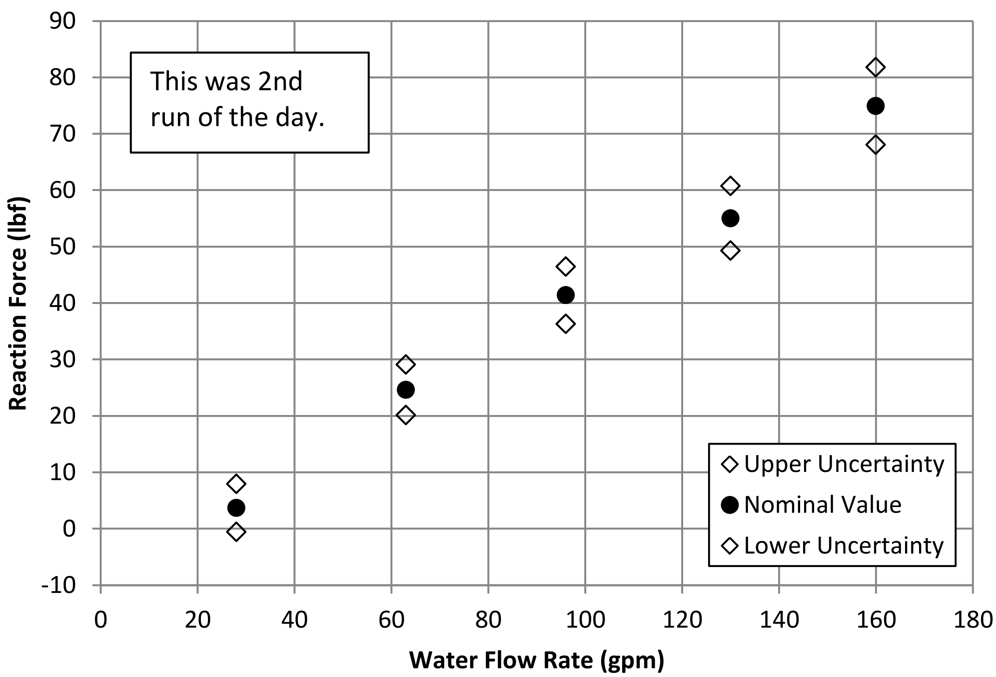


Figure H.3 – Nozzle reaction force for 15/16" combination nozzle on straight stream setting flowing CAFS.

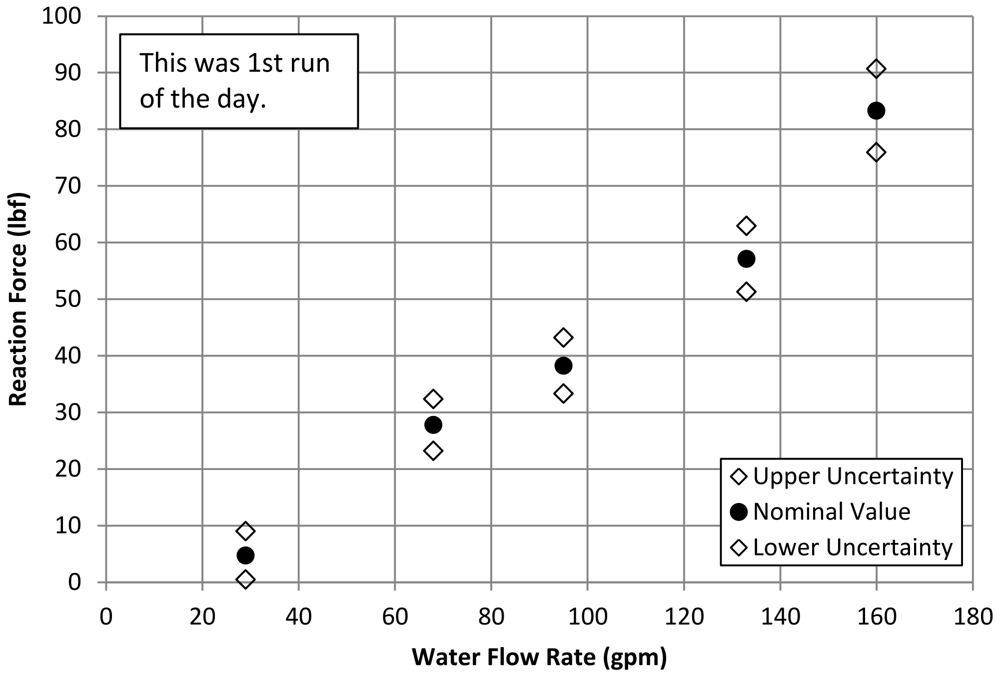


Figure H.4 – Nozzle reaction force for 15/16” combination nozzle on straight stream setting flowing water.

Comparison Plots

This section compares nozzle reaction force data between different testing conditions.

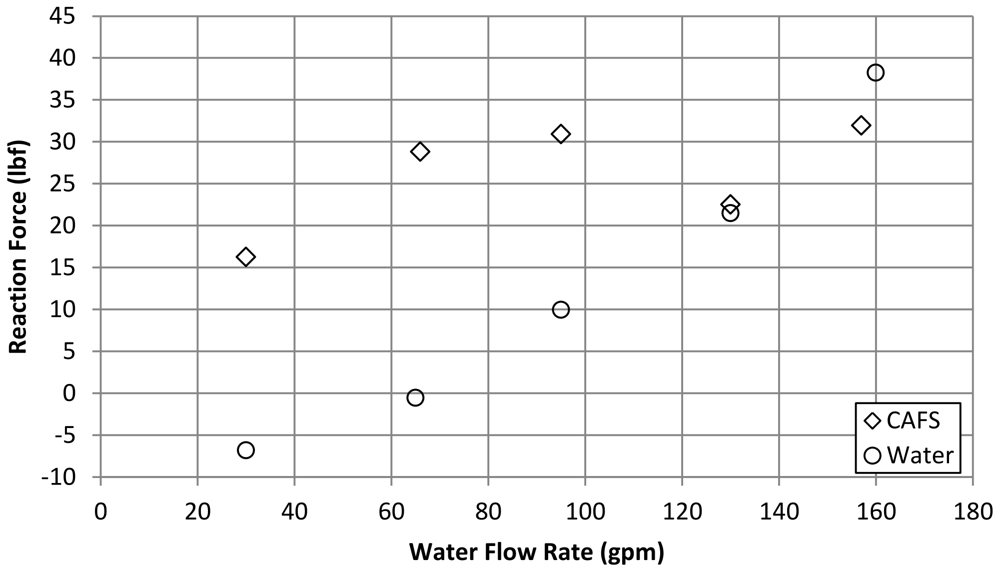


Figure H.5 – Nozzle reaction force for 1-1/8" smooth bore nozzle, comparing water versus CAFS.

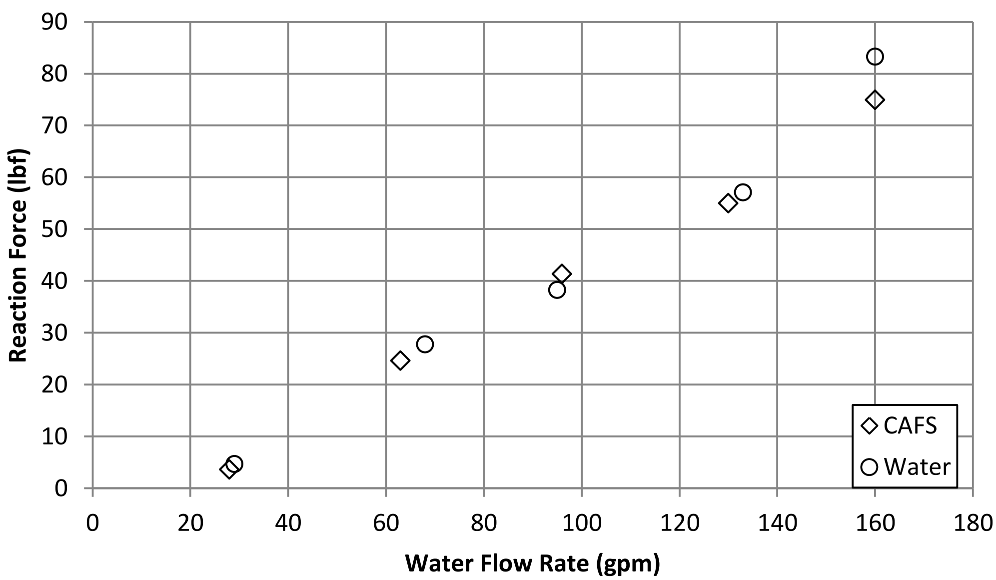


Figure H.6 – Nozzle reaction force for 15/16" combination nozzle on straight stream setting, comparing water versus CAFS.

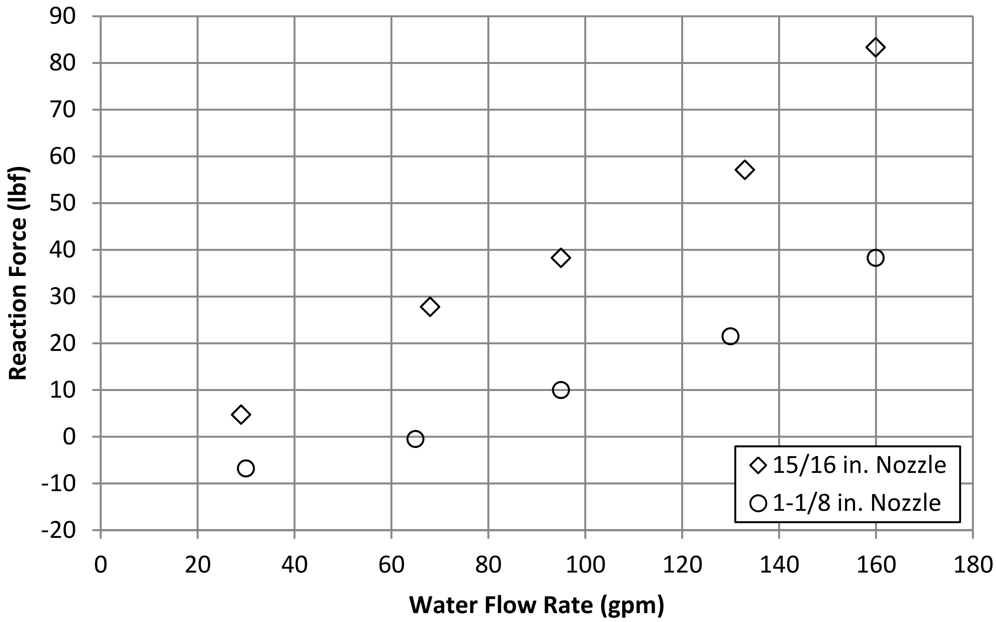


Figure H.7 – Nozzle reaction force for water flow, comparing 15/16" combination nozzle on straight stream setting versus 1-1/8" smooth bore nozzle.

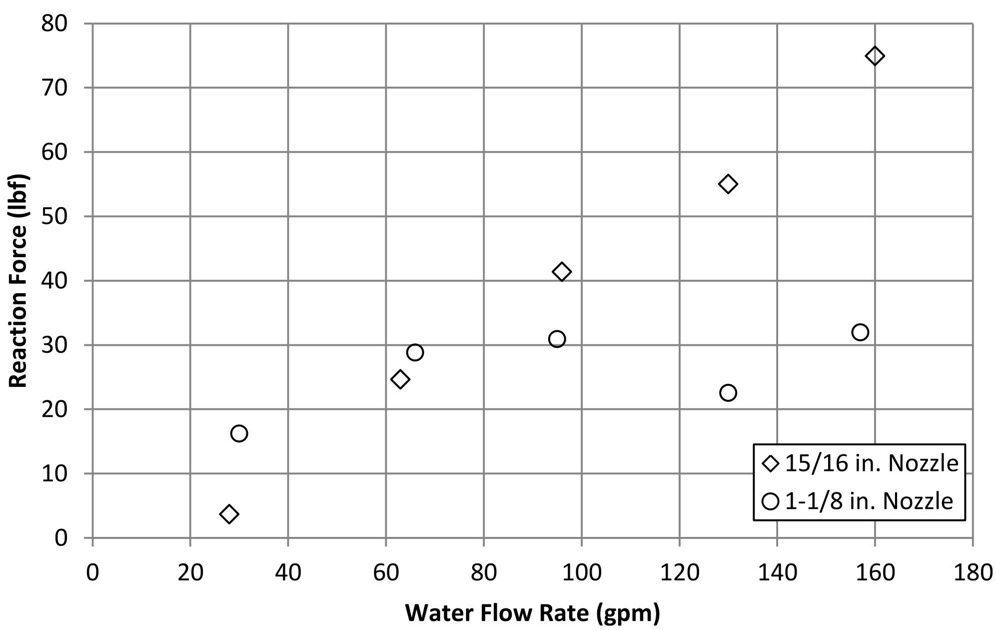


Figure H.8 – Nozzle reaction force for CAFS flow, comparing 15/16" combination nozzle on straight stream setting versus 1-1/8" smooth bore nozzle.

Model Comparison Plots

This section compares our results for nozzle reaction force with water to the standard IFSTA models used for firefighting field calculations. These IFSTA models are published in IFSTA's Fire Stream Practices, Seventh Edition, © 1989

Our model for nozzle reaction force with CAFS (presented in Chapter 5 of this report) is not plotted here because we were unable to reliably measure the air flow rate during our actual tests, so we are unable to compare to the model we developed for CAFS nozzle reaction force.

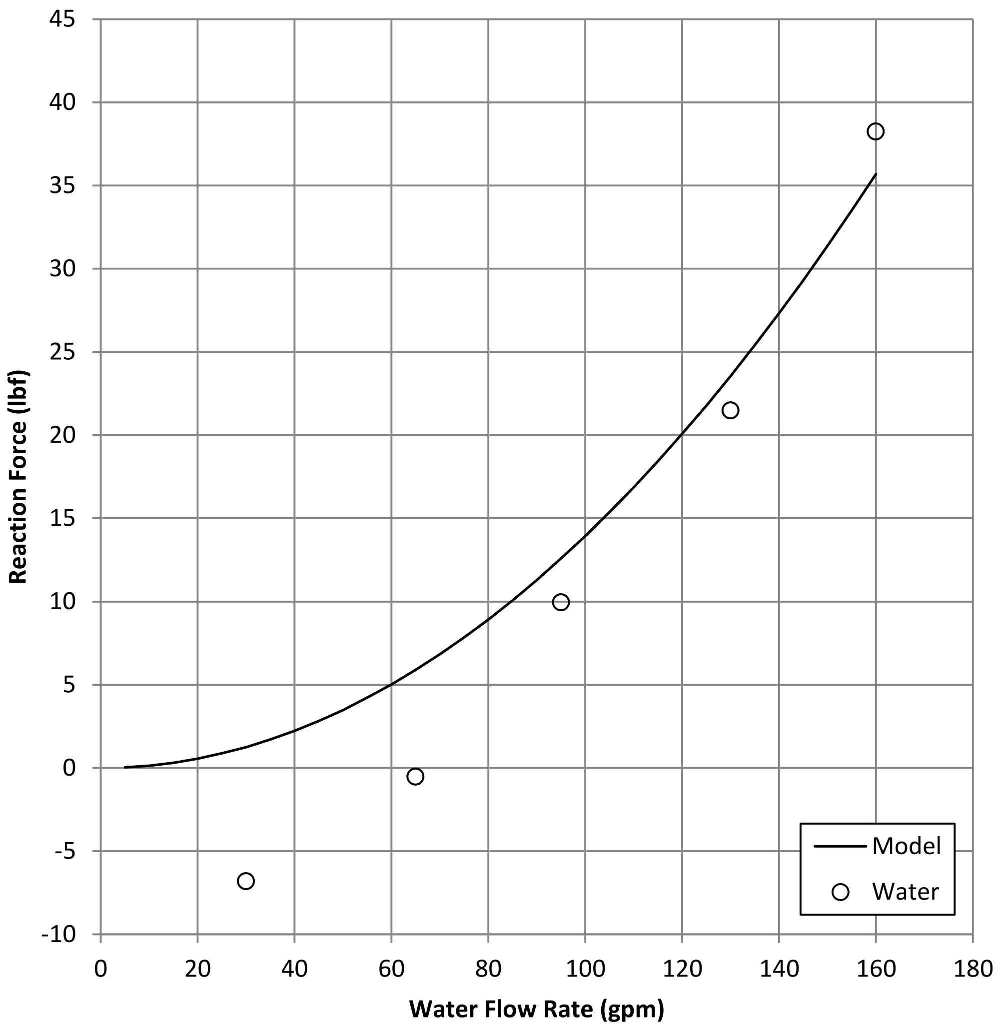


Figure H.9 – Measured nozzle reaction force for a 1-1/8" smooth bore nozzle flowing water compared with standard IFSTA equation (Fire Stream Practices 7th ed., Chapter 4, Equation L, page 197). The model of Equation L assumes no nozzle losses.

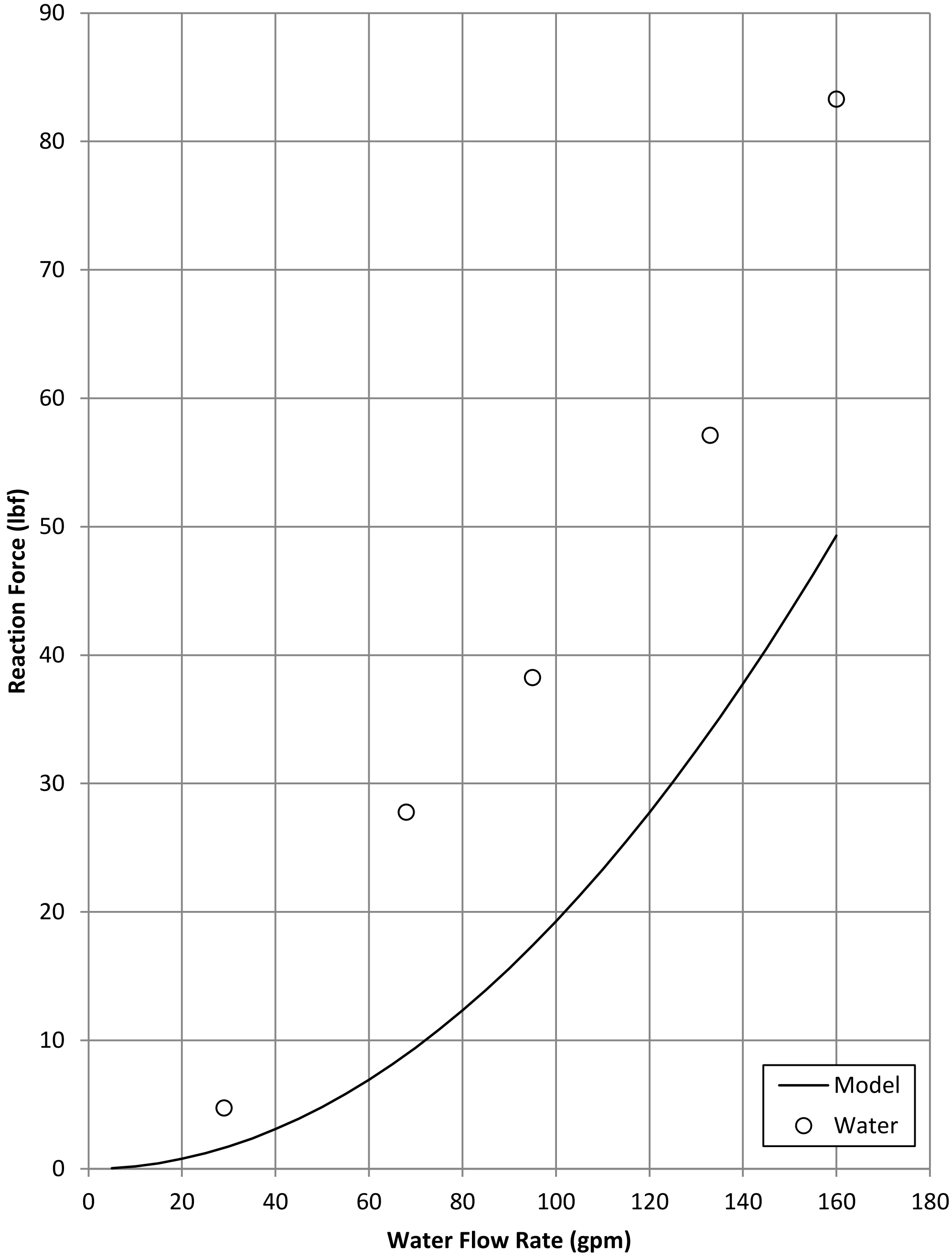


Figure H.10 – Measured nozzle reaction force for 15/16" combination nozzle on straight stream setting flowing water compared with standard IFSTA equation (Fire Stream Practices 7th ed., Chapter 4, Equation M, page 197). The model of Equation M assumes a nozzle discharge coefficient of 0.996 (see Fire Stream Practices 7th ed., Equations D and E).

Original Field Notes

This section contains additional information from our field notes which we recorded at the time of testing on May 5th, 2012.

Since the air flow meter on Water Tender 57 (the fire truck we used to perform these tests) was not operating most of the time, we recorded the air pressure read by the CAFS pressure gage instead. It may be possible to contact the manufacturer and estimate the air flow rate based on the pressure reading. Also, the air flow meter did provide a reading during a few of the test runs, and those readings are indicated in the tables below. We do not consider any of the air flow rate readings to be reliable since the gauge was only working intermittently.

Table H.5 – Original field notes for nozzle reaction force tests with 1-1/8" smooth bore nozzle flowing CAFS.

CAFS ON			
1-1/8" Smooth Bore Nozzle			
0.3% Foam Concentration			
70°F Fluid Temperature			
Solution Flow Rate	Air Pressure	Air Flow Rate	Comments
Q, (gpm)	P, (psi)	Q_{air}, (SCFM)	
30	136	53	
66	140	44	
95	144	38	
130	80	-	Seemed small!
157	164	-	

Table H.6 – Original field notes for nozzle reaction force tests with 1-1/8" smooth bore nozzle flowing water.

CAFS OFF			
1-1/8" Smooth Bore Nozzle			
0.0% Foam Concentration			
70°F Fluid Temperature			
Solution Flow Rate	Air Pressure	Air Flow Rate	Comments
Q, (gpm)	P, (psi)	Q_{air}, (SCFM)	
30	CAFS OFF	CAFS OFF	??? [apparatus read 30 lbf with a zero reading of 30 lbf; i.e. apparatus read no force at all]

65	CAFS OFF	CAFS OFF	
95	CAFS OFF	CAFS OFF	
130	CAFS OFF	CAFS OFF	GAUGE FAILURE
160	CAFS OFF	CAFS OFF	ALL FLOW RATES BASED ON PRESSURE

Table H.7 – Original field notes for nozzle reaction force tests with 15/16" combination nozzle on straight stream setting flowing CAFS.

CAFS ON			
15/16" Combination Nozzle			
0.3% Foam Concentration			
70°F Fluid Temperature			
Solution Flow Rate	Air Pressure	Air Flow Rate	Comments
Q, (gpm)	P, (psi)	Q_{air}, (SCFM)	
28	136	46	
63	144	36	
96	80	-	
130	164	-	
160	160	-	

Table H.8 – Original field notes for nozzle reaction force tests with 15/16" combination nozzle on straight stream setting flowing water.

CAFS OFF			
15/16" Combination Nozzle			
0.0% Foam Concentration			
70°F Fluid Temperature			
Solution Flow Rate	Air Pressure	Air Flow Rate	Comments
Q, (gpm)	P, (psi)	Q_{air}, (SCFM)	
29	CAFS OFF	CAFS OFF	
68	CAFS OFF	CAFS OFF	
95	CAFS OFF	CAFS OFF	
133	CAFS OFF	CAFS OFF	
160	CAFS OFF	CAFS OFF	

Raw Data

This section contains our original recorded data, before applying our measured calibration curves. If the existing nozzle reaction force measurement device is recalibrated, you can apply the new calibration curve to this raw data.

NOTE: All force measurements were taken downscale, and the downscale calibration curve was applied.

Table H.9 – Raw data for nozzle reaction force tests with 1-1/8" smooth bore nozzle flowing CAFS.

CAFS ON		
1-1/8" Smooth Bore Nozzle		
0.3% Foam Concentration		
70°F Fluid Temperature		
Solution Flow Rate	Force Reading	Force Zero Reading
Q, (gpm)	B_y, (lbf_y)	B_y, (lbf_y)
30	43	21
66	62	28
95	70	34
130	63	35
157	72	35

Table H.10 – Raw data for nozzle reaction force tests with 1-1/8" smooth bore nozzle flowing water.

CAFS OFF		
1-1/8" Smooth Bore Nozzle		
0.0% Foam Concentration		
70°F Fluid Temperature		
Solution Flow Rate	Force Reading	Force Zero Reading
Q, (gpm)	B_y, (lbf_y)	B_y, (lbf_y)
30	30	30
65	39	33
95	49	33
130	60	33
160	77	33

Table H.11 – Raw data for nozzle reaction force tests with 15/16" combination nozzle on straight stream setting flowing CAFS.

CAFS ON		
15/16” Combination Nozzle		
0.3% Foam Concentration		
70°F Fluid Temperature		
Solution Flow Rate	Force Reading	Force Zero Reading
Q, (gpm)	B_y, (lbf_y)	B_y, (lbf_y)
28	41	31
63	59	29
96	79	33
130	93	34
160	109	31

Table H.12 – Raw data for nozzle reaction force tests with 15/16” combination nozzle on straight stream setting flowing water.

CAFS OFF		
15/16” Combination Nozzle		
0.0% Foam Concentration		
70°F Fluid Temperature		
Solution Flow Rate	Force Reading	Force Zero Reading
Q, (gpm)	B_y, (lbf_y)	B_y, (lbf_y)
29	35	24
68	57	24
95	67	24
133	85	24
160	110	24

Hose Kinking Force Test Results

This section contains the test results from our hose kinking force tests.

For all hose kinking force tests, we used a 1-3/4” attack line that had been in service for under one year. The hose had a 100% polyester double jacket with an EPDM rubber lining. The hose was manufactured by Key Fire Hose Corporation as part of their Big 10 series. The part number of the hose was DP17-800.

Tabulated Data

This section provides tabulated data for the hose kinking force test results.

Table H.13 – Tabulated hose kinking force data for a hose line with fluid flowing through it. All uncertainties on hose kinking forces are ±0.5 lbf.

Hose Line with Fluid Flowing			
Plain Water		CAFS	
Liquid Flow Rate	Force to Kink Hose	Liquid Flow Rate	Force to Kink Hose
Q, (gpm)	F, (lbf)	Q, (gpm)	F, (lbf)
29	38	28	58
68	68	63	72
95	68	95	77
130	61	130	84
160	66	160	95

Table H.14 – Tabulated hose kinking force data for a charged hose line without fluid flowing through it. All uncertainties on hose kinking forces are ±0.5 lbf.

Charged Hose Line (no fluid flowing)			
Plain Water		CAFS	
Charge Pressure	Force	Charge Pressure	Force
P, (psig)	F, (lbf)	P, (psig)	F, (lbf)
145.0	84.0	211	(over range) 100
115.0	69.5	175	73
100.0	83.0	150	90
75.0	68.5	125	58
50.0	47.5	100	51
22.5	30.5	75	42
-	-	50	34
-	-	25	29

Plots

This section provides plots of the data for the hose kinking force test results.

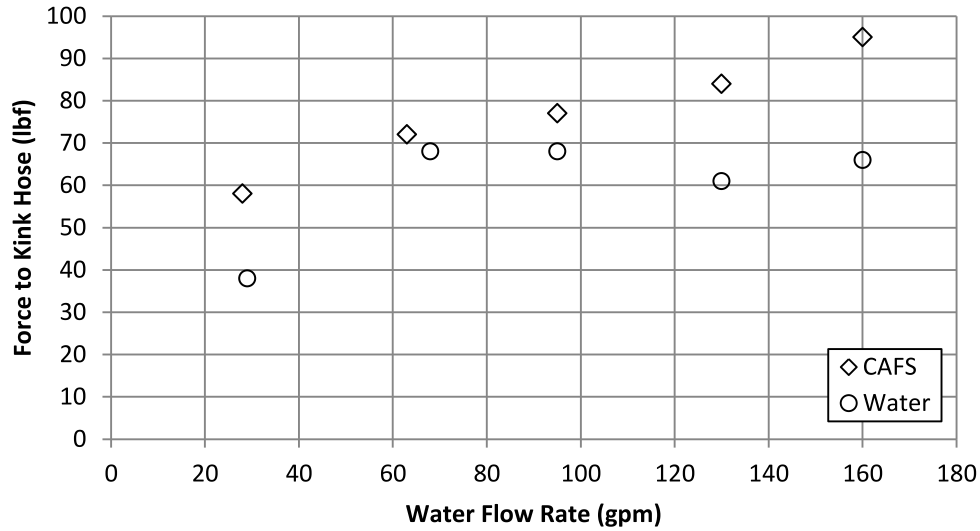


Figure H.11 – Force required to kink a fire hose using our apparatus. Kink tests were performed while the hose was flowing fluid. Uncertainties on all forces are ±0.5 lbf.

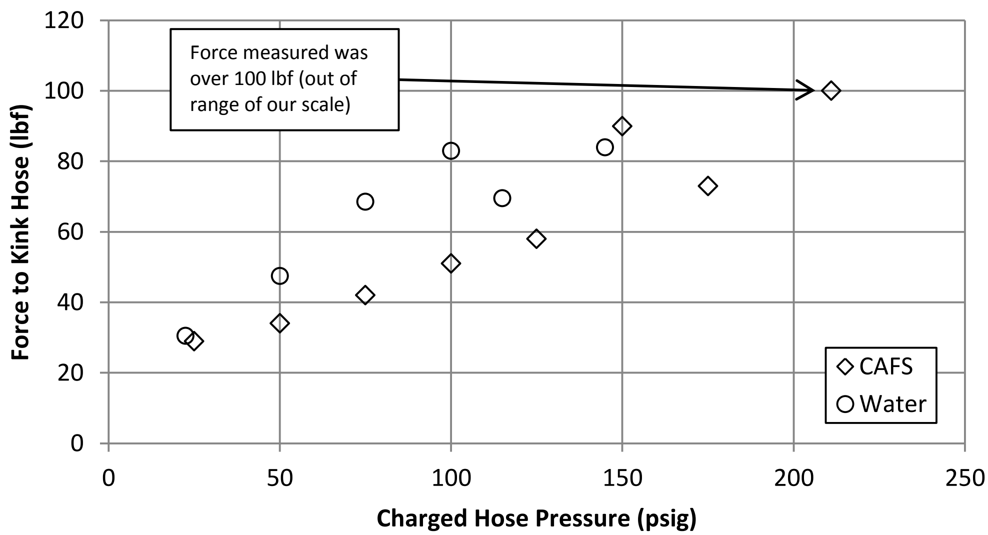


Figure H.12 – Force required to kink a fire hose using our apparatus. Kink tests were performed while the hose was charged, but not flowing fluid. Uncertainties on all forces are ±0.5 lbf.

Stream Throw and Distribution Test Results

This section contains the test results from our stream throw and distribution tests.

Tabulated Data

This section provides tabulated data for the stream throw and distribution test results.

Table H.15 – Maximum stream throw distances for a 15/16” combination nozzle on straight stream setting flowing 120 gpm of water at different angles, for CAFS on and for CAFS off. Uncertainty on all throw distances is ±0.5 ft.

Nozzle Angle Above Horizontal	Maximum Stream Throw with CAFS (ft)	Maximum Stream Throw with Water (ft)
0.0°	78	40
22.5°	122	60
45.0°	101	67

Table H.16 – Fluid mass flux rate at different grid points for a 15/16” combination nozzle flowing CAFS on straight stream setting at 120 gpm of water and angled at 22.5° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

CAFS ON					
15/16” Combination nozzle on straight stream setting					
0.3% Foam concentrate					
120 gpm water flow rate					
Nozzle angled at 22.5° above horizontal					
Fluid Mass Flux Rate (lbm/ft^2-min)					
Transverse Distance from Stream Centerline →	-12 ft	-6 ft	0 ft	6 ft	12 ft
↓ Longitudinal Distance from Nozzle ↓					
30 ft	0.000	0.000	0.644	0.443	0.000
40 ft	0.000	0.000	0.806	0.483	0.000
50 ft	0.000	0.000	0.846	0.765	0.000
60 ft	0.000	0.121	1.007	0.967	0.161
70 ft	0.000	0.403	1.450	1.571	0.161
80 ft	0.000	0.524	1.933	1.812	0.161
90 ft	0.000	0.000	1.450	0.846	0.081
100 ft	0.000	0.443	0.282	0.242	0.000
110 ft	0.000	0.121	0.121	0.000	0.000
120 ft	0.000	0.000	0.000	0.000	0.000

Table H.17 – Fluid mass flux rate at different grid points for a 15/16" combination nozzle flowing CAFS on straight stream setting at 120 gpm of water and angled at 45.0° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

CAFS ON					
15/16" Combination nozzle on straight stream setting					
0.3% Foam concentrate					
120 gpm water flow rate					
Nozzle angled at 45.0° above horizontal					
Fluid Mass Flux Rate (lbm/ft^2-min)					
Transverse Distance from Stream Centerline →	-12 ft	-6 ft	0 ft	6 ft	12 ft
↓ Longitudinal Distance from Nozzle ↓					
30 ft	0.000	0.198	0.000	0.099	0.000
40 ft	0.000	0.198	0.495	0.132	0.000
50 ft	0.000	0.264	0.760	0.429	0.000
60 ft	0.099	0.231	0.925	0.594	0.099
70 ft	0.198	0.363	0.958	0.958	0.165
80 ft	0.264	0.363	1.057	1.189	0.264
90 ft	0.165	0.000	0.462	0.925	0.462
105 ft	0.000	0.066	0.198	0.793	0.495
100 ft	0.000	0.000	0.099	0.000	0.000
110 ft	0.000	0.000	0.099	0.396	0.297
120 ft	0.000	0.000	0.000	0.099	0.000

Table H.18 – Fluid mass flux rate at different grid points for a 15/16" combination nozzle flowing water on straight stream setting at 120 gpm of water and angled at 22.5° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

CAFS OFF
15/16" Combination nozzle on straight stream setting
0.0% Foam concentrate
120 gpm water flow rate
Nozzle angled at 22.5° above horizontal
Fluid Mass Flux Rate (lbm/ft^2-min)

Transverse Distance from Stream Centerline →	-12 ft	-6 ft	0 ft	6 ft	12 ft
↓ Longitudinal Distance from Nozzle ↓					
30 ft	0.000	0.033	0.396	0.165	0.000
40 ft	0.000	0.396	0.363	0.000	0.000
50 ft	0.000	0.000	0.528	0.628	0.000
60 ft	0.000	0.000	0.628	0.594	0.099
70 ft	0.033	0.099	0.991	0.727	0.165
80 ft	0.000	0.330	1.123	0.594	0.231
90 ft	0.066	0.000	1.090	0.991	0.198
100 ft	0.033	0.264	1.585	0.528	0.099
105 ft	0.000	0.000	1.288	0.000	0.000
110 ft	0.000	0.099	0.925	0.297	0.066
115 ft	0.000	0.000	0.330	0.000	0.000
120 ft	0.000	0.000	0.066	0.066	0.000

Table H.19 – Fluid mass flux rate at different grid points for a 15/16" combination nozzle flowing water on straight stream setting at 120 gpm of water and angled at 45.0° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

CAFS OFF					
15/16" Combination nozzle on straight stream setting					
0.0% Foam concentrate					
120 gpm water flow rate					
Nozzle angled at 45.0° above horizontal					
Fluid Mass Flux Rate (lbm/ft^2-min)					
Transverse Distance from Stream Centerline →	-12 ft	-6 ft	0 ft	6 ft	12 ft
↓ Longitudinal Distance from Nozzle ↓					
30 ft	0.000	0.000	0.213	0.244	0.000
40 ft	0.000	0.061	0.274	0.366	0.000
50 ft	0.000	0.061	0.427	0.579	0.000
60 ft	0.000	0.061	0.640	0.610	0.183
70 ft	0.000	0.335	0.976	0.823	0.274
80 ft	0.000	0.823	1.280	0.945	0.244
90 ft	0.091	1.311	1.037	0.579	0.183

100 ft	0.152	0.762	0.457	0.183	0.091
105 ft	0.000	0.000	0.640	0.000	0.000
110 ft	0.000	0.061	0.427	0.122	0.061
115 ft	0.000	0.000	0.183	0.000	0.000
120 ft	0.000	0.000	0.091	0.000	0.000

Plots

This section provides plots of the data for stream throw and distribution test results.

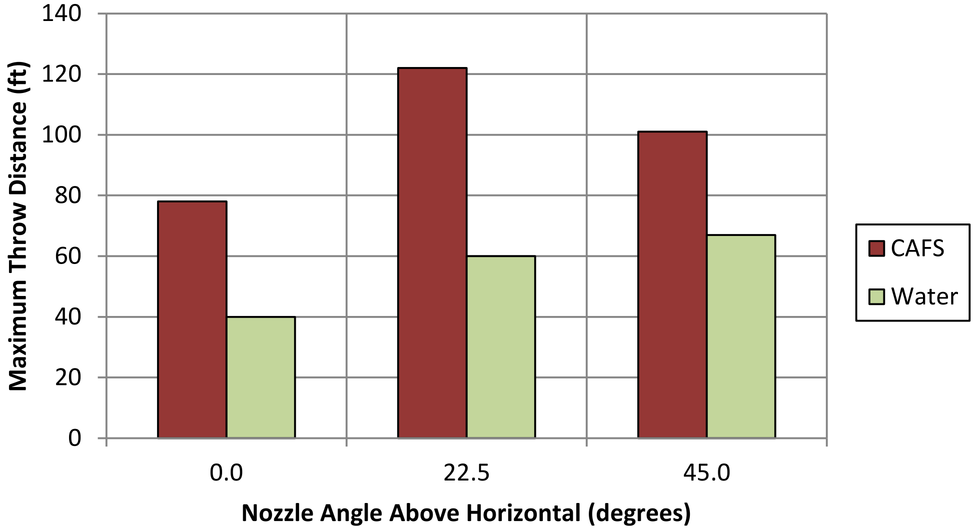


Figure H.13 – Maximum stream throw distances for a 15/16" combination nozzle on straight stream setting flowing 120 gpm of water at different angles, for CAFS on and for CAFS off. Uncertainty on all throw distances is ±0.5 ft.

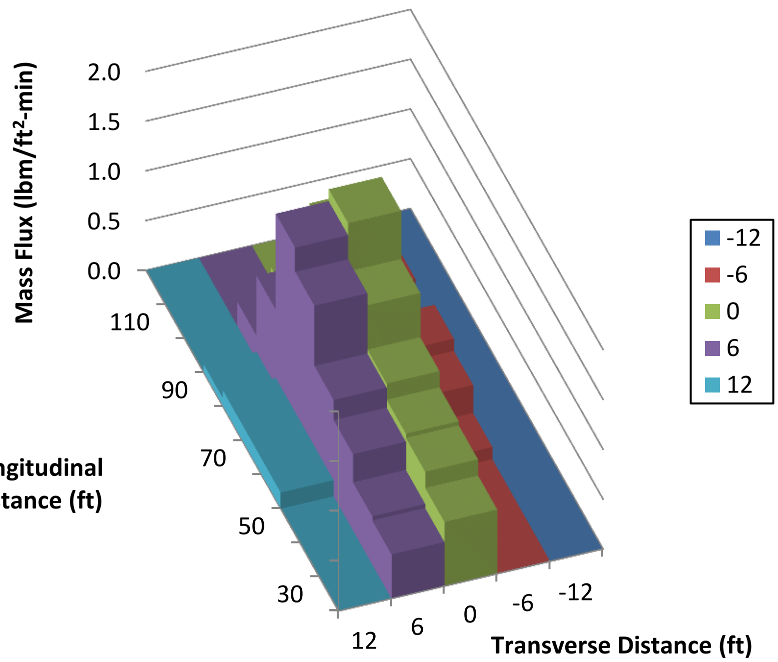


Figure H.14 – Fluid mass flux rate distribution for a 15/16" combination nozzle flowing CAFS on straight stream setting at 120 gpm of water and angled at 22.5° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

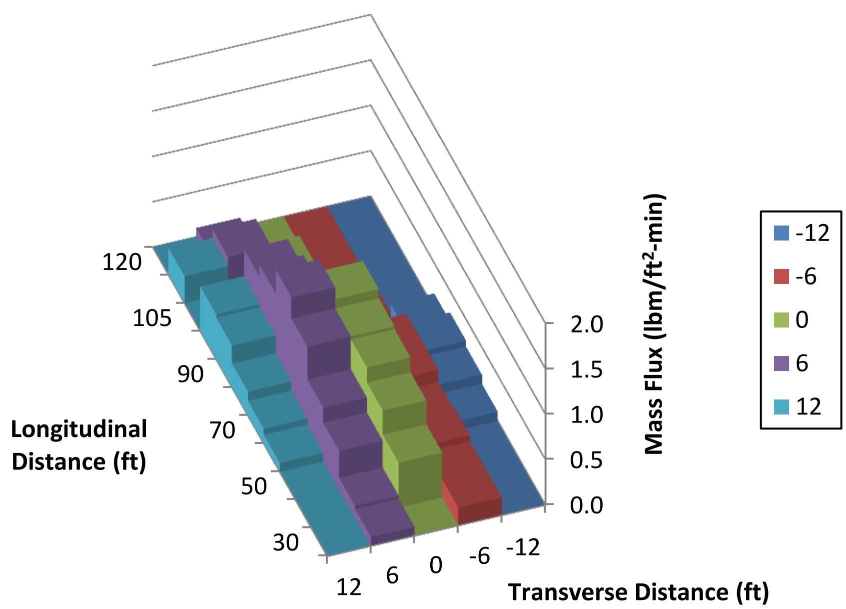


Figure H.15 – Fluid mass flux rate distribution for a 15/16" combination nozzle flowing

CAFS on straight stream setting at 120 gpm of water and angled at 45.0° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

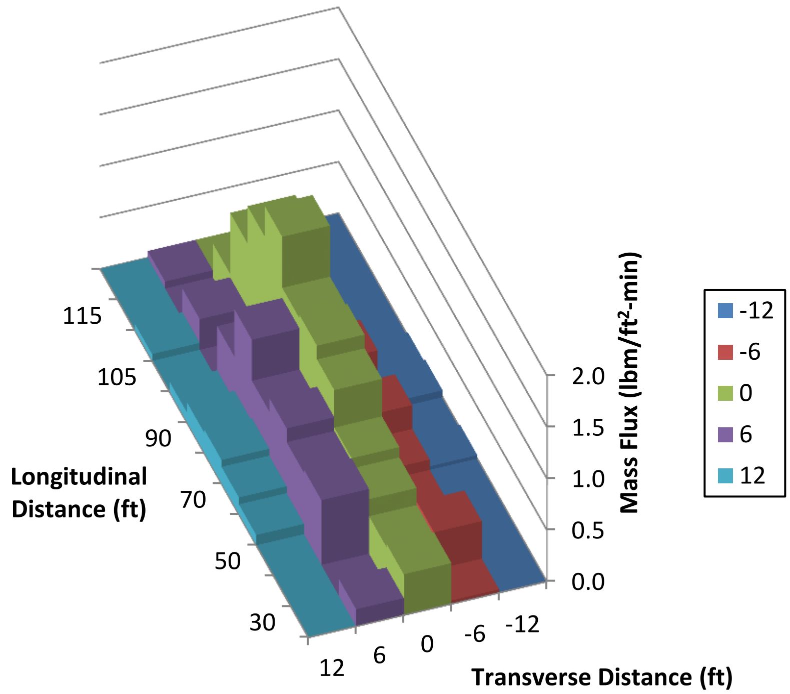


Figure H.16 – Fluid mass flux rate distribution for a 15/16" combination nozzle flowing water on straight stream setting at 120 gpm of water and angled at 22.5° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

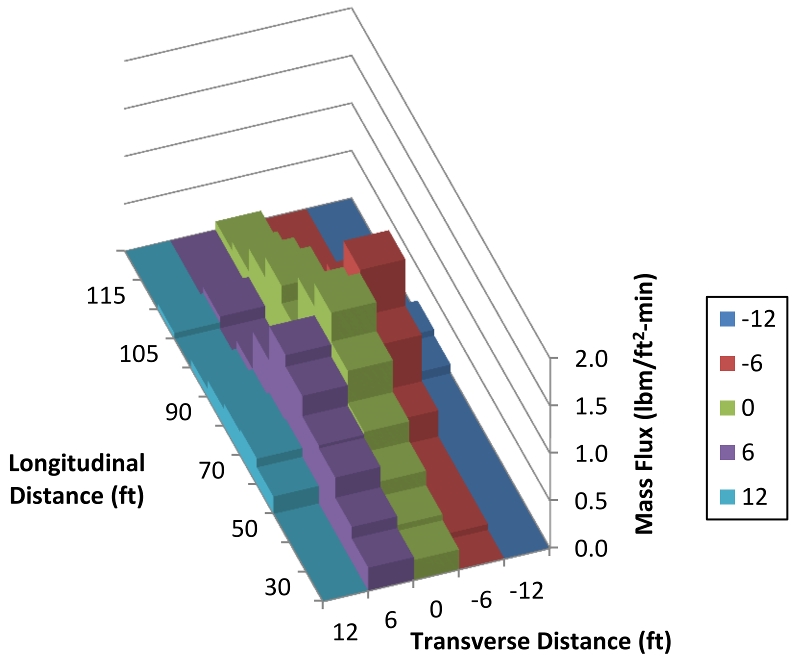


Figure H.17 – Fluid mass flux rate distribution for a 15/16" combination nozzle flowing water on straight stream setting at 120 gpm of water and angled at 45.0° above horizontal. Uncertainty on all mass flux rates is ±0.0165 lbm/ft^2-min.

Friction Force Test Results

This section contains the test results from our friction force tests. A short summary of these test results is provided in Chapter 6 of this report.

Tabulated Data

This section provides tabulated data for the friction force test results.

Table H.20 – Data table containing raw and calibrated friction test data for dry static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	12-May-12	
Motion	Static	Speed	N/A	Surface	Dry
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		

	Raw	Calibrated	Data		Uncertainty
Fake Wood Panneling	23.0	22.1	0.50	Average	0.04
	24.5	23.6	0.53	0.52	
	25.0	24.1	0.54	Std. Dev.	
	24.0	23.1	0.52	0.017	
	24.5	23.6	0.53		
Linoleum	25.0	24.1	0.54	Average	0.09
	29.0	28.2	0.63	0.59	
	28.5	27.7	0.62	Std. Dev.	
	27.5	26.7	0.60	0.043	
	25.0	24.1	0.54		
Meduim Weave Carpet	38.0	37.3	0.84	Average	0.04
	39.0	38.3	0.86	0.84	
	37.0	36.3	0.82	Std. Dev.	
	37.5	36.8	0.83	0.018	
	38.5	37.8	0.85		
Glazed Ceramic Tile	25.0	24.1	0.54	Average	0.06
	28.0	27.2	0.61	0.58	
	27.0	26.2	0.59	Std. Dev.	
	26.0	25.1	0.57	0.028	
	27.5	26.7	0.60		
Thick Weave Carpet	47.5	47.0	1.06	Average	0.07
	48.0	47.5	1.07	1.03	
	47.0	46.5	1.05	Std. Dev.	
	45.0	44.4	1.00	0.032	
	45.0	44.4	1.00		

Table H.21 – Data table containing raw and calibrated friction test data for dry static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Static	Speed	N/A	Surface	Dry
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Polished Concrete	31.5	30.7	0.69	Average	0.06
	29.5	28.7	0.65	0.66	

	28.5	27.7	0.62	Std. Dev.	
	30.0	29.2	0.66	0.026	
	30.5	29.7	0.67		
Concrete	43.5	42.9	0.97	Average	0.05
	41.5	40.9	0.92	0.93	
	41.5	40.9	0.92	Std. Dev.	
	41.0	40.4	0.91	0.022	
	42.0	41.4	0.93		
Asphalt	40.5	39.9	0.90	Average	0.04
	39.0	38.3	0.86	0.88	
	39.5	38.8	0.87	Std. Dev.	
	40.0	39.3	0.89	0.015	
	39.0	38.3	0.86		

Table H.22 – Data table containing raw and calibrated friction test data for dry static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	23-May-12	
Motion	Static	Speed	N/A	Surface	Dry
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Painted Deck	37.5	36.8	0.83	Average	0.06
	38.0	37.3	0.84	0.81	
	37.5	36.8	0.83	Std. Dev.	
	36.0	35.3	0.79	0.029	
	35.0	34.3	0.77		

Table H.23 – Data table containing raw and calibrated friction test data for wet (water) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	14-May-12	
Motion	Static	Speed	N/A	Surface	Wet (H_2O)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11

Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Fake Wood Panneling	27.0	26.2	0.59	Average	0.04
	26.5	25.6	0.58	0.59	
	27.0	26.2	0.59	Std. Dev.	
	28.0	27.2	0.61	0.013	
	27.0	26.2	0.59		
Linoleum	27.5	26.7	0.60	Average	0.04
	28.5	27.7	0.62	0.63	
	28.5	27.7	0.62	Std. Dev.	
	29.5	28.7	0.65	0.017	
	29.0	28.2	0.63		
Meduim Weave Carpet	37.0	36.3	0.82	Average	0.06
	39.0	38.3	0.86	0.86	
	39.0	38.3	0.86	Std. Dev.	
	40.0	39.3	0.89	0.025	
	39.0	38.3	0.86		
Glazed Ceramic Tile	21.5	20.6	0.46	Average	0.04
	22.5	21.6	0.49	0.46	
	21.5	20.6	0.46	Std. Dev.	
	21.5	20.6	0.46	0.016	
	20.5	19.6	0.44		
Thick Weave Carpet	45.0	44.4	1.00	Average	0.06
	46.6	46.0	1.04	1.00	
	45.5	44.9	1.01	Std. Dev.	
	44.5	43.9	0.99	0.026	
	43.5	42.9	0.97		

Table H.24 – Data table containing raw and calibrated friction test data for wet (water) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Static	Speed	N/A	Surface	Wet (H_2O)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force		Coefficient of Friction		

	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Polished Concrete	34.0	33.3	0.75	Average	0.04
	35.0	34.3	0.77	0.75	
	34.0	33.3	0.75	Std. Dev.	
	34.0	33.3	0.75	0.016	
	33.0	32.2	0.73		
Concrete	40.5	39.9	0.90	Average	0.08
	38.5	37.8	0.85	0.84	
	38.0	37.3	0.84	Std. Dev.	
	36.5	35.8	0.81	0.036	
	37.0	36.3	0.82		
Asphalt	35.0	34.3	0.77	Average	0.05
	36.0	35.3	0.79	0.80	
	35.5	34.8	0.78	Std. Dev.	
	37.5	36.8	0.83	0.022	
	36.5	35.8	0.81		

Table H.25 – Data table containing raw and calibrated friction test data for wet (water) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	23-May-12	
Motion	Static	Speed	N/A	Surface	Dry
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Painted Deck	33.0	32.2	0.73	Average	0.04
	33.0	32.2	0.73	0.73	
	33.0	32.2	0.73	Std. Dev.	
	32.0	31.2	0.70	0.016	
	34.0	33.3	0.75		

Table H.26 – Data table containing raw and calibrated friction test data for wet (0.3% Foam) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data

Tester	A. Morano		Date	14-May-12	
Motion	Static	Speed	N/A	Surface	Wet (Foam)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Fake Wood Panneling	22.0	21.1	0.47	Average	0.06
	25.0	24.1	0.54	0.51	
	24.0	23.1	0.52	Std. Dev.	
	23.5	22.6	0.51	0.026	
	23.0	22.1	0.50		
Linoleum	22.5	21.6	0.49	Average	0.10
	18.0	17.0	0.38	0.42	
	19.0	18.0	0.41	Std. Dev.	
	21.5	20.6	0.46	0.048	
	18.0	17.0	0.38		
Meduim Weave Carpet	41.5	40.9	0.92	Average	0.08
	38.0	37.3	0.84	0.88	
	38.5	37.8	0.85	Std. Dev.	
	41.5	40.9	0.92	0.038	
	39.5	38.8	0.87		
Glazed Ceramic Tile	15.0	14.0	0.31	Average	0.05
	15.0	14.0	0.31	0.31	
	16.0	15.0	0.34	Std. Dev.	
	14.0	13.0	0.29	0.019	
	14.0	13.0	0.29		
Thick Weave Carpet	37.5	36.8	0.83	Average	0.03
	37.0	36.3	0.82	0.82	
	37.0	36.3	0.82	Std. Dev.	
	37.0	36.3	0.82	0.008	
	36.5	35.8	0.81		

Table H.27 – Data table containing raw and calibrated friction test data for wet (0.3% Foam) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Static	Speed	N/A	Surface	Wet (Foam)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	

Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Polished Concrete	30.0	29.2	0.66	Average	0.07
	31.5	30.7	0.69	0.68	
	33.0	32.2	0.73	Std. Dev.	
	30.0	29.2	0.66	0.031	
	30.0	29.2	0.66		
Concrete	37.0	36.3	0.82	Average	0.05
	38.0	37.3	0.84	0.84	
	38.0	37.3	0.84	Std. Dev.	
	37.0	36.3	0.82	0.019	
	39.0	38.3	0.86		
Asphalt	29.0	28.2	0.63	Average	0.04
	29.0	28.2	0.63	0.63	
	28.0	27.2	0.61	Std. Dev.	
	29.5	28.7	0.65	0.013	
	29.0	28.2	0.63		

Table H.28 – Data table containing raw and calibrated friction test data for wet (0.3% Foam) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	23-May-12	
Motion	Static	Speed	N/A	Surface	Dry
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Painted Deck	30.0	29.2	0.66	Average	0.06
	30.5	29.7	0.67	0.64	
	28.0	27.2	0.61	Std. Dev.	
	30.0	29.2	0.66	0.025	
	28.5	27.7	0.62		

Table H.29 – Data table containing raw and calibrated friction test data for submerged (water) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	14-May-12	
Motion	Static	Speed	N/A	Surface	Sub (H_2O)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Fake Wood Panneling	33.0	32.2	0.73	Average	0.06
	32.5	31.7	0.71	0.69	
	30.5	29.7	0.67	Std. Dev.	
	30.0	29.2	0.66	0.029	
	31.5	30.7	0.69		
Linoleum	32.0	31.2	0.70	Average	0.07
	35.0	34.3	0.77	0.75	
	35.5	34.8	0.78	Std. Dev.	
	33.5	32.7	0.74	0.032	
	34.5	33.8	0.76		
Meduim Weave Carpet	41.5	40.9	0.92	Average	0.07
	44.5	43.9	0.99	0.96	
	44.0	43.4	0.98	Std. Dev.	
	44.5	43.9	0.99	0.031	
	42.5	41.9	0.94		
Glazed Ceramic Tile	20.5	19.6	0.44	Average	0.05
	22.5	21.6	0.49	0.46	
	21.5	20.6	0.46	Std. Dev.	
	22.5	21.6	0.49	0.023	
	20.5	19.6	0.44		
Thick Weave Carpet	45.0	44.4	1.00	Average	0.10
	47.5	47.0	1.06	0.99	
	44.5	43.9	0.99	Std. Dev.	
	43.0	42.4	0.95	0.048	
	42.0	41.4	0.93		

Table H.30 – Data table containing raw and calibrated friction test data for submerged (0.3% Foam) static friction coefficient measurements using a 50-lbf spring scale.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	14-May-12	
Motion	Static	Speed	N/A	Surface	Sub (Foam)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Fake Wood Panneling	24.0	23.1	0.52	Average	0.09
	25.0	24.1	0.54	0.52	
	26.0	25.1	0.57	Std. Dev.	
	24.0	23.1	0.52	0.043	
	21.0	20.1	0.45		
Linoleum	26.0	25.1	0.57	Average	0.09
	24.5	23.6	0.53	0.51	
	21.0	20.1	0.45	Std. Dev.	
	24.0	23.1	0.52	0.046	
	22.0	21.1	0.47		
Meduim Weave Carpet	40.5	39.9	0.90	Average	0.08
	42.0	41.4	0.93	0.89	
	41.5	40.9	0.92	Std. Dev.	
	38.0	37.3	0.84	0.038	
	39.0	38.3	0.86		
Glazed Ceramic Tile	14.0	13.0	0.29	Average	0.06
	11.0	9.9	0.22	0.25	
	12.0	10.9	0.25	Std. Dev.	
	13.0	11.9	0.27	0.030	
	11.0	9.9	0.22		
Thick Weave Carpet	37.5	36.8	0.83	Average	0.05
	37.5	36.8	0.83	0.81	
	37.0	36.3	0.82	Std. Dev.	
	35.0	34.3	0.77	0.024	
	37.0	36.3	0.82		

Table H.31 – Data table containing raw and calibrated friction test data for dry dynamic friction coefficient measurements using a 50-lbf spring scale at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	13-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Dry

Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty		
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11	
Calibrated	44.4	Offset	-1.254	Total	1.14	
NOTE: Uncertainty Reported at 95% Confidence Interval						
Material	Horizontal Pull Force (lbf)		Coefficient of Friction			
	Raw	Calibrated	Data		Uncertainty	
Fake Wood Panneling	17.5	16.5	0.37	Average	0.03	
	17.0	16.0	0.36	0.36		
	17.0	16.0	0.36	Std. Dev.		
	16.5	15.5	0.35	0.008		
	17.0	16.0	0.36			
Linoleum	20.0	19.0	0.43	Average	0.04	
	21.0	20.1	0.45	0.44		
	21.5	20.6	0.46	Std. Dev.		
	20.5	19.6	0.44	0.018		
	19.5	18.5	0.42			
Glazed Ceramic Tile	24.0	23.1	0.52	Average	0.03	
	23.0	22.1	0.50	0.51		
	23.5	22.6	0.51	Std. Dev.		
	23.5	22.6	0.51	0.008		
	23.5	22.6	0.51			

Table H.32 – Data table containing raw and calibrated friction test data for wet (water) dynamic friction coefficient measurements using a 50-lbf spring scale at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	14-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Wet (H_2O)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Glazed Ceramic Tile	23.5	22.6	0.51	Average	0.04
	24.0	23.1	0.52	0.50	
	23.5	22.6	0.51	Std. Dev.	
	23.0	22.1	0.50	0.013	
	22.5	21.6	0.49		

Table H.33 – Data table containing raw and calibrated friction test data for wet (0.3% Foam) dynamic friction coefficient measurements using a 50-lbf spring scale at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	14-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Wet (Foam)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Glazed Ceramic Tile	19.0	18.0	0.41	Average	0.03
	19.5	18.5	0.42	0.42	
	20.0	19.0	0.43	Std. Dev.	
	20.0	19.0	0.43	0.010	
	20.0	19.0	0.43		

Table H.34 – Data table containing raw and calibrated friction test data for submerged (water) dynamic friction coefficient measurements using a 50-lbf spring scale at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	14-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Sub (H_2O)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Glazed Ceramic Tile	22.0	21.1	0.47	Average	0.04
	22.5	21.6	0.49	0.49	
	23.5	22.6	0.51	Std. Dev.	
	23.5	22.6	0.51	0.015	
	23.0	22.1	0.50		

Table H.35 – Data table containing raw and calibrated friction test data for submerged (0.3% Foam) dynamic friction coefficient measurements using a 50-lbf spring scale at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	14-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Sub (Foam)
Sled Weight (lb)		Scale	50 Lb Spring	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.015	Calibration	1.11
Calibrated	44.4	Offset	-1.254	Total	1.14
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw	Calibrated	Data		Uncertainty
Glazed Ceramic Tile	18.0	17.0	0.38	Average	0.04
	17.0	16.0	0.36	0.38	
	18.0	17.0	0.38	Std. Dev.	
	19.0	18.0	0.41	0.016	
	18.0	17.0	0.38		

Table H.36 – Data table containing raw and calibrated friction test data for dry dynamic friction coefficient measurements using a force transducer at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Dry
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	56	22	0.50	Average	0.06
	54	21	0.47	0.49	
	56	22	0.50	Std. Dev.	
	56	22	0.50	0.028	
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	60	24	0.55		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		

	56	22	0.50		
	56	22	0.50		
	54	21	0.47		
	54	21	0.47		
	51	19	0.44		
	51	19	0.44		
	49	18	0.41		
	56	22	0.50		
Tile	56	22	0.50	Average	0.07
	56	22	0.50	0.47	
	56	22	0.50	Std. Dev.	
	56	22	0.50	0.035	
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	51	19	0.44		
	49	18	0.41		
	51	19	0.44		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	51	19	0.44		
	48	18	0.40		
Linoleum	51	19	0.44	Average	0.02
	51	19	0.44	0.44	
	54	21	0.47	Std. Dev.	
	51	19	0.44	0.008	
	52	20	0.45		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		

	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	115	54	1.21	Average	
	112	52	1.17	1.07	
	112	52	1.17	Std. Dev.	
	108	50	1.12	0.104	
	103	47	1.06		
	102	47	1.05		
	99	45	1.01		
	96	43	0.98		
	96	43	0.98		
	94	42	0.95		
Medium Weave Carpet	92	41	0.93		0.21
	92	41	0.93		
	96	43	0.98		
	96	43	0.98		
	98	45	1.00		
	102	47	1.05		
	103	47	1.06		
	110	51	1.15		
	112	52	1.17		
	115	54	1.21		
	115	54	1.21		
	120	56	1.27		
	88	39	0.88	Average	
	92	41	0.93	0.98	
	96	43	0.98	Std. Dev.	
	99	45	1.01	0.142	
Thick Weave Carpet	103	47	1.06		0.28
	103	47	1.06		
	108	50	1.12		
	112	52	1.17		
	110	51	1.15		
	112	52	1.17		

	110	51	1.15		
	108	50	1.12		
	103	47	1.06		
	102	47	1.05		
	97	44	0.99		
	92	41	0.93		
	88	39	0.88		
	83	37	0.82		
	79	34	0.77		
	79	34	0.77		
	78	34	0.76		
	78	34	0.76		

Table H.37 – Data table containing raw and calibrated friction test data for wet (water) dynamic friction coefficient measurements using a force transducer at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Wet (H2O)
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	51	19	0.44	Average	0.09
	49	18	0.41	0.43	
	51	19	0.44	Std. Dev.	
	51	19	0.44	0.046	
	51	19	0.44		
	51	19	0.44		
	54	21	0.47		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	54	21	0.47		
	51	19	0.44		
	51	19	0.44		
	48	18	0.40		
	48	18	0.40		

	48	18	0.40		
	44	16	0.35		
	46	17	0.38		
	44	16	0.35		
	46	17	0.38		
	46	17	0.38		
Tile	51	19	0.44	Average	0.04
	54	21	0.47	0.42	
	51	19	0.44	Std. Dev.	
	51	19	0.44	0.020	
	51	19	0.44		
	49	18	0.41		
	49	18	0.41		
	49	18	0.41		
	49	18	0.41		
	51	19	0.44		
	48	18	0.40		
	48	18	0.40		
	48	18	0.40		
	48	18	0.40		
	51	19	0.44		
	49	18	0.41		
	51	19	0.44		
	48	18	0.40		
	48	18	0.40		
	48	18	0.40		
	48	18	0.40		
	49	18	0.41		
Linoleum	63	26	0.58	Average	0.03
	63	26	0.58	0.56	
	62	25	0.57	Std. Dev.	
	60	24	0.55	0.013	
	60	24	0.55		
	60	24	0.55		
	60	24	0.55		
	62	25	0.57		
	62	25	0.57		
	62	25	0.57		
	62	25	0.57		
	62	25	0.57		
	62	25	0.57		
	62	25	0.57		

	62	25	0.57		
	62	25	0.57		
	62	25	0.57		
	60	24	0.55		
	60	24	0.55		
	60	24	0.55		
	62	25	0.57		
	62	25	0.57		

Table H.38 – Data table containing raw and calibrated friction test data for wet (water) dynamic friction coefficient measurements using a force transducer at 0.550 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Dynamic	Speed	0.550 fps	Surface	Wet (H2O)
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	51	19	0.44	Average	0.03
	51	19	0.44	0.42	
	49	18	0.41	Std. Dev.	
	51	19	0.44	0.016	
	51	19	0.44		
	49	18	0.41		
	51	19	0.44		
	51	19	0.44		
	49	18	0.41		
	48	18	0.40		
	51	19	0.44		
	49	18	0.41		
	48	18	0.40		
	48	18	0.40		
	48	18	0.40		
	49	18	0.41		
	51	19	0.44		
	48	18	0.40		
	51	19	0.44		
	51	19	0.44		

	48	18	0.40		
	49	18	0.41		
Tile	56	22	0.50	Average	0.06
	56	22	0.50	0.51	
	60	24	0.55	Std. Dev.	
	56	22	0.50	0.028	
	56	22	0.50		
	56	22	0.50		
	54	21	0.47		
	56	22	0.50		
	56	22	0.50		
	57	23	0.51		
	56	22	0.50		
	57	23	0.51		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	60	24	0.55		
	60	24	0.55		
	60	24	0.55		
	62	25	0.57		
	62	25	0.57		
	60	24	0.55		
	56	22	0.50		
Linoleum	54	21	0.47	Average	0.09
	56	22	0.50	0.48	
	56	22	0.50	Std. Dev.	
	56	22	0.50	0.043	
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	54	21	0.47		
	54	21	0.47		
	41	14	0.32		

	49 51 51 56	18 19 19 22	0.41 0.44 0.44 0.50		

Table H.39 – Data table containing raw and calibrated friction test data for wet (0.3% Foam) dynamic friction coefficient measurements using a force transducer at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Wet (Foam)
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	56	22	0.50	Average	0.06
	56	22	0.50	0.48	
	54	21	0.47	Std. Dev.	
	49	18	0.41	0.029	
	51	19	0.44		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	55	22	0.49		
	54	21	0.47		
	54	21	0.47		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
Tile	44	16	0.35	Average	0.05
	41	14	0.32	0.31	

	44	16	0.35	Std. Dev.	
	44	16	0.35	0.023	
	44	16	0.35		
	40	14	0.30		
	40	14	0.30		
	40	14	0.30		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
Linoleum	44	16	0.35	Average	0.04
	44	16	0.35	0.29	
	40	14	0.30	Std. Dev.	
	39	13	0.29	0.022	
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	38	12	0.28		
	38	12	0.28		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	35	11	0.24		
	38	12	0.28		
	39	13	0.29		
	38	12	0.28		
	38	12	0.28		
	39	13	0.29		

Table H.40 – Data table containing raw and calibrated friction test data for wet (0.3% Foam) dynamic friction coefficient measurements using a force transducer at 0.550 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	23-May-12	
Motion	Dynamic	Speed	0.550 fps	Surface	Wet (Foam)
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	56	22	0.50	Average	0.07
	56	22	0.50	0.46	
	56	22	0.50	Std. Dev.	
	56	22	0.50	0.033	
	56	22	0.50		
	56	22	0.50		
	54	21	0.47		
	54	21	0.47		
	54	21	0.47		
	56	22	0.50		
	54	21	0.47		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	49	18	0.41		
	49	18	0.41		
	51	19	0.44		
	49	18	0.41		
	51	19	0.44		
	49	18	0.41		
	50	19	0.42		
Tile	39	13	0.29	Average	0.02
	38	12	0.28	0.29	
	38	12	0.28	Std. Dev.	
	38	12	0.28	0.011	
	35	11	0.24		
	39	13	0.29		

	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	38	12	0.28		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	40	14	0.30		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	32	9	0.21	Average	
	35	11	0.24	0.23	
	35	11	0.24	Std. Dev.	
	35	11	0.24	0.019	
	35	11	0.24		
	31	9	0.20		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
Linoleum	33	10	0.22		0.04
	31	9	0.20		
	33	10	0.22		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	33	10	0.22		
	35	11	0.24		
	33	10	0.22		
	31	9	0.20		
	33	10	0.22		
	32	9	0.21		

Table H.41 – Data table containing raw and calibrated friction test data for submerged (water) dynamic friction coefficient measurements using a force transducer at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Sub. (H2O)
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	48	18	0.40	Average	0.09
	48	18	0.40	0.46	
	51	19	0.44	Std. Dev.	
	56	22	0.50	0.045	
	56	22	0.50		
	56	22	0.50		
	51	19	0.44		
	48	18	0.40		
	49	18	0.41		
	56	22	0.50		
	57	23	0.51		
	56	22	0.50		
	56	22	0.50		
	49	18	0.41		
	48	18	0.40		
	51	19	0.44		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	48	18	0.40		
	48	18	0.40		
Tile	56	22	0.50	Average	0.05
	56	22	0.50	0.50	
	54	21	0.47	Std. Dev.	
	56	22	0.50	0.023	
	56	22	0.50		
	57	23	0.51		
	60	24	0.55		
	56	22	0.50		
	56	22	0.50		
	51	19	0.44		

	55	22	0.49		
	56	22	0.50		
	56	22	0.50		
	57	23	0.51		
	56	22	0.50		
	56	22	0.50		
	60	24	0.55		
	57	23	0.51		
	56	22	0.50		
	60	24	0.55		
	57	23	0.51		
	57	23	0.51		
	63	26	0.58	Average	
	56	22	0.50	0.53	
	51	19	0.44	Std. Dev.	
	46	17	0.38	0.063	
	51	19	0.44		
	60	24	0.55		
	63	26	0.58		
	60	24	0.55		
	56	22	0.50		
	56	22	0.50		
Linoleum	54	21	0.47		0.13
	56	22	0.50		
	67	28	0.63		
	63	26	0.58		
	60	24	0.55		
	56	22	0.50		
	56	22	0.50		
	63	26	0.58		
	63	26	0.58		
	63	26	0.58		
	63	26	0.58		
	63	26	0.58		

Table H.42 – Data table containing raw and calibrated friction test data for submerged (water) dynamic friction coefficient measurements using a force transducer at 0.550 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	21-May-12	
Motion	Dynamic	Speed	0.550 fps	Surface	Sub. (H2O)

Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	51	19	0.44	Average	0.03
	51	19	0.44	0.42	
	49	18	0.41	Std. Dev.	
	48	18	0.40	0.017	
	48	18	0.40		
	51	19	0.44		
	50	19	0.42		
	51	19	0.44		
	48	18	0.40		
	48	18	0.40		
	48	18	0.40		
	49	18	0.41		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	49	18	0.41		
	48	18	0.40		
	48	18	0.40		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
	51	19	0.44		
Tile	54	21	0.47	Average	0.04
	54	21	0.47	0.49	
	56	22	0.50	Std. Dev.	
	56	22	0.50	0.019	
	51	19	0.44		
	54	21	0.47		
	54	21	0.47		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	51	19	0.44		
	54	21	0.47		
	56	22	0.50		
	56	22	0.50		

	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
	56	22	0.50		
Linoleum	44	16	0.35	Average	0.11
	40	14	0.30	0.26	
	39	13	0.29	Std. Dev.	
	34	10	0.23	0.053	
	39	13	0.29		
	39	13	0.29		
	44	16	0.35		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	31	9	0.20		
	31	9	0.20		
	39	13	0.29		
	35	11	0.24		
	33	10	0.22		
	31	9	0.20		
	28	7	0.16		
	30	8	0.18		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		

Table H.43 – Data table containing raw and calibrated friction test data for submerged (0.3% Foam) dynamic friction coefficient measurements using a force transducer at 0.275 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	23-May-12	
Motion	Dynamic	Speed	0.275 fps	Surface	Sub. (Foam)
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25

NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty
Fake Wood Panneling	38	12	0.28	Average	0.06
	39	13	0.29	0.27	
	39	13	0.29	Std. Dev.	
	39	13	0.29	0.030	
	35	11	0.24		
	32	9	0.21		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	38	12	0.28		
	35	11	0.24		
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	38	12	0.28		
	39	13	0.29		
	31	9	0.20		
	35	11	0.24		
	39	13	0.29		
	39	13	0.29		
	38	12	0.28		
Tile	46	17	0.38	Average	0.05
	46	17	0.38	0.36	
	47	17	0.39	Std. Dev.	
	48	18	0.40	0.025	
	46	17	0.38		
	44	16	0.35		
	44	16	0.35		
	44	16	0.35		
	44	16	0.35		
	44	16	0.35		
	44	16	0.35		
	44	16	0.35		
	46	17	0.38		
	46	17	0.38		
	46	17	0.38		
	46	17	0.38		
	44	16	0.35		

	44	16	0.35		
	44	16	0.35		
	39	13	0.29		
	40	14	0.30		
	46	17	0.38		
Linoleum	35	11	0.24	Average	0.02
	35	11	0.24	0.24	
	35	11	0.24	Std. Dev.	
	35	11	0.24	0.007	
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	33	10	0.22		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	33	10	0.22		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		

Table H.44 – Data table containing raw and calibrated friction test data for submerged (0.3% Foam) dynamic friction coefficient measurements using a force transducer at 0.550 fps.

CAFS Senior Project Friction Testing Data					
Tester	A. Morano		Date	23-May-12	
Motion	Dynamic	Speed	0.550 fps	Surface	Sub. (Foam)
Sled Weight (lb)		Scale	F. Trans.	Scale Uncertainty	
Uncalibrated	45.0	Cal. Const.	1.87	Calibration	
Calibrated	44.4	Offset	14.7	Total	0.25
NOTE: Uncertainty Reported at 95% Confidence Interval					
Material	Horizontal Pull Force (lbf)		Coefficient of Friction		
	Raw (counts)	Calibrated	Data		Uncertainty

Fake Wood Panneling	35	11	0.24	Average	0.05
	39	13	0.29	0.27	
	38	12	0.28	Std. Dev.	
	35	11	0.24	0.022	
	39	13	0.29		
	39	13	0.29		
	39	13	0.29		
	35	11	0.24		
	39	13	0.29		
	39	13	0.29		
	38	12	0.28		
	39	13	0.29		
	35	11	0.24		
	35	11	0.24		
	35	11	0.24		
	38	12	0.28		
	35	11	0.24		
	39	13	0.29		
	38	12	0.28		
	35	11	0.24		
	36	11	0.26		
	35	11	0.24		
Tile	35	11	0.24	Average	0.06
	32	9	0.21	0.21	
	32	9	0.21	Std. Dev.	
	35	11	0.24	0.028	
	35	11	0.24		
	35	11	0.24		
	33	10	0.22		
	35	11	0.24		
	34	10	0.23		
	31	9	0.20		
	31	9	0.20		
	31	9	0.20		
	31	9	0.20		
	31	9	0.20		
	35	11	0.24		
	31	9	0.20		
	30	8	0.18		
	30	8	0.18		
	30	8	0.18		
	28	7	0.16		

	28	7	0.16		
	31	9	0.20		
Linoleum	30	8	0.18	Average	0.07
	24	5	0.11	0.15	
	22	4	0.09	Std. Dev.	
	24	5	0.11	0.035	
	28	7	0.16		
	28	7	0.16		
	31	9	0.20		
	31	9	0.20		
	28	7	0.16		
	30	8	0.18		
	25	6	0.12		
	28	7	0.16		
	31	9	0.20		
	31	9	0.20		
	28	7	0.16		
	24	5	0.11		
	28	7	0.16		
	30	8	0.18		
	25	6	0.12		
	28	7	0.16		
	24	5	0.11		
	24	5	0.11		

Appendix I
Apparatus Operating Instructions

Here are instructions we developed for how to use our apparatuses to take data.

Nozzle Reaction Force Measurement Apparatus Instructions

Securing the Apparatus

1. Place the apparatus on level ground and orient it in the desired direction. Make sure the stake holes are pointing in the direction you will be shooting water.
2. Drive stakes into the ground through the stake holes.
3. Place weights over the stakes to hold the apparatus down. You may want to do a quick calculation to determine how much weight is required to counteract the moment created by the nozzle reaction force.

IMPORTANT! If you are using the stand to raise the nozzle and give you the capability to yaw the entire device, do not yaw the device too much. The stand is designed to handle the nozzle reaction force when it is applied from the forward direction, and yawing the device too much may cause the stand to tip over.

IMPORTANT! If you are using the stand, bear in mind that the stand must be stake to the ground and weighted down, just like the apparatus by itself.

Securing Your Nozzle in the Apparatus

1. Remove the Holder Sub-Assembly (see Appendix E for a drawing of the Holder Sub-Assembly) from the rest of the apparatus.
2. Slide the fire hose nozzle into the center channel. Make sure you have couplings filling the entire length of the channel. You may need to insert a chain of double-male and double-female couplings before the nozzle so that you have enough coupling length to fill the entire length of the channel. All couplings in the channel should have their lugs aligned, with one lug pointing straight down into the groove at the bottom of the channel.
3. IMPORTANT! Ensure that the coupling in front of the channel (the first coupling that is not contained in the length of the channel) is aligned so that two lugs contact the front face of the block (i.e. one of the three lugs is pointing straight up, and the other two lugs are pressed against the front face of the block). This will allow the nozzle reaction force to be transmitted through the coupling straight into the block of wood, rather than relying on friction to support the nozzle reaction force.
4. Tighten the hose clamp with a screwdriver.
5. Reinstall the Holder Sub-Assembly into the rest of the apparatus. For force measurements, make sure that you install the Holder Sub-Assembly with the nozzle

aligned at 0.0° above horizontal, as force measurements are only taken with the nozzle aligned at 0.0° above horizontal. If another angle is required for stream throw or distribution testing, install the Holder Sub-Assembly at the appropriate angle.

Taking a Measurement

NOTE: You may find it desirable to record only up-scale or down-scale readings if you treated your up-scale and down-scale calibration curves separately. To achieve an up-scale or down-scale reading, manually apply force to the apparatus in the proper direction, and then slowly release your applied force.

NOTE: You can put any force measurement device on the apparatus to measure the moment created by the nozzle reaction force.

1. Measure and record the lever arm that the nozzle reaction force is acting at. Be sure to measure the lever arm from the hinge point, NOT from the base of the apparatus.
2. Open the nozzle valve slowly.
3. Allow the fire engineer to adjust the pump settings until the desired solution flow rate is established.
4. Close the nozzle valve slowly.
5. Record the zero reading on the scale.
6. Open the nozzle valve slowly.
7. Record the reading on the scale.
8. If you are flowing CAFS, you may find it valuable to record the temperature of the fluid at this point. Record the temperature of the fluid with the nozzle mostly closed (fluid should be only just churning out of the nozzle when you measure the temperature, instead of flying out in a very fast stream).
9. Close the nozzle valve slowly.

Hose Kinking Force Measurement Apparatus Instructions

In order to use the apparatus follow these steps:

1. Arrange the apparatus with the rotating axle furthest away from you, and with the cable wound on the pulley with the free end on the right.
2. Place the hose so it runs to the left of the center axle and to the right of the rotating axle.
3. Pull on the cable, causing the apparatus to rotate. This will bend the hose around the center axle. This can be done by hand or with an electric winch. An assistant is needed in order to keep the hose from dragging on the ground and skewing the results.
4. Using the spring scale, record the maximum force needed to kink the hose.
5. Slowly release the tension in the cable and allow the hose to unkink.

Stream Throw and Distribution Test Instructions

1. Ready the collectors by poking a roofing nail through the bottom cups and stacking another cup on top.
2. Stake the collectors into the ground at the specified intervals, forming a collection grid.
3. Setup your nozzle at the desired flow rate and angle.
4. Open the nozzle to spray for 60 seconds, and then promptly close the nozzle.
5. Record the amount of mass that fell into each collector by weighing each cup and noting its location in the grid. Be sure to empty each cup after taking the measurement, and replace the top cup into the bottom one.

Friction Force Measurement Apparatus Instructions

Test Conditions Defined

- Dry – Surface and test sample free of any water and/or particulate matter.
- Wet (Water) – Clean surface covered with 16 oz water per 4 ft^2 of test sample.
- Wet (Foam) – Clean surface covered with 16 oz foam solution mixed at 0.3% per 4 ft^2 of test sample. Foam solution should be agitated for one minute by shaking vigorously in a 5 gallon bucket.
- Submerged (Water) – Clean surface submerged evenly by ¼ in of water.
- Wet (Foam) – Clean surface submerged evenly by ¼ in of foam solution mixed at 0.3%. Foam concentrate should be evenly mixed with the water.

Static Testing Procedure (Using 50-lbf Spring Scale)

1. Clean and prepare test surfaces. Test surfaces should be free of particulate matter and prepared as described above for the desired test condition.
2. Lift fire boot test sled and place on surface.
3. Attach spring scale to fire boot sled. Pull slightly to make sure the fire boot sled will slide straight.
4. Reset maximum force slider.
5. Pull slowly with increasing force until fire boot begins to slide across the test surface. Be careful not to generate large accelerations, as they will create false readings by the maximum force slider.
6. Record the value of the maximum force slider.
7. Repeat steps 2 through 6 for additional measurements.

Dynamic Testing Procedure (Using Force Transducer)

1. Connect strain gage inputs to the Wheatstone bridge inputs on the minestrone device. See the following URL for complete instructions: <http://129.65.116.176/ME507/lab_mini04.shtml>.

2. Connect the minestrone device to a Windows computer using any standard USB cable.
3. Open Hyperterminal on the windows based computer and connect to the minestrone.
4. Clean and prepare test surfaces. Test surfaces should be free of particulate matter and prepared as described above for the desired test condition.
5. Set winch to desired speed.
6. Lift fire boot test sled and place on surface.
7. Attach force transducer and winch to fire boot sled. Pull slightly with winch to make sure the fire boot sled will slide straight.
8. Test to make sure the minestrone is collecting data. Press “G” on the keyboard in the terminal window.
9. If the minestrone is working, turn on the winch. Press “G” while the sled is moving at constant velocity. The minestrone collects data over a period of approximately 1 second.
10. WARNING: Make sure the winch does not retract too far. This will damage the device. The safety shutoff for the winch does not work because the tub is in the way.
11. Record the data output from the minestrone.
12. Repeat steps 6 through 11 for additional measurements.