University of Arkansas, Fayetteville

ScholarWorks@UARK

5-2019

Scale Model and Flow Visualization of Jack Rabbit II Chlorine Field Test

Charlotte Williams
University of Arkansas, Fayetteville

Follow this and additional works at: https://scholarworks.uark.edu/cheguht

Part of the Other Chemical Engineering Commons

Citation

Scale Model and Flow Visualization of Jack Rabbit II Chlorine Field Test

An Undergraduate Honors Thesis

in the

Ralph E. Martin Department of Chemical Engineering

College of Engineering

University of Arkansas

Fayetteville, Arkansas

By

Charlotte Williams

Abstract

The release of hazardous gases, especially accidental releases, can have a major impact on the surrounding environment and population. The history of accidental hazardous gas releases is filled with plant destruction, civilian injury, and even death. Knowledge of how these gases travel and disperse once released can significantly lessen physical harm and improve emergency procedures. The Jack Rabbit II field test was conducted in pursuit of this knowledge for a chlorine release. In this field test, a purpose-built chlorine tank was surrounded by CONEX trailers assembled in the desert in Utah to model an urban setting. Multiple releases of chlorine in this setting were conducted, and the concentrations downwind were measured and analyzed. Because of the limitations of field tests, a wind tunnel model of this field test program would be beneficial. Such model testing would allow for more releases while changing many of the test variables. A wind tunnel model would have repeatable tests, allowing for ensemble averages to improve data. In pursuit of this goal, a 1:50 scale model of the field test was created. Once the model was complete, several preliminary tests were conducted to test the design of the experiment. Using fog to represent chlorine, videos of these preliminary tests were obtained and compared to the field test videos.

1. Introduction

Hazardous gases are an important topic in chemical process safety. Accidental releases of hazardous gases pose a serious threat to the surrounding areas; both civilization and the environment can be severely harmed. The ability to model and predict the dispersion of the accidental releases of hazardous gases would significantly improve safety measures taken and possibly help prevent serious collateral damage. The worst-case scenario for a hazardous gas release is a release at low wind speeds. Low wind speeds are associated with decreased turbulence, which allows the hazardous gas to dissipate very slowly. Because of this, these releases have a larger impacted area that could be harmed.

A plant in Flixborough, England exploded in 1974 due to a sudden release of cyclohexane. A cloud of approximately 30 tons of cyclohexane was ignited and destroyed the plant, resulting in 28 casualties, 36 injuries, and a 10-day fire at the plant. The consequences of this explosion were mitigated by the fact it occurred on a weekend. However, the surrounding civilian population was still affected: approximately "1821 nearby houses and 167 shops and factories" were damaged, and "53 civilians were reported injured." In 1989 in Pasadena, Texas, there was an explosion in a "high-density polyethylene plant" as seen in Figure 1. An 85,000-pound cloud of ethylene, isobutane, hexane, and hydrogen was accidentally released and ignited.

Figure 1: Pasadena Explosion 1984 *[1]*

This explosion "resulted in 23 fatalities, 314 injuries, and capital losses of over $715 million."

For a third example, consider a plant in Bhopal, India that produces methyl isocyanate (MIC) as

an intermediate chemical. In 1984, the MIC unit was nonoperational, and an undesired reaction

caused an accidental release of about 25 tons of MIC vapor. "The toxic cloud spread to the

adjacent town, killing over 2000 civilians and injuring an estimated 20,000 more." [2]

In order to model hazardous gas releases, different types of testing must be used. One of

the most common types of testing is full-scale field tests. Full-scale field tests involve replicating

or designing a hazardous gas release in an area that is controllable. However, full-scale field tests

have several disadvantages. Field tests are big, expensive, dangerous and not repeatable due to

the nature of atmospheric turbulence. It is expensive to create a full-scale model of the release,

including the materials. Field tests are dangerous because they are an actual release into the

atmosphere with the potential to harm people and the environment. Measures are taken to

minimize this risk by performing the tests in an isolated area. The main disadvantage of field

tests is that they are not repeatable and represent a single, unique realization of the release.

Because of this, no ensemble averaging can be done, and a single test must be assumed to be

completely representative. Field tests are only a snapshot of what the release could possibly look like and therefore may not be a complete representation of the average behavior expected during a release.

Due to the disadvantages of full-scale field tests, wind tunnel scaled tests are often conducted instead. Wind tunnel tests have the benefit of being repeatable, thus allowing for multiple releases. From this, the data from the tests can be checked for errors, and it is possible to make ensemble averages for improved data. In addition, the testing conditions are much easier to control in a wind tunnel than in a field test. However, the scaling of the wind tunnel test and the release must be accurate in order to provide correct data.

Modeling gas flow in a wind tunnel is a broad area of research in that there are many different wind tunnel applications. It can range from extreme conditions, such as supersonic flow with combustion, to atmospheric conditions with ultra-low-speed air flow. Russia alone has 44 wind tunnels that operate at speeds greater than Mach 1, several of which model jet engines to determine the aerodynamic forces [3]. The Von Karman Institute for Fluid Dynamics uses a low speed wind tunnel to model the exhaust exiting a road vehicle [4]. The world's largest ultra-low speed wind tunnel at the Chemical Hazards Research Center (CHRC) at the University of Arkansas has modeled previous gas releases, such as the methylisocyanate release in Bhopal, India. [5] The ultra-low speed wind tunnel tests are of particular interest because they model the worst-case scenario for wind conditions of a hazardous gas release.

In addition to the Bhopal incident, the CHRC wind tunnel was used to model the dispersion of a finite duration release of gas from an area source. Jessica Morris PhD modeled the dispersion of a cloud of a finite release as it traveled down the tunnel at atmospheric, ultra-low wind speeds. The experimental parameters included the release duration, wind speed, and

distance downwind for concentration measurement. Using both Laser Doppler Velocimetry (LDV) and Flame Ionization Detector (FID), the concentration time history during each release and vertical velocity profiles were measured for each variation of testing conditions. [6]

The Jack Rabbit II field test was a full-scale field test conducted to study how chlorine traveled and dispersed once released. In this field test, a chlorine tank was surrounded by CONEX trailers assembled in the desert in Utah in order to model an urban setting. Multiple releases of chlorine in this setting were conducted, and the concentrations downwind were analyzed [7]. The objective of this study was to create a scale model of the field test setting and perform flow visualization. Once the model was complete, several preliminary tests were conducted to test the design of the model. Using fog to represent chlorine, videos of these preliminary tests were obtained and compared to the field test videos.

2. Model Setup

2.1 Scaling

To model the Jack Rabbit II experiments, a 1:50 length scale was used. Dimensions of the trailers and the gravel pad were divided by 50 to achieve the proper model size. Other variables were scaled using the Froude number was used to relate the field test and the model. Froude number is a dimensionless ratio that describes flow in an open channel.

$$Fr = \frac{V}{\sqrt{g * L}}$$

In the Froude number, V is a characteristic velocity (m/s), g is the acceleration of gravity (m/s^2), and L is some characteristic length (m) [8]. In order to calculate the model numbers, the field test and model Froude numbers were set equal to each other, where the subscript f means field test and the subscript m means model.

$$Fr_f = Fr_m$$

$$\frac{V_f}{\sqrt{g_f * L_f}} = \frac{V_m}{\sqrt{g_m * L_m}}$$

Since gravity is the same in both the field test and the model, it can be removed from this relation.

$$\frac{V_f}{\sqrt{L_f}} = \frac{V_m}{\sqrt{L_m}}$$

Because the model is a 1:50 scale, the characteristic lengths will always be $L_f = 50 * L_m$. Thus, the relation can be simplified further.

$$\frac{V_f}{\sqrt{50}} = \frac{V_m}{\sqrt{1}}$$

$$\frac{V_f}{\sqrt{50}} = V_m$$

This relationship was used to scale the wind speed and time in the tunnel tests.

2.2 Physical Model

The floor of the wind tunnel acted as the desert playa in the field test. A 600 ft by 400 ft elevated gravel pad on which the releases were conducted was constructed on site aligned with the historical prevailing wind direction. At the center of the gravel pad, a concrete pad was constructed where the chlorine was released. To replicate the gravel pad, 3/8 in. thick plywood was used that matched the elevation of the gravel pad. This provided a total pad area of eight feet wide and twelve feet long in the wind tunnel. The plywood was painted a brown-grey color to appear more like the gravel pad. Surface roughness along the wind tunnel floor creates turbulence similar to that of normal atmospheric conditions.

The main feature of the model was 83 trailers on the gravel pad during the 2015 test season. The dimensions of each of the trailers from the field test were provided and scaled to

determine the proper dimensions for the scale model. In the field test, the trailers were not all the same size, varied in length, width and height. Because of this, the model trailers were both O-scale train model trailers and aluminum bar that was cut and milled to the proper size.
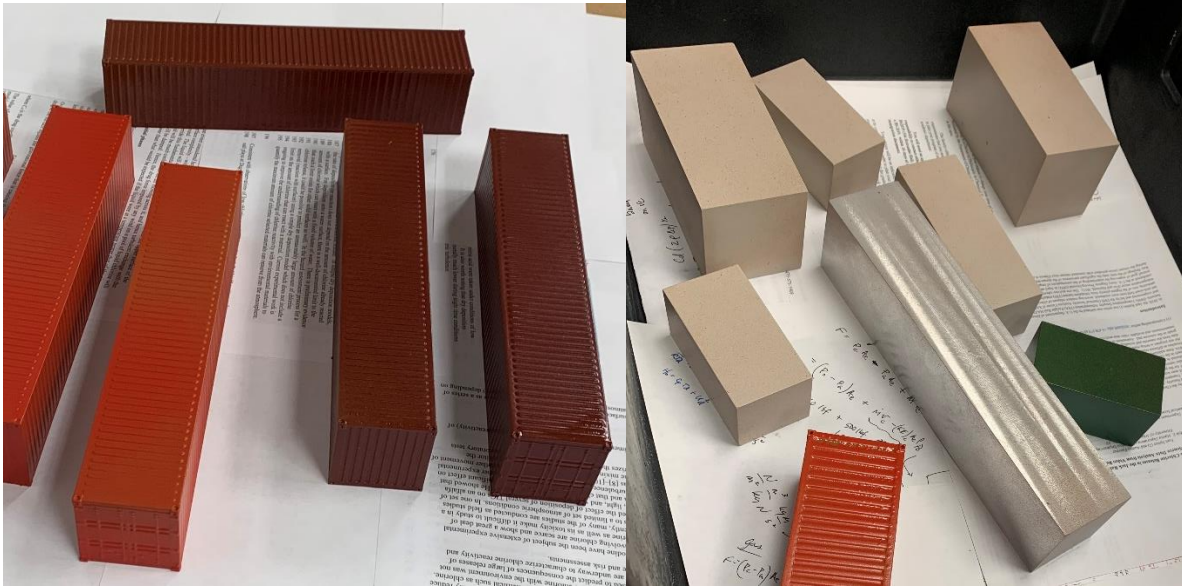

Figure 2: O-Scale Train Model (Left) and Aluminum Bar (Right) Trailers

O-scale train models are on a 1:48 scale. However, detailed measurements of their dimensions showed that these train model trailers matched some of the trailers in the model. The O-scale train model trailers were used when available, and aluminum bar was used to make the remaining trailers. To make the model look more like the field test, the trailers were colored appropriately. The O-scale train model trailers and some of the odd shaped aluminum bar trailers were spray painted as shown in Figure 2. The rest of the aluminum bar trailers were covered in paper model printouts. A train model website had a file of 150 printable trailers in O-scale [9]. The approximate matching colors were printed, cut, and glued over the aluminum bar as shown in the figure below.

Figure 3: Paper Covered Aluminum Bar Trailers

From the provided GPS coordinates of the four corners of each trailer, the location of all 83

trailers was marked on the plywood. These locations are outlined in the model layout on the next
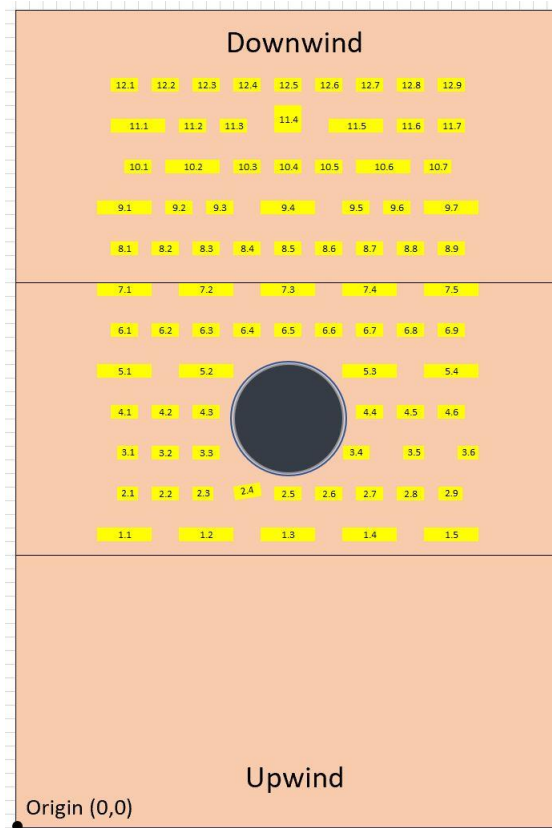
page.

Figure 4: Model Layout

In this figure, the yellow boxes represent the trailers. The dark filled circle is the concrete pad hole cut into the plywood.

The field test was a point source release of chlorine from the bottom of the tank. Due to the wind tunnel setup, this could not be replicated exactly. Instead of a point source release, the model used an area source release from the area source box. Because of this, the field test cannot be replicated over the area source, so the control volume for the experiment is outside of the plexiglass disc (blue circle shown in Figure 4). In the model, the flow would enter vertically into the wind tunnel from the area source box underneath the wind tunnel. A circle with a diameter of 19.75 inches, which was the scaled size of the concrete pad that the tank stood on, was cut into the plywood to allow the flow in. The flow would then encounter the plexiglass disc, forcing the flow to move outward as observed in the 2015 field tests. The plexiglass disc was cut in a circle

with a diameter of 21.5 inches so that it was slightly larger than the circle in the plywood, ensuring that the flow near the edge of the disc would not continue directly vertical. In order to control the height of the flow release in the model, the plexiglass disc was held up on three threaded rods and nuts as seen in the figure below.
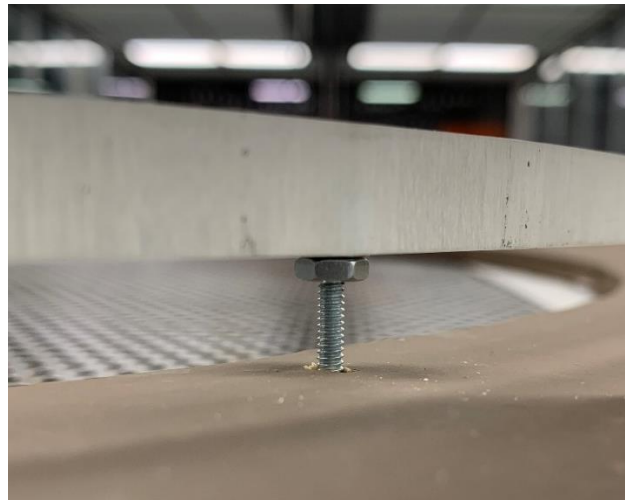

Figure 5: Plexiglass Disc Setup

This setup allowed for easy adjustment of the height of the plexiglass disc. The threaded rods selected had a small diameter (#4 screws) to minimize the effect on the flow while still large enough to support the weight of the plexiglass. Because of the necessary setup with the plexiglass disc, the model cannot replicate the field test inside of the concrete pad. Therefore, the control volume of the model is outside of the plexiglass disc.

Once all the pieces were assembled, the model was then constructed and placed in the wind tunnel as seen below.

Figure 6: Model

3. Experiment

It was possible to replicate the first four trials of the Jack Rabbit II field test using the model in the wind tunnel. The selection of which trial to attempt to replicate first was based on cameras, wind direction, and wind speed. Trial 2 was eliminated because it was missing cameras 1-4, as seen in Figure 12. With the remaining three trials, the average wind speeds and directions were compared to determine the optimum first experiment conditions.

Table 1: Comparison of Wind Conditions by Trial

Trial	Avg Wind Speed (m/s)	Avg Wind Direction (°)	Angle from Pad Normal: 345°
1	1.45	147.4	17.6
3	3.77	169.5	-4.5
4	1.77	196.3	-31.3

The wind direction was the angle from which the wind originated. The "Angle from Pad Normal" was determined by adding 180° to the wind direction, then subtracting the wind direction from the pad direction (345°). This difference is important because that is the angle that the model must be rotated in the wind tunnel to achieve the proper wind direction across the gravel pad. Trial 1 was selected due to its low wind speed and small angle (17.6°) correction.

3.1 Wind

In the field test, wind measurements were at a height of two meters at several locations. For each trial, a single wind speed and direction was selected as the most accurate representation of the test. The chosen wind speed and direction measurements were taken just prior to the test start. The calculations for the model were done based on these selected values. The scaled value for the height of the wind measurements is four centimeters. The appropriate wind speed of the tunnel had to be determined at this height to match the field test. Using Froude number scaling, the wind speed for the model can be determined with the wind speed from the field test as shown below.

$$V_m = \frac{V_f}{\sqrt{50}} = \frac{1.45 \, m/s}{\sqrt{50}} = 0.205 \, m/s$$

From this, the wind speed in the wind tunnel at 4 cm high had to be 0.205 m/s. However, the fans of the wind tunnel are controlled by RPM input data. Based on previous tests conducted in the

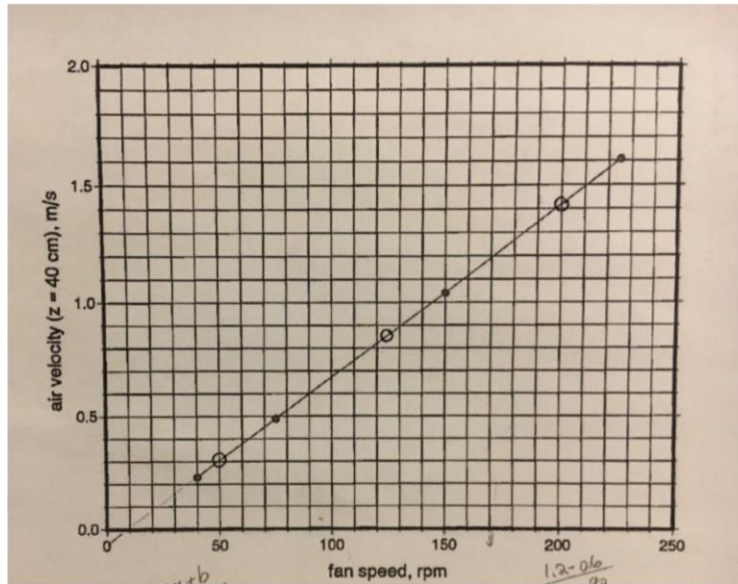wind tunnel, the relationship between velocity and RPM is relatively linear as seen in the figure below.

Figure 7: Wind Tunnel Fan Speed vs Velocity [6]

A previous test conducted with Laser Doppler Velocimetry (LDV) developed a velocity profile of the wind tunnel at 50 and 90 RPM. Some of the data points from this test were taken at 3 cm and 6 cm. Using an exponential relationship, the wind speeds at 4 cm were approximated at 0.192 m/s and 0.404 m/s for 50 and 90 RPM respectively [6]. From these values, the appropriate fan RPM for this experiment could be interpolated as follows.

$$\frac{(x - 50)\ RPM}{(90 - 50)\ RPM} = \frac{(0.205 - 0.192)\ m/s}{(0.404 - 0.192)\ m/s}$$

$$\frac{x - 50}{40} = \frac{0.013}{0.212}$$

$$x = 52.45\ RPM$$

Based on these calculations, the fans were set to 53 RPM during the experiment.

Since the wind direction was not parallel to the gravel pad during the field test, the model needed to be rotated in the wind tunnel. In the field tests, the gravel pad was directed at 345°,

13

with North at 360°. In Trial 1, the wind was coming from an angle of 147.4°, but 180 degrees was added to this value to better relate it to the pad direction. Thus, the wind was aimed at 327.4°, which was θ=17.6° from the pad centerline as shown in the figure below.
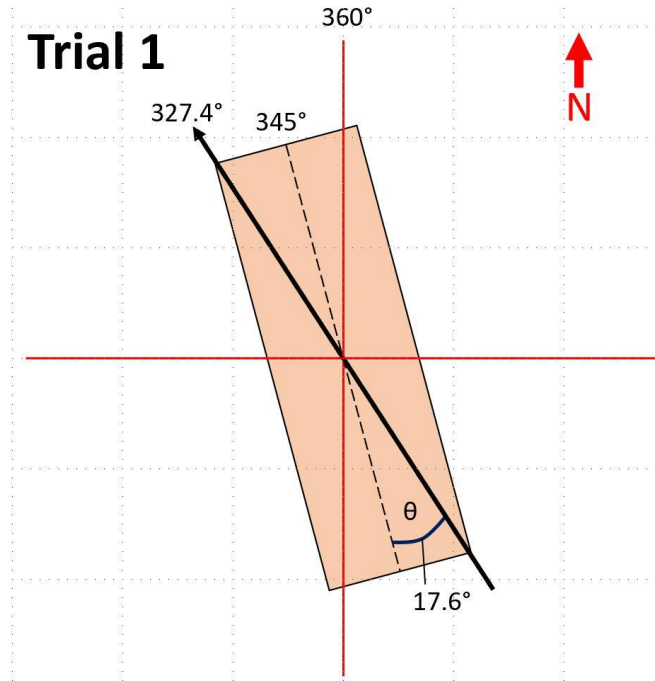

Figure 8: Trial 1 Model Rotation

This meant that the model in the wind tunnel needed to be rotated 17.6° clockwise. The rotation angle of the model in the wind tunnel was checked with both a protractor and trigonometric measurements.

3.2 Flow

To avoid the hazards associated with chlorine and to allow for good flow visualization, fog was added to the flow of the release in the model. For the initial tests, the fog was produced from a Rosco 1500 fog machine. The fog used for the final tests was produced from a Virhuck 400W fog machine.
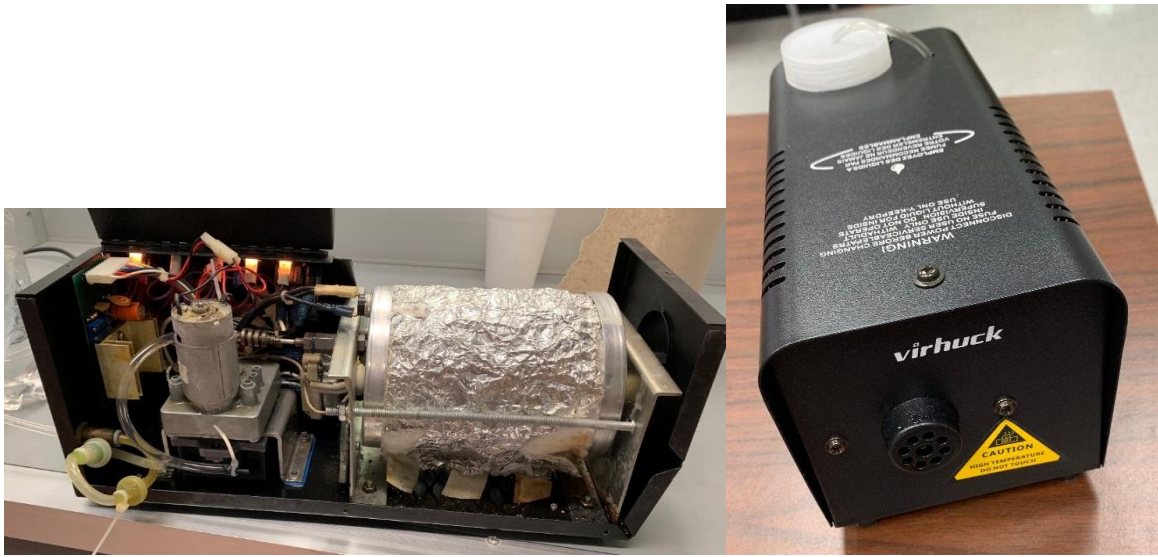
Figure 9: Rosco 1500 Fog Machine (Left) and Virhuck 400W Fog Machine (Right)

The fog fluid run through the machine differed for each test set. For Test Set 1, the fog fluid was a solution of 50% glycerin and 50% water. This solution produced opaque fog, but it was not very dense. This solution also caused clogging problems in the fog machine so that the machine had to be cleansed with water after each use and regularly taken apart for maintenance, such as replacing damaged tubing. For Test Set 2, the Rosco fog fluid designed for the machine was used. This fluid produced a denser fog cloud and did not clog the machine like the glycerin solution due to the additives in the fluid. For Test Set 3, the fluid was switched to the CryoFreeze fluid (1,2-propylene glycol and water) in the Virhuck fog machine. This fluid produced a denser fog cloud than the Rosco fluid produced and had denser-than-air effects. The denser fog is desired in order to better replicate the field test videos and to produce clear flow visualization.

Once the fog was produced from the fog machine, it eventually traveled into the area source box. The area source box was a metal box connected to the bottom of the wind tunnel. The top of the box was a sheet full of tiny holes. When the box was open, the fog in the box was allowed to flow into the tunnel. When the box was shut, the holes at the top of the box were

blocked to prevent fog entering the tunnel. Instead, two slats on the sides of the box opened, allowing the excess fog to dump out underneath the tunnel.

The fog took different paths to the area source box depending on the test set. In each test set, the fog was transported to the area source box by means of a dryer hose. In Test Set 1, the fog traveled down the hose straight into the bottom of the area source box. In Test Set 2 and 3, the fog in the dryer hose was sent through a chiller before entering the area source box.

Figure 10: Fog Chiller

The figure above shows the fog chiller before it was prepped for a test. In order to cool the fog, the blue bucket of the chiller was filled with ice. The surface area of the hose in contact the ice ensured maximum chilling in a short amount of time. Chilling the fog had the desired effect of producing a denser fog cloud that remained closer to the ground during tests.

Because of low flow rate production from the Rosco fog machine in Test Sets 1 and 2, the fog couldn't rise out of the area source box into the wind tunnel. A fan had to be placed directly in front of the Rosco fog machine to force the fog through the hose and up into the area source. However, this fan only had an on/off switch. To control the fan speed, and thus the flowrate, the fan was connected to a VARIAC transformer.

Figure 11: VARIAC Transformer

The VARIAC adjusted the input voltage to the fan to control the fan speed. The VARIAC was set to approximately 50 volts to force the fog into the area source box. The fan was not necessary for Test Set 3.

3.3 Cameras

The camcorder used in the experiment was a Canon VIXIA G10. For this experiment, three camera locations were selected to record the releases. From the twelve possible cameras, Cameras 1, 4, and 9 were chosen for their overview of the test area and variation in perspective. The approximate locations for these cameras can be seen in the figure on the next page.
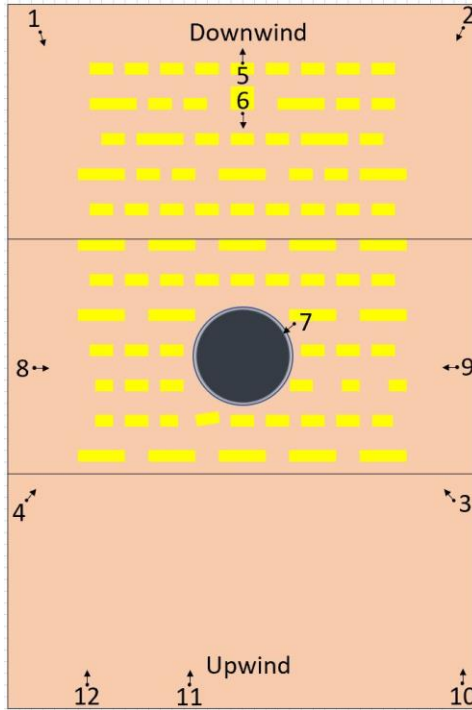
Figure 12: Approximate Camera Locations

The cameras' GPS coordinates provided from the field test were used to determine the location

for the cameras in the model.

Table 2: Initial Model Camera Locations

	Field Test			Model		
	From Origin		From Ground	From Origin		From Floor
Camera	x (ft)	y (ft)	z (ft)	x (in)	y (in)	z (in)
1	-30.53	646.62	30	-7.33	155.19	7.2
4	-33.28	130.52	30	-7.99	31.32	7.2
9	565.76	287.56	5	135.78	69.02	0

These locations were marked with in the wind tunnel to allow for easy transition between camera

locations. For Camera 9, the camcorder was simply placed on the floor to achieve the right

elevation. For Cameras 1 and 4, the camcorder was placed on a tripod. These cameras needed to

be at 7.2 inches high off the floor. However, the minimum height of this tripod was 12.56 inches.

18

Figure 13: Camera on Tripod

To determine the correct camera locations at the tripod height, trigonometry was used in order to place the cameras at a greater distance from the pad while maintaining the same camera angle. These calculations can be found in the appendix, and the results are summarized in the table below.

Table 3: Final Model Camera Locations

	From bottom left corner of board 1		From floor
Camera	x (in)	y (in)	z (in)
1	-25.68	182.99	12.56
4	-37.16	8.24	12.56
9	135.78	69.02	0

Once cameras 1 and 4 were placed in the new extended location, the zoom feature was utilized to create the same viewing area as in the field tests. Because of this, the view between model and field test are very similar, but not exactly the same.

4. Flow Visualization

Each test in the wind tunnel followed approximately the same procedure. The wind tunnel was started at least 30 minutes before the tests began to allow the fans to stabilize. After placing the camcorder in the desired location, the camcorder started recording, and the fog machine was turned on. Then the wind tunnel room was completely closed for 15 minutes to allow the wind flow through the room to stabilize. Once the room was stable, the fog machine was started from the control room with a remote controller. In Test Sets 1 and 2, the Rosco fog machine continued to produce fog for approximately 30 seconds to allow the area source box to fill with fog. In Test Set 3, the Virhuck fog machine continued to produce fog for only 6-8 seconds because it produced a higher flow rate than the Rosco fog machine.

The release of chlorine in the field test was estimated to last for 35 seconds. For the model, the release time was scaled using the Froude number.

$$t_m = \frac{t_f}{\sqrt{50}} = \frac{35 \ s}{\sqrt{50}} = 5 \ s$$

Once the testing began, it was noticed that a release time of 5 seconds was not long enough for the fog to fully disperse like in the field test. Because of this, an unscaled released time of 35 seconds was used. Using an Arduino control system in the model test, the area source box was then opened for 35 seconds with fog continuously flowing into the tunnel during this time. After the 35 seconds passed, the area source box shut, cutting of the fog flow and allowing any remaining fog to be dumped underneath the tunnel. Once the box shut, the fog machine was stopped via remote control. Approximately one minute after the area source box shut, the test was complete. This time was determined to be enough for the fog to clear the model, thus allowing for a complete video. Once the test was complete, the room evacuation began. Evacuation entailed stopping the camcorder, unplugging the fog machine to avoid unnecessary

heating, and starting the exhaust system. The exhaust system removed the fog from the room, preventing a buildup of fog as the testing continued. The fog evacuation lasted about 10-15 minutes. The camcorder was moved to the next location during this time as well. Once evacuation was complete, the cycle started over again, beginning with closing off the wind tunnel room for restabilization. Due to the required stabilization of the wind tunnel room, the initial recordings for each test were approximately 25 minutes long. Before analysis, the videos were trimmed to include a few seconds before and after the test duration, and thus are about 1 minute and 45 seconds long.

4.1 Initial Testing

In Test Sets 1 and 2, the Rosco 1500 was used to produce fog into the tunnel. The fog fluid for the first test set was the 50% glycerin solution. In Test Set 2, the fog fluid used was the Rosco fog fluid.

Figure 14: Camera 4 in Test Set 1 (Left) and Test Set 2 (Right)

The figure above contains snapshots of the camera 4 tests from the initial testing. When comparing the two videos, it is apparent that the second test set with the Rosco fog fluid produced a slightly denser fog flow than in the first test set. The red lines in Figure 14 show the height that the fog rose above the model. Unlike the chlorine in the field test, the fog in the scale model continued to rise after release. This was improved upon in the final testing.

4.2 Final Testing

In Test Set 3, the CryoFreeze fluid was used by the Virhuck 400W fog machine to produce fog for the test.

Figure 15: Camera 4 in Test Set 2 (Left) and Test Set 3 (Right)

As seen in the video comparison above, the Virhuck fog machine in Test Set 3 produced a much denser fog flow than the Rosco fog machine did in Test Set 2. In the third test set, the fog behaved more like the chlorine from the field test in that it remained closer to the ground.

To completely compare the scale model to the field test, each camera recording was compared to that of the first trial of the field test.

Figure 16: Camera 1 in Field Test (Left) and Model (Right)

In order to compare the videos from Camera 1, the videos were stopped when the flow reached the edge of the green trailer marked in Figure 16 by the red arrow. In the field test, it took the chlorine 7 seconds to reach the edge of the green trailer. In the model, it took the fog 8 seconds

to reach the edge of the green trailer. This shows that the flowrate of the fog in the model is a bit lower than the flowrate of the chlorine in the field test. The videos were also used to compare the rising height of the flow. The height of the flow is marked by a red line in Figure 16. The height of the chlorine above the green trailer in the field test is 0.9cm. The height of the fog above the green trailer in the model is 1.3cm. The measurements for the height of the flow were taken from the videos, which is why measurements are so small. This will also be true for the rest of the camera video comparisons.

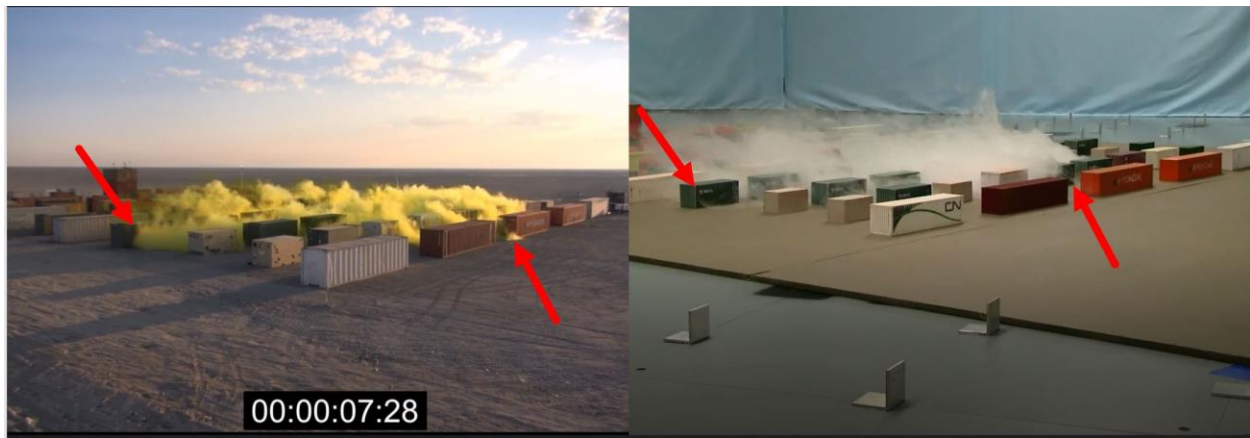Next, the videos recorded from Camera 4 were compared.

Figure 17: Camera 4 in Field Test (Left) and Model (Right)

In order to compare the videos from Camera 4, the videos were stopped when the flow reached the edge of the green trailer marked in Figure 17. It took the chlorine 8 seconds to reach the left edge of the green trailer, but it took the fog 10 seconds. In addition, the fog at the edge of the green trailer is significantly less dense than the chlorine. At this same point in the videos, the upwind reach, marked in Figure 17, of the flow was compared. In the field test, the chlorine has just begun to reach past the first row of trailers. However, in the model the fog has only reached between the second and first rows of trailers. The fog in the model does eventually extend past the first row of trailers, but this does not occur until 14 seconds after the release.

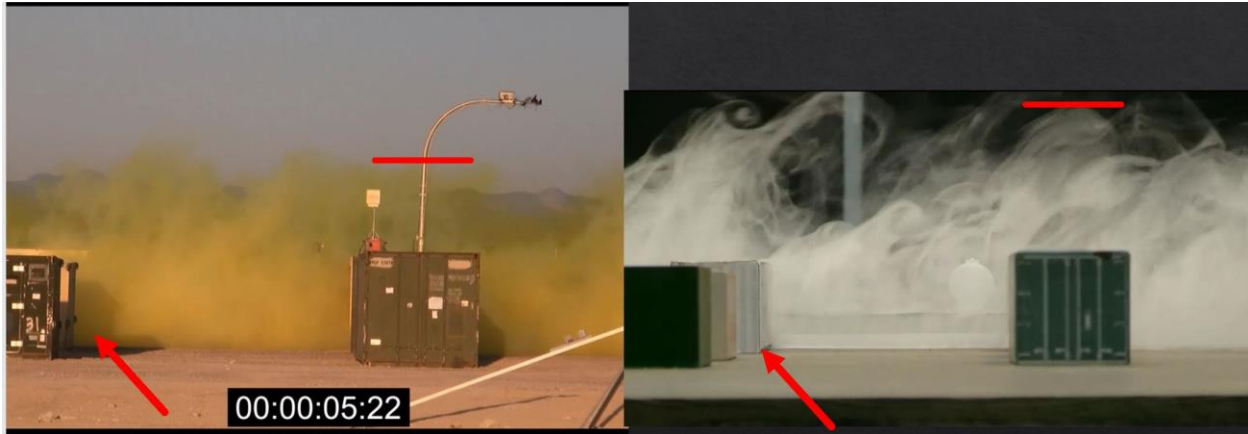Lastly, the videos recorded from Camera 9 were compared.

Figure 18: Camera 9 in Field Test (Left) and Model (Right)

Unlike with the first two cameras, the field test and model videos for Camera 9 were both stopped 6 seconds after the release. The point of comparison between the two videos is marked by the red arrow in Figure 18. In the field test video, the chlorine has clearly reached the end the white trailer. In the model video, the fog has not quite reached the end of the white trailer yet. The videos were also used to compare the rising height of the flow. The height of the flow is marked by a red line in Figure 18. The height of the chlorine above the green trailer in the field test is 1.4cm. The height of the fog above the green trailer in the model is 2.2cm.

5. Conclusions

A major issue with matching the model and field test videos is the density and the flowrate of the fog. The fog continued to rise instead of staying at ground level because it is lighter than air, unlike the chlorine. However, the fog in Test Set 3 showed improvement from that first two test sets in that the fog remained closer to the ground and thus was more similar to the field test. The low flowrate of fog in the model contributed to the inaccuracy in the dispersion of the fog flow compared to the chlorine in the field test. Because of the low flowrate, the fog did

not disperse to the same extent that the chlorine did, as seen in the time comparisons of the model and field test videos.

There is some uncertainty in analyzing the videos of the field test. The chlorine appears in both aerosol and gaseous form. Though the gaseous form has a green color, it is difficult to see, so most of the video comparison is based upon the visual appearance of the aerosol. Thus, the accuracy of the model in regard to the gas flow cannot be determined solely from videos. There is also error associated with the cameras used in the experiment. Since the camera used in the experiment is not the same type of camera used in the field tests, there are visual differences between the two sets of videos. For example, the camera used in the experiment seems to have a narrower field of view than the cameras used in the field test, so the view is not as wide at the proper zoom in the experimental videos. This could affect the video comparisons between the experiment and the field test. Overall, the majority of errors in relation to measurements were kept below 2% error in order to maintain accuracy to the field test.

6. Future Applications

This experiment has several options for improvement. The model wind speed was determined at 4cm, scaled down from the 2m wind speed measurement of the field test. The fan setting had to be interpolated from known data because the velocity profiles of the wind tunnel were taken at 3 and 6cm. A step to confirm this interpolation accuracy would be to use LDV to measure the velocity at 4cm.

A major improvement to the experiment is the plan to add a mixture of 36% SF_6 in air to the fog in order to better simulate the chlorine. SF_6 was selected because it is similar in molecular weight to chlorine, but it does not have the hazards associated with chlorine. Also, SF_6

can be measured by the existing equipment in the lab to produce concentration measurements. The SF_6 will be fed to the flow at the front of the fog machine so that there is ample mixing of SF_6 and fog prior to entering the area source box. SF_6 will add the appropriate density to the fog causing it to not rise up as it did in the experiment. The flowrate can then be matched to the scaled flowrate of the field test by the controlling the SF_6 flow instead of relying on the Virhuck fog machine flowrate. The flowrate of the model needs to match the flowrate of the chlorine at the edge of the concrete pad. Once the flowrate of the model matches that of the field test, the release time can then be properly scaled to 5 seconds.

This experiment is a preliminary effort to modeling the rest of the Jack Rabbit II field tests. By conducting several experiments using this setup, it is possible to reproduce the Jack Rabbit II field tests multiple times in the simulated environment. This allows for a full view of the field test and makes it possible to find time averages by conducting multiple releases. Once it is confirmed that the model can accurately replicate the Jack Rabbit II field tests, the model can be used to depict situations outside of the field tests. The ability to control multiple parameters allows for a wide range of possible simulations, which is ideal for predicting how a chlorine release will travel in a variety of situations.

References

[1] B. Allen, "Health and Safety at Work," 7 November 2011. [Online]. Available: https://www.healthandsafetyatwork.com/feature/phillips-66-lesson-learned-late. [Accessed 29 March 2019].

[2] D. A. Crowl and J. F. Louvar, "Seven Significant Disasters," in *Chemical Process Safety: Fundamentals with Applications*, Boston, Prentice Hall, 2011, pp. 23-29.

[3] Federal Research Division, "Wind Tunnels of the Eastern Hemisphere," Library of Congress, Washington, D.C., 2008.

[4] Von Karman Institute, "Von Karman Institute for Fluid Dynamics," [Online]. Available: https://www.vki.ac.be/index.php/research-consulting-mainmenu-107/facilities-other-menu-148/low-speed-wt-other-menu-151. [Accessed 04 2019].

[5] J. Havens, H. Walker and T. Spicer, "Bhopal atmospheric dispersion revisited," *Journal of Hazardous Materials,* pp. 33-40, 2012.

[6] J. M. Morris, "Experimentation and Modeling of the Effects of Along-Wind Dispersion on Cloud Characteristics of Finite-Duration Contaminant Releases in the Atmosphere," University of Arkansas, Fayetteville, 2018.

[7] D. Spicer, Interviewee, *Jack Rabbit II Field Test Information.* [Interview]. 04 2019.

[8] American Meteorological Society, "Froude Number," 12 12 2014. [Online]. Available: http://glossary.ametsoc.org/wiki/Froude_number. [Accessed 04 2019].

[9] Kraft Trains, "Build Your Own Free Printable 150 Types," [Online]. Available:

https://krafttrains.com/Paper_Struchers_for_Trains/O/Containers-

(O)/20ft_Containers/20ft_Containers-(O_Scale).htm. [Accessed 04 2019].

Appendix

cam 1

7.2   12.19

1.6

48.06

d

$d = 81.37$ in

(19.15, 115.08)

10.1

48.06

40.11

cam 1 (-7.33, 55.19)

26.48

81.37

67.91

cam 1 model
(-25.64, 182.99)

44.83

Y
X

cam 4

7.2   12.19

1.65

h   d

	X	Y
mark 3.3	34.1	64.63
cam 4	-7.99	31.32

trailer 3.3: 7mm → 8ft
dam 1mm
6mm → 6.86ft
↓
1.65 in model

image   field

image   model

trailer 3.3   1.2cm → 4.7in
.7cm → 2.75in add onto x of trailer

$h^2 = (-7.99 - 34.1)^2 + (31.32 - 64.63)^2$

$h = 53.68$ in → $d = 90.88$ in

3.3 mark (34.1, 64.63)

53.68

33.31

$\theta \approx 5.9°$

(-7.99, 31.32) cam 4   42.09

90.88

56.39

cam 4
model   71.26

(-37.16, 8.24)