FPE Wave Tank

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Sponsor:
WPI Fire Protection and Engineering

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Authorship

The contents of this report are a result of the collaboration by all of the authors. It would be incorrect to say that one person took authorship over any section. We completed all writing and editing together.

Executive Summary

Oil has many purposes, and the drilling of oil will not cease, even if gasoline-powered vehicles are phased out in the coming years. Despite many technological and safety improvements within the oil drilling industry, errors still occur. With the chance for failure and the chance for oil spilling into the environment, cleaning oil spills as efficiently as possible is crucial. When oil is spilled in the ocean, the oil forms a surface layer resting on top of the water. While it would be feasible to collect this spilled oil with physical and mechanical means, it is often more efficient and safer for the environment to burn the surface layer of oil. This process may be efficient, but it still leaves pollutant residue in the environment.

To study and improve this process, oil burns that simulate ocean conditions are a necessary component. The goals of this MQP are to provide the WPI Fire Protection Engineering department with a watertight tank that:

1. Simulates ocean conditions through the creation of waves, formed by a paddle.
2. Is modular, providing a small storage footprint and simple transport to alternative test sites.
3. Can endure high temperatures for prolonged burn testing.

The paddle of the tank features a robust design that allows it to maintain rigidity while displacing hundreds of gallons of water each time it creates a new wave. With waves being sent continuously down the length of the tank, a "beach" is necessary to absorb the energy of the waves, preventing reflection in the tank. This beach is made of expanded steel sheet and features a 6:1 slope, which falls into the acceptable ratios for wave tank beach design. Underneath this sloping beach is a series of 3 expanded steel sheets that span the width of the tank. These expanded steel sheets have diamond-shaped holes, and these holes sequentially reduce in size to more effectively reduce the energy of the waves.

The tank and frame are made entirely out of steel, and the tank is separate from the frame. With the frame being separate, this increases assembly time because more parts need to be properly aligned, but also reduces the manpower necessary to move the tank sections. This design choice is also necessary, as the modularity leads to a smaller storage footprint.

To increase the durability of the tank, a circulating deluge system will reside on top of the tank. This deluge system will constantly circulate water from the inside of the tank and will run through iron piping that has been drilled out. The drilled holes of the iron pipe provide exits for the water, where the water is sprayed onto the walls of the tank to cool them. This cooling system will ultimately prevent the overheating and deformation of the metal panels that are subjected to the continuous high heat of the burning experiments.

Introduction

Oil is used to heat our homes and power large portions of our economy. However, oil spills in the ocean are extremely harmful to the environment, poison our food supply, and can cause problems that linger for years. For these reasons, it is of great importance that we find the most efficient means of cleaning up oil spills. Traditionally, ocean oil spills are cleaned via the burning of the spilled crude oil, formally known as In Situ Burning. Although this is the current most effective method, it has been shown that roughly 40% to 60% of crude oil burns produce leftover residue that can also be harmful to the environment. [1]Therefore, additional research on In Situ Burning is still required, which is why wave tanks are used to study better means of cleaning oil spills in a controlled ocean-simulated environment. Most wave tanks spend their life stationary due to their heavyweight and large size. However, the wave tank we designed and built is the first of its kind due to its modular design. Modularity allows the WPI Fire Protection Engineering (FPE) department to conduct tests under the fume hood in the UL Fire Protection Engineering Performance Lab and then store it elsewhere when space is needed for other experiments. It also allows controlled, smaller-scale tests to be performed next to larger wave tanks at other locations. This modularity provides the opportunity for the test matrix to be condensed in the same location as the larger tank before scaling up the test. Currently, there exist no other modular wave tanks that are also built to house burn testing.

Background

Wave tanks are used for a multitude of reasons, like observing the behavior of waves under certain conditions. The waves are formed by a paddle of some sort at one end, with a "beach" opposite the paddle. This beach is designed to absorb the energy of the incoming waves, thus reducing or preventing the chance of waves reflecting off the side of the tank. This is important because to truly study the behavior of the wave, there shouldn't be any reflected energy upsetting the sinusoidal nature of the waves.

Before designing and constructing the wave tank, research was done into existing wave tanks. Both the University of Maine and the University of New Hampshire have wave tanks, but both are non-modular and are not designed for burn tests. Additionally, SL Ross has a wave tank that is designed for burning, but it is not modular. The company OMEY Labs constructs modular wave tanks, but they do not function as burn tanks, like the UNH and UMaine tanks. Through our research, our tank stands alone as the only modular and burn-ready wave tank in the world.

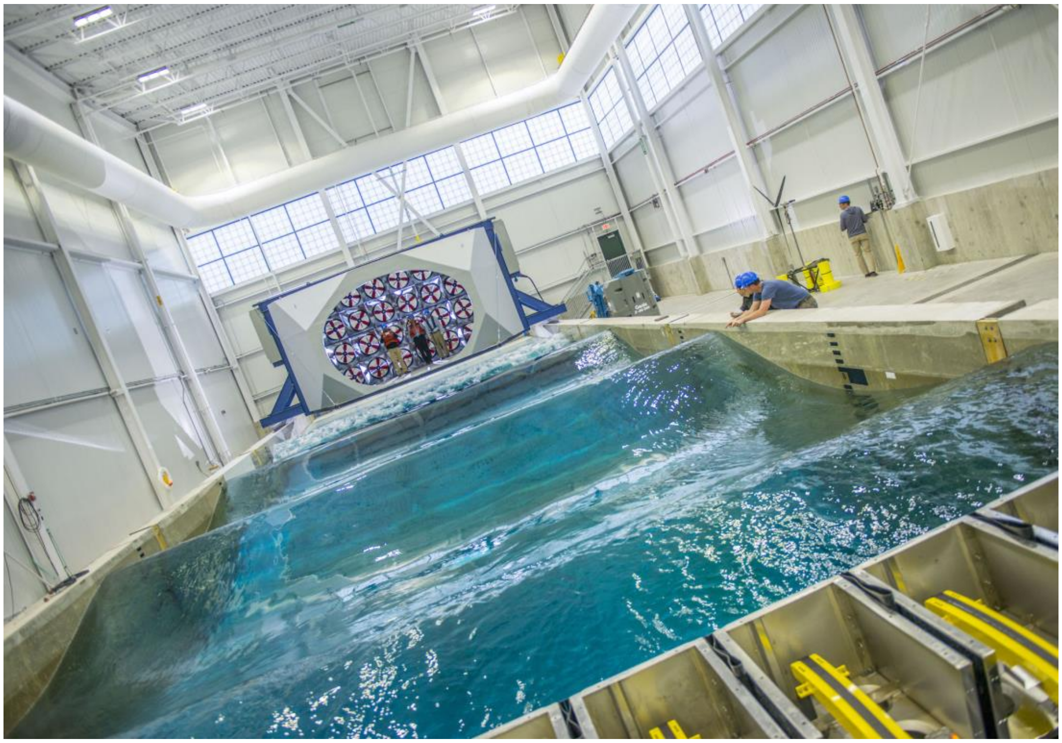


Figure 1: Wave Tank at UMaine

While our tank can create waves and dampen the energy of the waves like other wave tanks, we are not studying the motion of the waves. Our tank's purpose is to serve as a vessel for ocean simulated oil spill cleanup testing. Previously, the WPI FPE department could only test stagnant water burns, unless they visited a facility like CRREL (Cold Regions Research Engineering Laboratory), whose burn-ready wave tank can be seen below.

Figure 2: WPI FPE burn test and CRREL wave tank

The creation of this modular wave tank allows the WPI FPE department to observe oil spill burns and collect the relevant data under ocean conditions on-site, or in tandem at a separate test facility. This functionality offers the opportunity to confirm and compare test results with other burn tests conducted in other tanks side by side.

Design Concepts

Throughout the design process of our wave tank, the team did extensive research into tanks that already exist in the real world (Insert previous example ex. CRELL and design aspects). Utilizing these existing designs, our first instinct was to take an exact model and cut it into multiple chunks to allow for the modularity aspect of our goal to come to fruition. However, throughout our concept stage, we quickly realized that the scope of the project was going to be more difficult because of a variety of factors we forgot to take into account in our first versions of our tank.

Model #1

The principle surrounding our first design was to take the largest pieces of steel sheet we could find on McMaster-Carr while they were also some of the thinnest to keep the price as low as possible. Our team ended up settling on using 2’ by 4’ by 0.03” steel sheets in our first design (Figure 3) to create the bottom of the tank and 2’ by 3’ by 0.03” steel sheets for our walls to allow our design dimensions to be 3’ tall by 4’ wide by 12’ long. These tentative design requirements were provided by Nathaniel Sauer during our first meeting to allow us a rough idea of what size the wave tank would be (Appendix A). This first model included 18 individual steel sheet panels as well as one piece of clear acrylic that would span the majority of the length of the tank to allow easy visibility underneath the water.

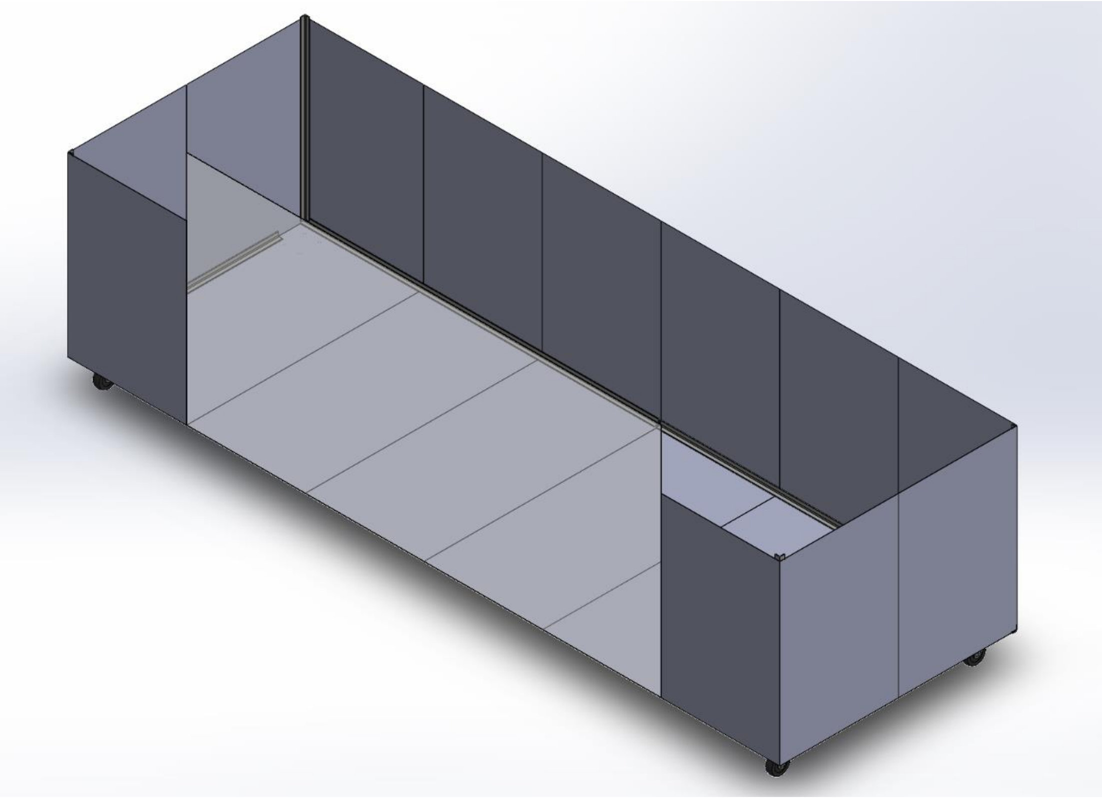


Figure 3: Model #1 - Assembly

12’ x 4’ x 3’

This wave tank was designed to be inexpensive and have a very low storage footprint since each visible section piece could be removed individually. Because of the high modularity of the tank, it subsequently relied too heavily on fasteners. This proved to be a problem because the high number of fasteners would inevitably lead to parts not fitting properly and leaking as well as being very difficult to initially build and rebuild after. This design also relied on the tank being stiff enough to be supported only on 4 casters placed in the corners of the tank which we realized after talking to our advisors and performing some barebones water simulations that the metal sheets would be too thin and lead to excess flex which would prevent the tank from being sealed properly. Seeing as crude oil would be mixed into this water, questionable water tightness is something we could not overlook.

Model #2

After talking over our first design with our advisors, we quickly realized that many aspects of the tank would not work well in a real-world scenario. First, the overall structure of the tank was too flimsy under our SolidWorks pressure simulations, so to fix this but keep the cost down, we implemented a skeleton I-beam frame which allowed us to keep the frame rigid during testing while also allowing us to keep cost and down by keeping the thickness of the steel plates down as well. This design iteration also included the addition of our wave beach to allow the waves generated by the wave maker to be dissipated at the end of its travel rather than be bounced back and ruin the simulation tests.

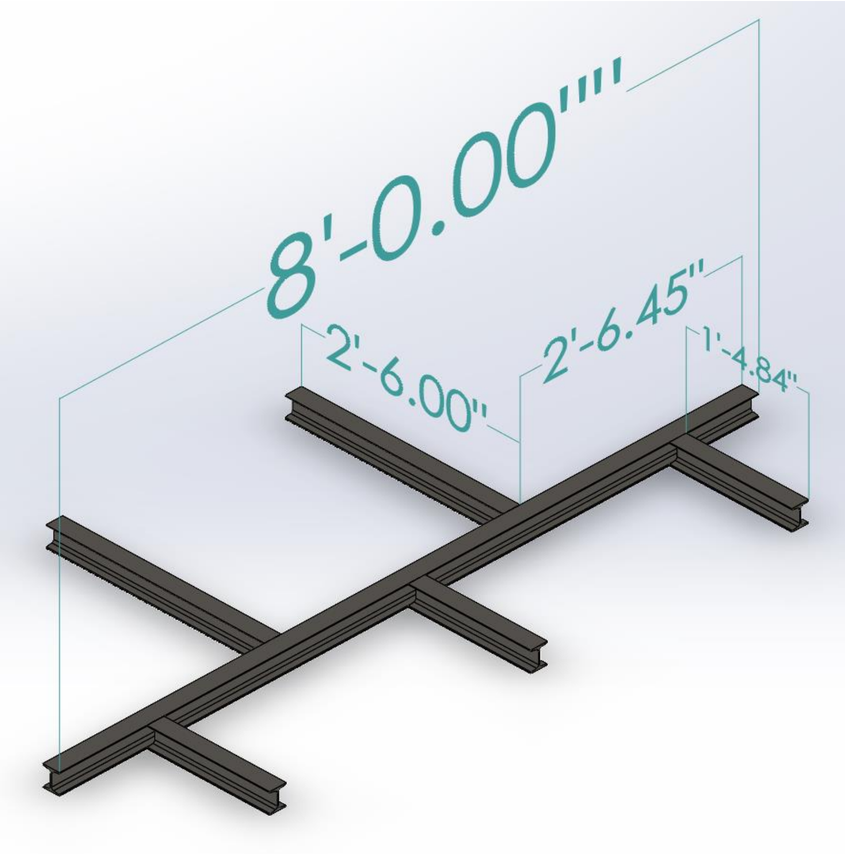


Figure 4: Welded Frame Section - End

This section is made by welding sections of the I-beam together with butt joints.

Weight: 100 lbs. Each

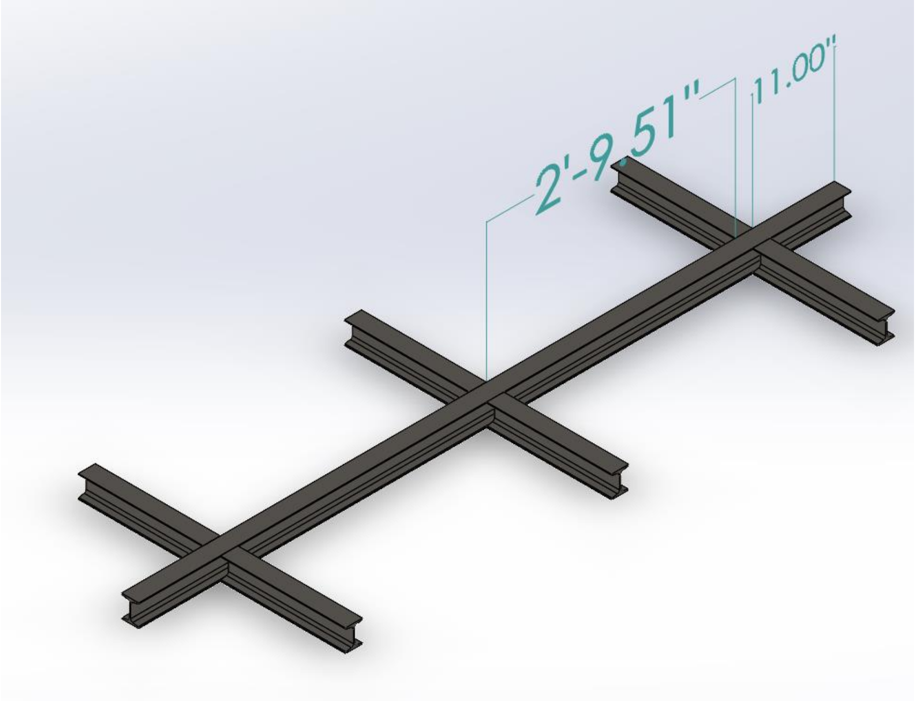


Figure 5: Welded Frame Section - Middle

This section is made by welding sections of the I-beam together with butt joints.

Weight: 95 lbs. Each

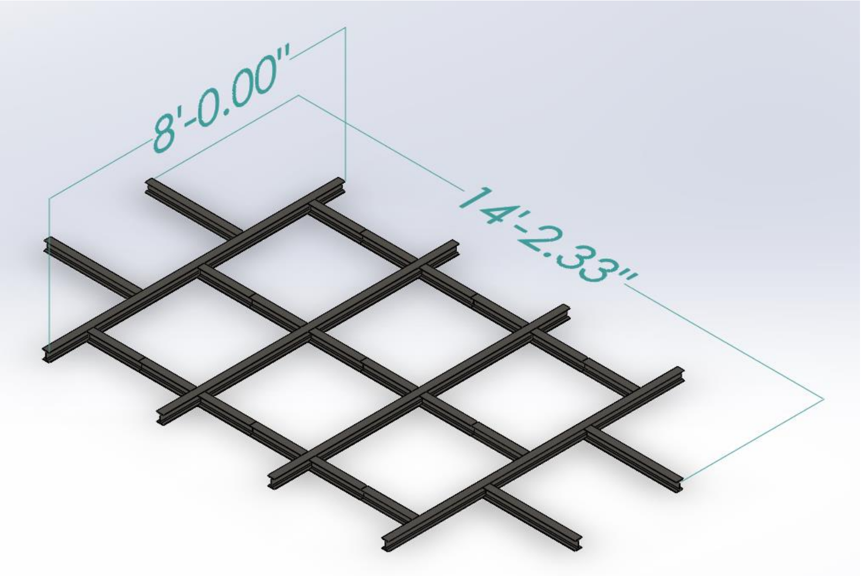


Figure 6: Frame Assembly

After assembling the 4 separate pieces, angle brackets are welded to the ends where the 4 sections will meet each other (3 meeting points per section) and will be fastened together.

Total Weight: 390 lbs.

The skeleton frame pictured above is designed to be the main backbone for our tank, allowing it to support the weight of the water as well as making the frame rigid enough to prevent any movement caused by the oscillations of the waves. It is made of Steel I-Beam with the skeleton being welded at all 90-degree joints and bolted together in 3 separate areas to create 4 distinct segments to allow for easy disassembly when tests are completed. On top of the frame, the tank was slightly redesigned to include thicker steel sheets. The design would consist of 18 - 3’ by 3’ by ⅛” steel sheets to increase rigidity. This changed our water-holding dimensions to now be 3’ tall by 6’ wide by 12’ long which could now hold over 1000 gallons of water and allow for much larger burns.

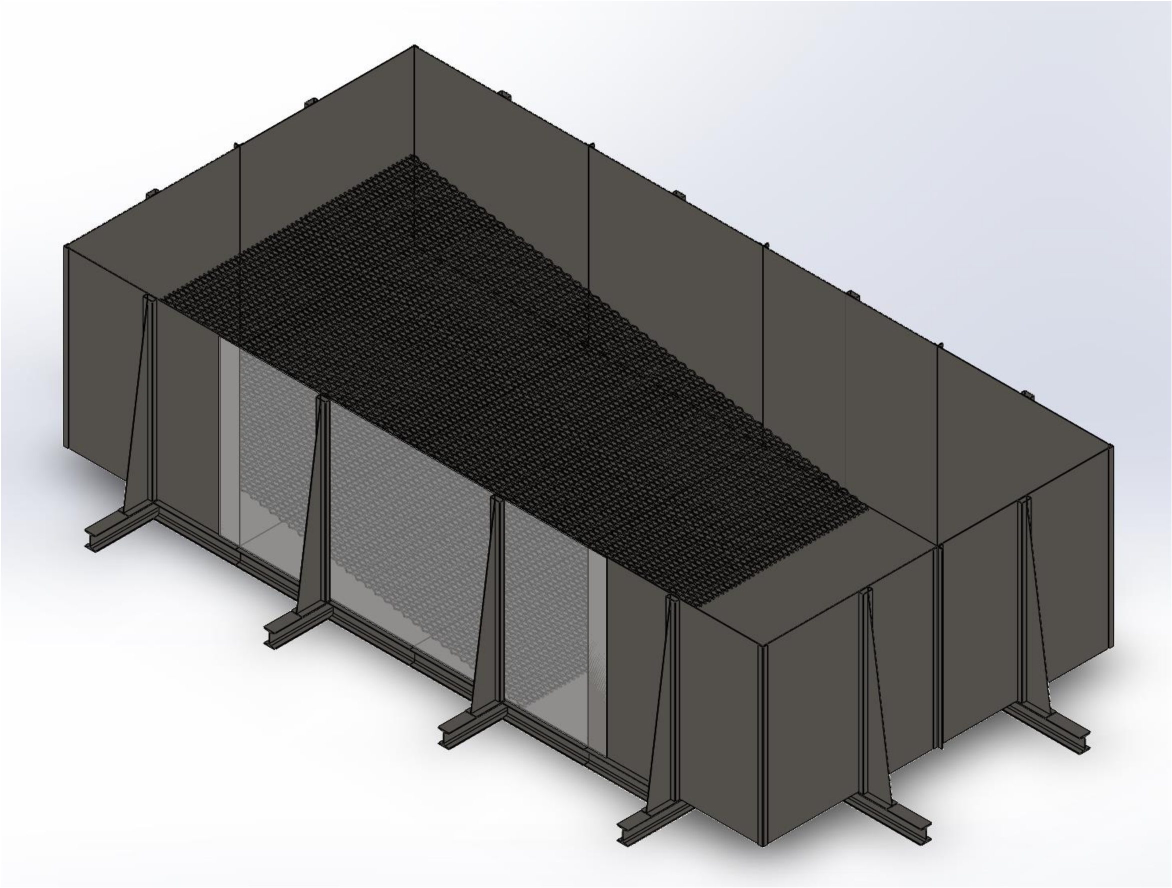


Figure 7: Model #2 - Assembly

12’ x 6’ x 3’

In addition to the improvements over the first model, our team added the beach into the model which will be used to prevent the waves from oscillating back into the paddle after it would reach the end of the tank. Picking the slope was key in this design since if it was set too steep, the water would just glide straight through the expanded steel sheet. If it was too shallow, the water would just glide right over it. Through research done by the Malek-Ashtar University of Technology, they determined that the optimal angle was to have the beach set at a 6:1 ratio of length to height. This allows enough of the wave to be stopped by the metal but also allows easy flow back down into the tank (Khalilabadi).

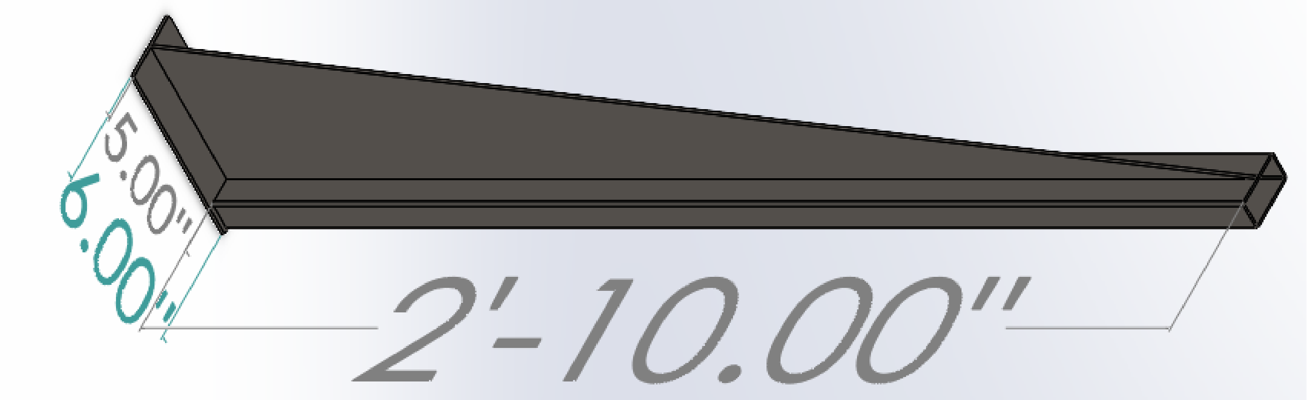


Figure 8: Buttress Assembly

Weight: 8 lbs. Each

Total Weight: 96 lbs.

The final addition to this model was the inclusion of 12 buttresses holding onto each outside section of the frame. These were added to prevent the outside walls from flexing under the weight of the water and the waves inside the tank to keep the tank as stiff as possible as well as negating any additional waves made from the oscillation of the tank rather than the paddle so that data collected would be accurate. These buttresses would be cut from the same material that the panels are made of with the inclusion of a steel tube for added support and will be all welded together as figure 8 shows. During installation, the bottom rectangular plate will have slots drilled into them to be fastened into the I-Beam frame.

Final Design Selection

Our final design required additional modifications to prevent the steel from warping under high heat scenarios as well as decreasing the cost and complexity of the build. Because of these factors, it was necessary to remove the acrylic panel from our design because of the prohibitively expensive cost as well as its questionable durability under high heat. Because of the heat, it was also necessary to include a deluge system to cool down the walls near the burn center as well as include a pump and filter to allow clean water to be circulated into the tank. This final iteration also shows the new wave absorber as well as our wave paddle.

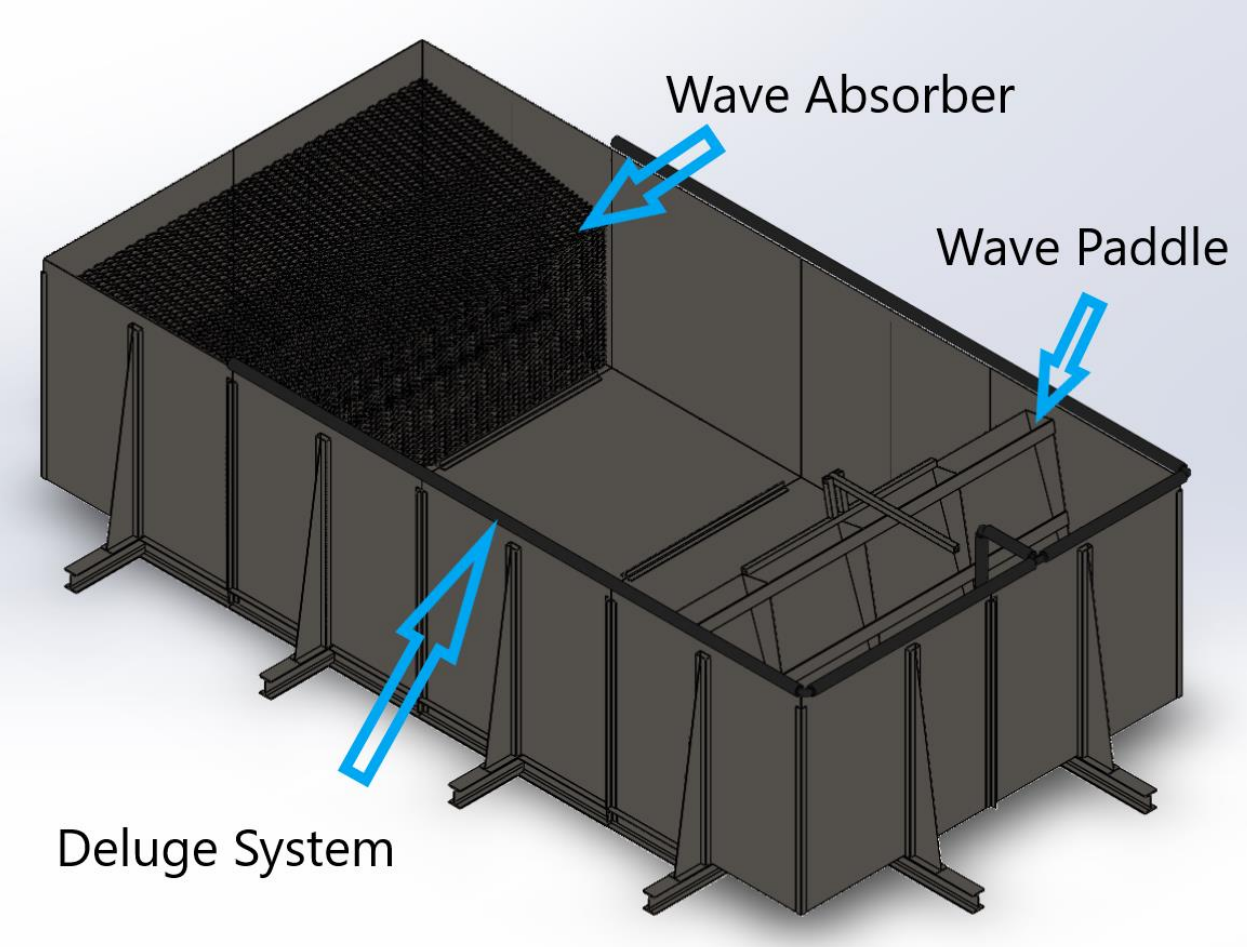


Figure 9: Final Model Assembly

12’ x 6’ x 3’

Total Estimated Weight: 1800 lbs

Deluge System

To increase the durability of the tank and the safety of the operators, it was decided to implement a deluge system. This deluge system will serve to cool the walls of the tank to prevent them from reaching very high temperatures, and potentially deforming and failing. The deluge system will be fed by a pump that draws water from the bottom of the tank, away from the oil and fire on the surface. In addition to the pump, there will also be a filter in line with the pump to prevent oil from circulating within the deluge system. The top of the system would be made of 2 - 9’ long iron pipes that will have small holes drilled in the side which would be facing towards the inside walls to cool them down as the burn tests were performed. The rest of the system would be made of rubber hose and fittings.

Water Storage Totes

The environmental impact of a project like this can be immense, therefore it was the team’s goal to minimize our footprint as much as possible. To do this, the team purchased 4 – 275 gallon water storage totes that were repurposed food storage totes to allow us to contain the water after a burn test and reuse the water for another test down the road rather than having to dispose of the water through EHS every time the tank had to be disassembled for movement.

Figure 10: Water Storage Totes

Paddle

The paddle will be constructed out of 3 of the same steel sheets used to make the exterior of the tank, 2 on the front, and 1 used to cut out triangular braces and slits to add additional bracing and prevent flexing when being used. The paddle will be mounted to the bottom of the frame using a 6’ stainless steel rod with 2 pillow blocks attached to the bottom of the end frame. The motor and subsequent mounting for the motor will be provided by the FPE department when it will be completed.

New Wave Absorber/Beach Design

Because of the length of our tank and the height of the water in the tank, our initial beach design had to be remodeled to accommodate larger waves. Since the tank is not long enough to support a full-length beach, a new model was developed with design cues used from the CRREL tank which used multiple horizontal sheets of expanded metal of different sizes to decrease the momentum of the waves internally within the beach assembly. This allows for much larger waves to be made within the tank as well as also no impeding on the burn zone in the center of the tank.

Final Reinforcements

To finish off our final design, the team added additional angle iron on all joints where the flume sections would meet up to allow for easier assembly and disassembly of the tank and to increase the water tightness of the overall design.

Construction Plan

Before assembling our tank, we needed to fabricate some pieces from stock material. The frame of our design is the most crucial aspect. It provides not only the base for the tank to rest on, but also provides mounting points for the support buttresses and the paddle that resides in the tank. The frame's design relies on two forms of joints: *butt* joints and *tee* joints.

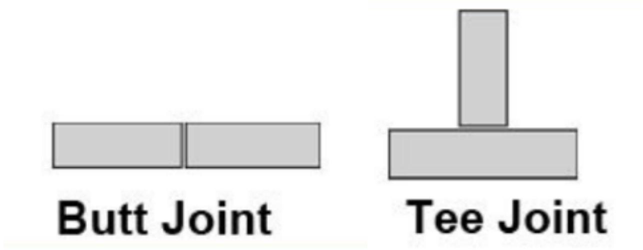


Figure 11: The two joint types used for forming the frame and the respective sections.

The frame is designed utilizing I-Beams. As seen below, the shape of an I-Beam leaves little surface area for welding. A butt joint results in a large gap because of the depth of the web, and a tee joint relies on the vertical part in between the flanges of the I-Beam for welding purposes.

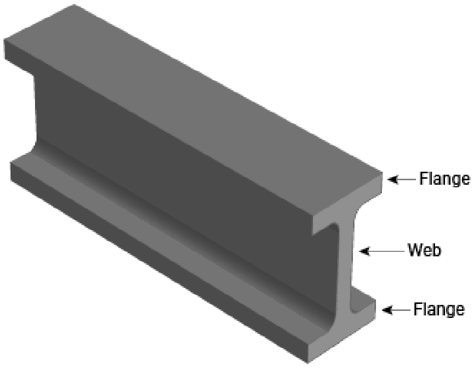


Figure 12: Identifiers for I-Beam

These drawbacks combined with the necessity of modularity pushed our design to utilize spare angle iron material to aid in the formation of our frame. Pictured below is the joining of two I-beam sections at a butt joint. Angle iron has been welded inside of the web of the I-Beam of both sections, and for modularity, a bolt and nut are driven through the angle iron. This allows for quick assembly and disassembly of the frame while ensuring the frame does not shift under testing conditions.

Figure 13: Angle iron with bolt and nut, used for joining modular frame sections.

Shown below is an image of one of the 4 sections that the frame is composed of. Each section of the frame has 5 tee joints. These joints are formed similarly to the aforementioned butt joint. Angle iron was placed on the inside of the joint, filling the web of the frame. This provides more area for welding, and in turn, makes a stronger and more durable weld.

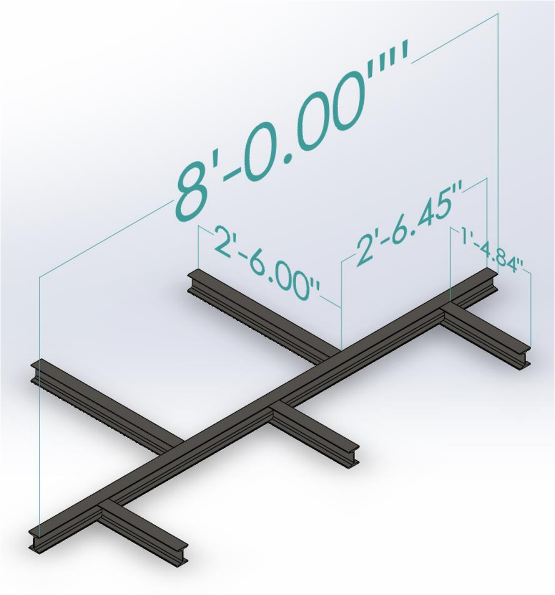


Figure 14: End section of modular frame

The steel panels that make up the tank walls and base are 36” x 36” inch hot rolled steel. To form our tank sections, mill scale was removed from the stock material with angle grinders to provide a better surface for welding. To ensure 90° joints, a jig was made to help with the alignment of panels. The jig was made in a sawhorse shape, welded at 90 degrees. This provided a flat surface for our panels to rest on. The panels could then be clamped down once in a position to prevent movement when welding. The panels were welded with a ¼ ” lip, which allowed for more weld area and in turn stronger panel joints.

Figure 15: Sawhorse style jig to ensure right angle joints between panels.

The final form of the 4 modular sections can be seen below. The two end sections are seen on the left, and an example of the middle section is seen on the right. Scrap stock material was placed on the middle seams of our panels and was welded to both sides to permanently join them.

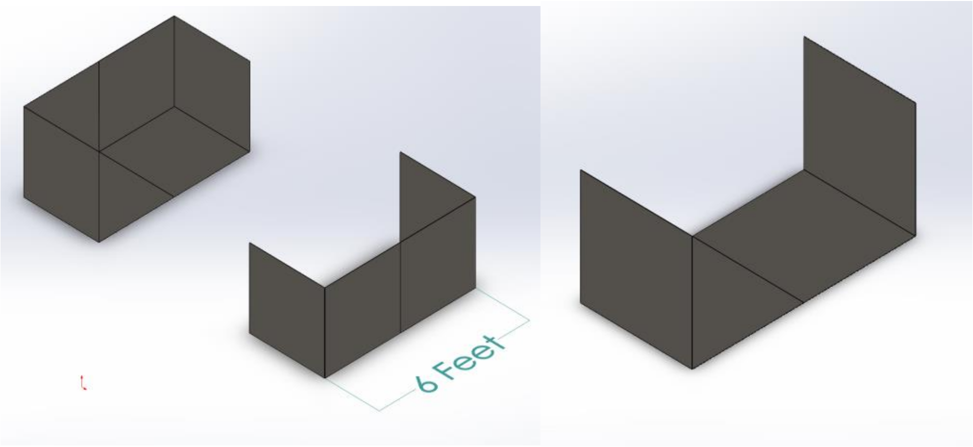


Figure 16: Left, the final product of modular end sections.
Right, the final product of modular middle sections

Much like the joining of butt joints on our frame, angle iron was used again to join the tank sections on the inside and out. Seen below on the left is the placement of welded angle iron on the outside of the flume sections, where the flume sections meet. In the middle is where angle iron has also been welded on the inside of the tank where the panels meet. On the right is an image of the nut and bolt driven through the angle iron on the outside of the tank, bringing the panels snugly together. Due to poor tolerancing of the stock material from the supplier, before the panels can be joined, a neoprene weather gasket is placed in all fastener-reliant joint seams to provide increased water retention for the tank.

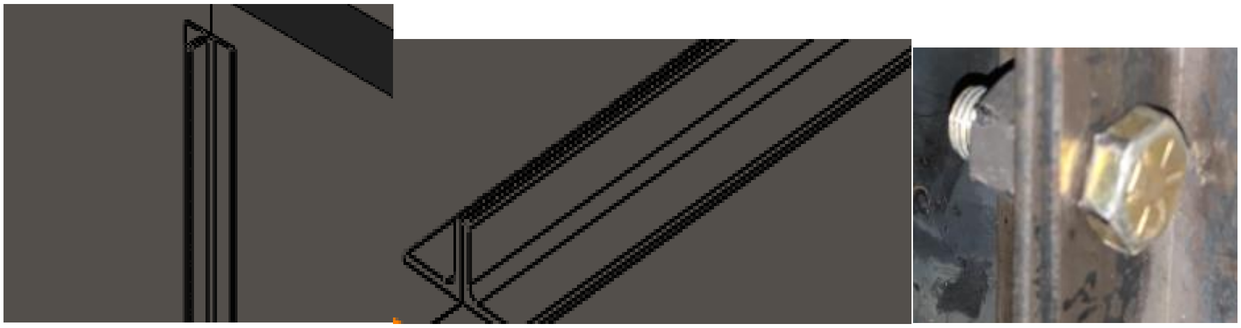


Figure 17: Left - Angle Iron for vertical mating of panels

Middle - Angle iron for horizontal mating of panels

Right - Nut and bolt used to bring together panels and angle iron

Once the frame was constructed, the buttresses were created. To properly position the buttresses, holes were drilled through the base plate material, as well as the I-Beam sections that extend beyond the tank walls. With these holes, the buttresses would be fastened down with a nut and bolt in a position that prevents excessive movement of the walls of the tank. The buttresses were formed by cutting triangles out of the steel panel stock material. The scrap material from this process was used as the base plate, and the vertical component is a rectangular tube. Seen below on the left is the welding of the triangular piece to the rectangular tube. On the right, the position and alignment of the buttresses can be seen, with the bolts driven up through the I-Beam, securing them in place.

Figure 18: Buttress being welded together

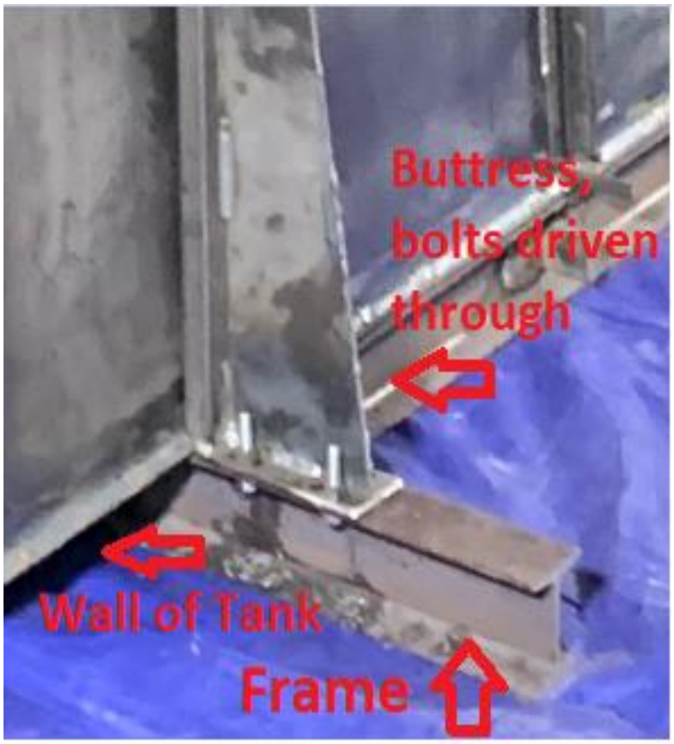


Figure 19: Placement of buttress on protruding I-Beam Frame

Seen below is the final paddle design. Triangular steel pieces are welded onto the paddle for increased strength, with rectangular strips of steel running perpendicular to these pieces for increased torsional rigidity. Leftover rectangular tubing was bored through to form a semi-circle shape that fits onto a stainless steel shaft, and this tubing was welded to the shaft and the paddle. At both ends of the stainless steel shaft, pillow blocks are attached. This design of the paddle allows for an acceptable range of motion for forming waves within the tank. Similar to how the buttresses were positioned, holes were drilled through the I-Beam frame, and subsequently through the tank itself. Gasketing material with holes is placed over the holes of the tank to prevent leaking, and bolts are driven through these. The holes of the pillow blocks then rest on the bolts and are secured with nuts. This secures the paddle in the tank, and because the bolts are driven through the frame as well, the paddle is very secure.

Figure 20: Paddle after assembly, being hoisted by a gantry into the tank

Synthesis and Analysis

When building a tank designed to hold 1000 gallons of water, our group knew every seam of the flume needed to be as close to watertight as possible. Therefore, the necessary time was taken to ensure that right-angle cuts were near-perfectly square and all bracing was strong enough to withstand the force of water when the tank was finally filled. Our group also worked within budget constraints by using materials donated by the Civil Engineering department from Kaven Hall.

To begin flume construction, the steel sheets were separated into groups based on how flat they were. When sheets are pulled and cut, they can warp and bend. It was important to keep the bending directions congruent with touching sheets to maximize surface area along seams, therefore allowing a more watertight seal to be formed between them. It was also recommended by our co-advisor that we leave one-quarter inch spacing along the bottom seams of each section to allow for better welds. Without these one-quarter inch spacing, both sides of the right angle panel connections could not be welded.

For the frame, bevels were cut between each I-beam joint to leave enough space for the gasket when the tank would eventually be completed. After completing the frame, the material used on the buttresses was doubled to increase strength and create more surface area for welding the buttress components together.

Welding the angle iron to each inside and outside seam of the flume was done systematically to make sure that the angle iron would pull each seam tight enough to prevent leaks but with enough space for the gasket to fit. Holes for the bolts were also drilled while the angle iron was attached to the flume to prevent misalignment when screws would eventually be put in to further tighten the seam around the gasket.

To attach the constructed buttresses, each buttress bottom was aligned with its partner I-beam and aligned to drill holes between the two. The buttress and I-beam were then labeled to allow both of them to be matched in the future since the holes were drilled specifically for each.

To construct the paddle, an extra strip of sheet metal was welded to the top surface for increased torsional strength against the movement of water. A steel bar was also used for attaching the paddle to the bottom of the tank, further increasing torsional strength. Based on the steel bar's rigidity, no additional center pillow block was needed for the paddle bottom. One pillow block on either end of the bar connected the steel bar to the tank. These pillow blocks were centered one-half inch from the outer tank walls to prevent friction during paddle motion.

These design choices were made during the build and served to enhance the strength and mobility of the wave tank. While our group did not have prior experience in welding and construction of such a large tank, our co-advisor assisted in changing some of our original build plans to better suit the requirements of the project.

Conclusions and Recommendations

The first test of filling the tank with water was a success. Certain joints in the tank were prone to leakage due to difficult gasket placement as well as welding imperfections, but this would be improved with better-sized gaskets and more welding at joints. An addition of adhesive gaskets will also make the build process much more realistic with only two or three people. A sealant for the welds will also assist in water retention by covering any micro-imperfections in the flume corners. Main components like the tank walls and buttresses did not allow any leaking during the use of the paddle, as they were reinforced throughout the building process. The secondary containment was torn at points throughout the construction process, so a more tear-resistant tarp will need to be used for future tests.

Pumping water in and out of the tank did not meet any challenges. While the deluge system had not been properly tested due to building time constraints, tests of the pump showed that enough pressure was generated to efficiently cool the tank walls during burn experiments. Due to a mistake in ordering the pump filter, a higher flow-rate filter was ordered in place of the original. Finally, the paddle motor will need to be tested before burn experiments can be run. This component is scheduled to be tested in the coming weeks when the first burn experiment is conducted, however, it has been calculated to properly move the paddle under forces generated by 1000 gallons of water.

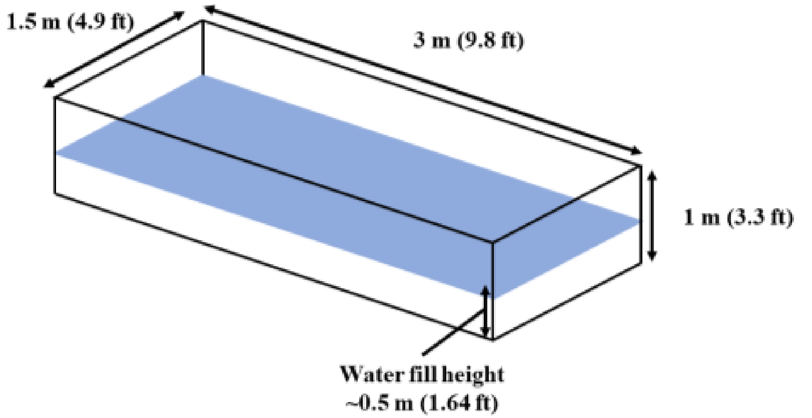
Appendices

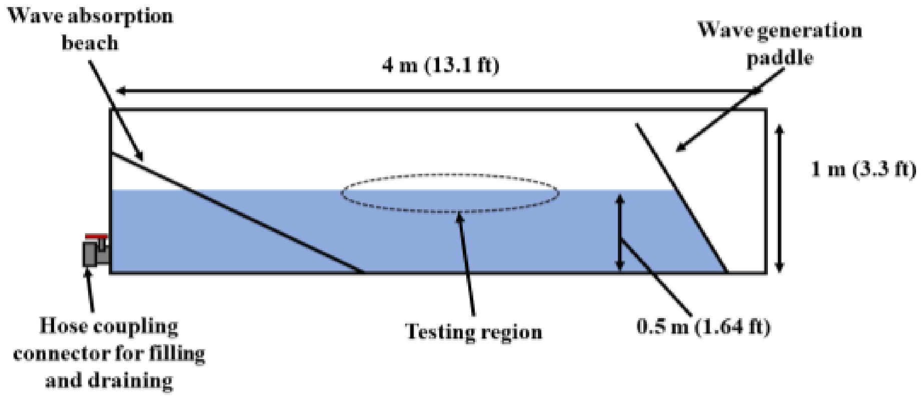
Appendix A: Initial Design Requirements

Tentative dimensions of the tank:
1.5 m wide (4.9 feet) x 4 m long (13.1 feet) x 1 m (3.3 feet) tall walls
Water will only be filled to a 0.5 m (1.64 ft) depth, as this is shallow enough for a person wearing waders/ boots to stand in if needed. At these dimensions the tank will hold 793 gallons (3 m^3), and the water weight alone will be 6614 lbs (3000 kg). Dimensions could be increased to 2m wide x 4m long x 1.5m high (0.8 m fill depth. Although this would require 1690 gallons to fill.

Wave-tank must be able to:

- Accommodate a 50 cm diameter fire with ample room between the pool and tank to allow for fuel containment, instrumentation, and movement
- Withstand harsh conditions (multiple high-intensity fires, corrosive environments, harsh chemicals etc.)
- Be relatively modular, the smaller the storage footprint the better
- Have equipment and instrumentation mounted with relative ease anywhere on/in the tank
- Wave generation method needs to be computer controllable
- Have filling and draining point(s) for easy setup and breakdown





Appendix B: Deluge Calculations

Deluge Calculation:

In order to prevent the thin sheet metal walls of the tank from warping or failing, it was concluded that a deluge (cooling) system would be necessary. Our problem was modeled to find the rate of water flow necessary on the tank walls to prevent deformation. By modeling the process of burning oil near, but not in contact with the walls, we concluded that only radiation would be taken into account.

In Chapter 11, Section 3.3 (Radiation) of the text “Fundamentals of Fire Phenomena”[1] it is stated “If the object is the wall itself, then Equation (11.13) simplifies to the rate of radiation received by the wall as” :

$$\dot{q}_{\mathrm{r}} = \frac{A\sigma(T^4 - T_{\mathrm{w}}^4)}{1/\epsilon_{\mathrm{g}} + 1/\epsilon_{\mathrm{w}} - 1} \tag{11.14}$$

Where A signifies area, sigma signifies the Stefan Boltzmann constant, and

ϵ_{w} = emissivity of the wall

ϵ_{g} = emissivity of the gas

T = target temperature

T_{w} = wall temperature

The text further elaborates that the emissivity of the wall can be set to a value of 1, and that the emissivity of the wall can be set to a value of 0.5 for small-scale laboratory tests. Knowing this, we calculated the net radiation flux on the walls, and used that flux to find the necessary water amount. Burning oil temperature was found, and room temperature was used.

$$A_{Tank} = 36ft(Perimeter) * 1.5ft(Exposed\ Wall) * 0.0929(ft^2\ to\ m^2\ conversion) = 5.0167m^2$$

$$q_r = \frac{(5.0167m^2)(5.67*10^{-8})(1273^4 - 294^4)}{2} = 372,437\ \frac{J}{S}$$

With this information, we can use the heat of vaporization for water to find the necessary water flow rate.

$$(372,437\ \frac{J}{S})(\frac{1g\ H_20}{2257\ J}) = 165.01\frac{g}{s} = 0.165\frac{Liters(H_20)}{s}$$

Therefore, we now know the necessary water flow rate to cool the walls of the tank, being 0.165 liters / second, or 9.9 liters / minute.

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[1] “Compartment Fires.” *Fundamentals of Fire Phenomena*, by J. G. Quintiere, Wiley, 2006, pp. 349–350.

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