

An Analysis of Oil Combustion on Snow

A Major Qualifying Project Report

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Abstract

In an effort to understand the possible outcomes of in-situ burning on snow and ice in Arctic regions, an experiment to study the effect of oil and snow in various conditions was proposed, conducted, and analyzed. Experiments were conducted with various ratios of oil to snow and with different spill diameters, while recording the snow packing densities. The influences of each of these three parameters were characterized and the groundwork for further investigation was drafted.

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1.0 Introduction

Large scale oil spills are fortunately not a common occurrence; however they do happen, and must be dealt with through various clean-up methods. One such method is in-situ burning, the burning of oil in place. The oil pool is bounded by a mechanism such as booms in the water and burnt off the surface. This is a common practice and was utilized in the BP *Deepwater Horizon* oil spill cleanup. This large spill took place in the ocean, where in-situ burning has been employed many times and is known to have very high burn efficiency. Currently, the oil industry is expanding rapidly, especially to large untapped oil reserves in the arctic regions of the world. These regions pose a new scenario for the in-situ burning of oil, as the oil spills are no longer on water. Instead these spills take place on ice and in snow, which are new variables. To study the effects of snow on the in-situ burning of oil, four parameters were identified, and can be seen in Figure 1-1. The project focused on studying the mass ratio of oil to snow, the porosity of snow, and the diameter of the spill in order to describe each parameters effects on in-situ burning characteristics including critical oil ratio, burn off efficiency, and mass loss/burn rate.

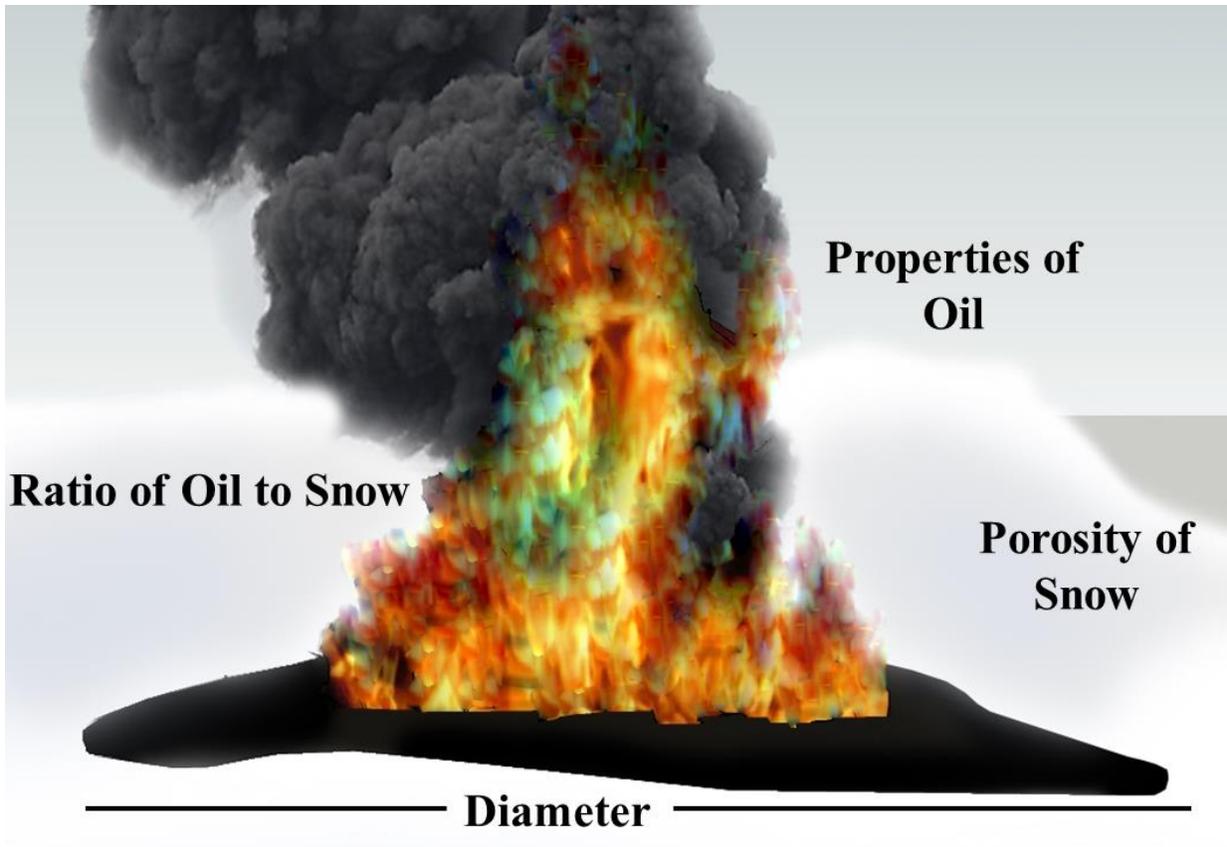


Figure 1-1: Parameters of In-situ Burning on Snow

2.0 Background

Oil spills have to be cleaned in a very efficient manner in order to prevent contamination and long term environmental damage. Oil spilled on open water can be mechanically removed and recovered with the use of a skimming device or sorbent material, as well as spraying the floating oil with a chemical dispersant which facilitates the emulsification of oil with water. However, other methods must be utilized when spills occur on ice or in other inaccessible areas. The forms of oil clean up most commonly used are recovery, dispersants and in-situ burning. In-situ burning in the arctic is when the spilled oil is confined to create a pool on top of snow or ice and then ignited. In the event of a spill Russia and the United States use in-situ burning, usually only if recovery is not a feasible option (WWF, *Oil Spill Response*). In-situ burning is gaining more popularity as an effective oil disposal method because of its high efficiency and environmental recovery.

In-situ burning has many benefits over mechanical recovery. In-situ burning is not as labor intensive in comparison to manual or mechanical recovery. Skimmers require the oil waste to be stored and disposed of properly, while in-situ burning only requires the disposal of the burn residue (WWF). In-situ burning is appropriate for ice and snow environments that the equipment needed for mechanical recovery cannot access, this is because it requires less labor, materials. In-situ burning, however, is impeded by high winds and cold temperatures which reduce the ability to conduct a safe and effective burn.

In-situ burning can occur on snow and ice as long as there is a sufficient oil layer that can be ignited. Ice is impenetrable to oil unless cracks are present or the oil is at a temperature which

can melt the ice, this provides a good surface for the oil to be contained and pool on. Snow on the other hand can absorb the oil because of its high porosity. When presented with an oil spill that has occurred over snow, the proper procedure is to pile the snow together and then ignite the oil. This only works if the oil present in the snow has a weight concentration 30% or greater (Potter & Buist, *In-situ Burning for Oil*). Sometimes an igniting fluid and an emulsion breaker might be required if the oil becomes too emulsified. Oil can also pool over ice slush which is common in the fall in the arctic because of the freezing and unfreezing of ice (Potter & Buist). In very thin oil layers the heat is transferred to the water in the snow and ice which can prevent the oil from being ignited (Fingas, *Review of Behavior*). The minimum oil layer required for ignition of fresh crude oil is 1mm, for weathered unemulsified crude oil or diesel fuel 2-5mm, and for heavy fuel oils 10mm (Potter, Buist & Trundel, *Spill Response*). The larger the oil layer the more that can burn, which will increase the overall efficiency. This is why a crude oil pool of 20 mm can burn at an efficiency of 95% which is greater than an oil layer of 5mm which can be done at 80%, this is because the oil layer burns down to the minimum height of ignition which in this case is 1mm. The surface area of the oil pool also affects the efficiency. Oil pools of over two meters in diameter can burn at over 90% efficiency (Potter & Buist). Even though the oil cannot be recovered this method is beneficial to returning the ecosystem back to normal due to its high efficiency of oil removal.

If oil recovery is not an option in-situ burning is good secondary option; however there are several environmental apprehensions. In-situ burning produces byproducts including polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC) and carbon dioxide (Potter, Buist & Trundel). The polluting emissions are not as destructive as the potential the oil has to

damaging the local environment. When in-situ burning is completed the remaining oil residue is cleaned up with absorbents, this reduces the oil that can negatively affect the ecosystem. The EPA has completed studies analyzing areas that have experienced in-situ burning after the fact. The wildlife returns and the ecosystem seems to go back to normal, which is more effective than if it was done via absorption alone in which the affected area would have a larger amount of oil remaining (Fingas). In-situ burning in the arctic is currently a developing popularity as an alternative to mechanical recovery.

Previous studies have been done of in-situ burning on water. However, it is not known how the addition of snow affects the characteristics of in-situ burning. Further research must be done in order to determine how effective in-situ can be for oil removal in the arctic.

3.0 Methodology

An experimental set up has been developed in order to study the previous mentioned parameters; oil and snow weight ratio, container diameter, and snow porosity. Shown in Figure 3-1 is a cut way of the experimental layout. The container filled with oil and snow will be placed in a protective tray on a load cell. A metal tray is used to avoid any possible leakage or overflow from the container. A shield was implemented to insure lab safety and to protect the surrounding environment from any strong flames. Every trial utilized a camera to capture the experiment for later analysis.

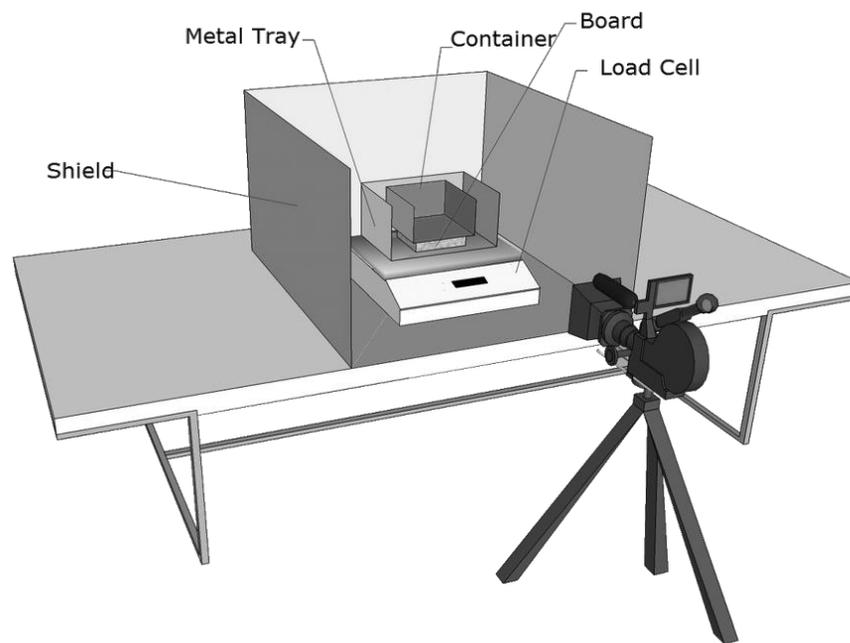


Figure 3-1: Experimental Setup

The focus of this study was to study in-situ burning of oil in various oil ratios, snow porosities and spill diameters. The first challenge of this project was to recreate snow in a laboratory environment that was environmentally safe and economically efficient. An ice maker was

installed in the lab in order to create small ice cubes and an ice shaver was utilized to crush the ice in order to replicate snow, Figure 3-2 shows the ice before and after being crushed by the ice shaver.



Figure 3-2: Ice cubes before and after the ice shaver

To contain the snow open boxes were assembled from heat resistance borosilicate glass in different sizes. Pre-cut sheets were glued together using both high temperature cement, rated up to 1500°F, and water proof epoxy glue. A glued container is shown in Figure 3-3. The containers had cross-sectional areas of 6.45 cm², 48.79 cm² and 145.56 cm², and the sizes can be seen on the models in Figure 3-4. These different measurements were chosen in order to allow for study of burning behavior of oil in different diameters containers.



Figure 3-3: Large container assembled using high temperature cement

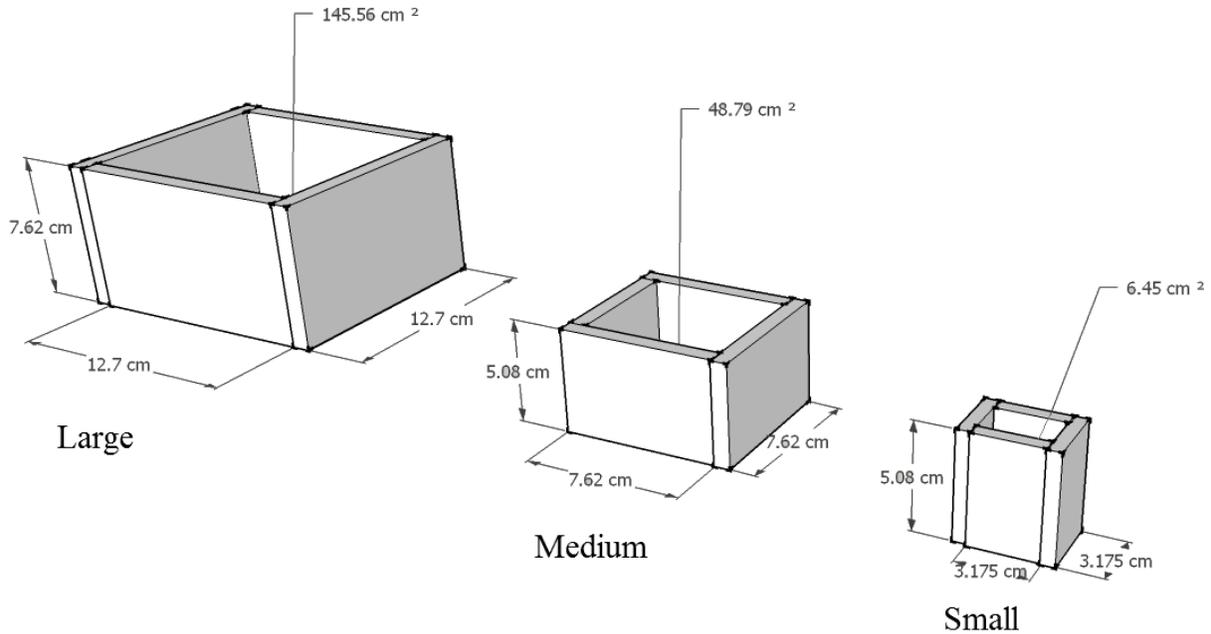


Figure 3-4: Three sizes of containers created to study the influence of spill diameter

In order to study any of the parameters, it was necessary to create an oil solution that would simulate crude oil well. The oil solution utilized was a mixture of SAE 30 motor oil and petroleum ether. The mixture has been shown in published experiments and theses to have properties within the range of crude oil. It has also been shown the mixture, when ignited, would have complete combustion. In order to achieve this complete burn, an experiment was conducted by burning 75 ml of SAE 30 motor oil with increasing amounts of petroleum ether in a stainless steel pan. The ratio of 3:1 SAE 30 oil to petroleum ether achieved a successful 100% burn efficiency leaving no oil remaining in the pan. Table 3-1 shows the property of the oil mixture (Bellino 2012).

Table 3-1: Properties of Oil Mixture

Parameter	Symbol	Value
Density	ρ	884 kg/m ³
Flash Point	T _{ft}	161 °C
Boiling Point	T _{bp}	236 °C
Thermal Conductivity	k	0.146 W/m·K
Specific Heat	C _p	1.912 J/kg·K
Thermal Diffusivity	α	905x10 ⁻⁷ m ² /s

After identifying the ideal ratio for the oil solution, free burn experiments were done using the three glass containers. A free burn, which is a baseline test without snow or ice, was conducted by filling pans with the oil solution, igniting it and allowing the oil to burn until the fire self-extinguishes. Performing a free burn provided a baseline to later compare against the behavior of oil burning in the presence of snow. During these experiments, a load cell was used to measure the mass loss; a container in a cold water bath is shown in Figure 3-5. The pans were put into a water bath during the free burns to prevent overheating and maintain lab safety. Overheated pans could break and possibly leak flaming oil resulting in possibly hazardous lab conditions.

Throughout the free burn lab a load cell was utilized to obtain the following weights: empty container, container with oil solution and to record the weight over time during the actual burn. The raw data gathered was later used to calculate the mass loss and the mass loss rate.

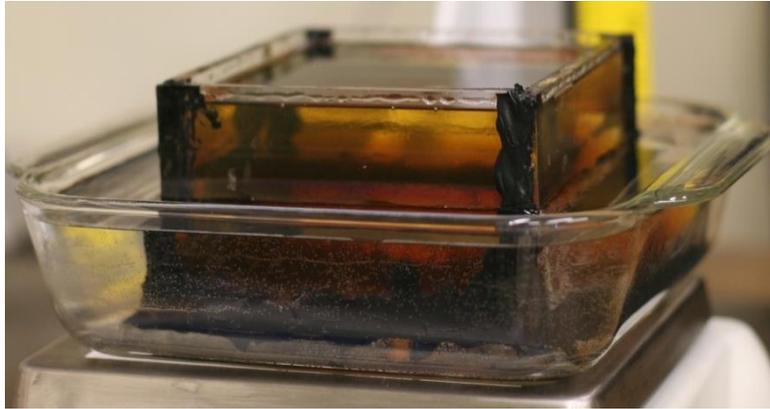


Figure 3-5: Large container free burn in cold water bath

The second phase of this project was to determine the combustion behavior of oil mixed with snow. Since the containers were much deeper than necessary, the containers were filled with water and frozen with a block of ice that half-filled the container. This block of ice replicates snow falling on top of ice, which is typical in arctic environments, a container with ice, snow, and oil is presented in Figure 3-6. This also lowered the amount of snow and oiled required to fill the container and perform experiments. In order study the burning characteristics of oil in each sized pan the ratio of oil to snow was adjusted until ignition did not occur. Ratios were selected so that the same ratio was tested in different diameter containers, which allowed for direct comparison of burn rates based on the container diameter. The snow was packed, rather than simply poured, into the containers to aid in oil pooling, however the oil still diffused throughout the snow to an extent in all experiments.



Figure 3-6: Small container snow trial with ice block, snow, and oil

Throughout the experiment a load cell was utilized to gather the following weights: container with ice, snow, oil, and mass loss over time. In addition a ruler was used to measure the height of the ice and snow layers in order to allow for the calculation of the density of snow. Table 3-2 shows the successful trials in which the flame is sustained for more than 30 seconds. The tables also show the varying containers size, weight of snow, weight of oil, oil to snow weight ratios and snow packing densities. These variations would aid in providing a wide array of data for analysis.

Table 3-2: Table of Snow Trials

Container	Ratio (g Oil / g Snow)	Oil Weight (g)	Snow Weight (g)	Snow Packing Density (g/cm ³)
Large	0.28	103	362	0.64
Large	0.70	72	103	0.21
Large	0.75	133	178	0.36
Large	0.84	165	197	0.32
Medium	0.75	41	54	0.45
Medium	0.84	22	26	0.20
Small	0.83	5	3	0.34

4.0 Results

The containers that were used for this project had square openings and of the following lengths: 2.54 cm, 6.99cm, and 12.07 cm. The surface area for the small, medium and large containers are as follows: 6.45cm^2 , 48.79 cm^2 and 145.56 cm^2 . This was done to test a variety of sizes, from the small container to the medium is almost a square increase of area, while from the medium container to the large is three times the surface area. The pool diameters being analyzed for the small, medium and large containers are 2.87 cm, 7.88 cm and 13.61cm.

The experiments conducted yielded time interval data in the form of masses obtained from the load cell. These masses were changed into mass loss by subtracting them from the original mass of the trials. These resulting mass losses were plotted against time for each trial. Figure 4-1 shows the mass loss versus time for the free burn trials (baseline without snow or ice), and Figure 4-2 shows the graphs for all of the snow trials. Individual graphs and equations may be found in the appendix.

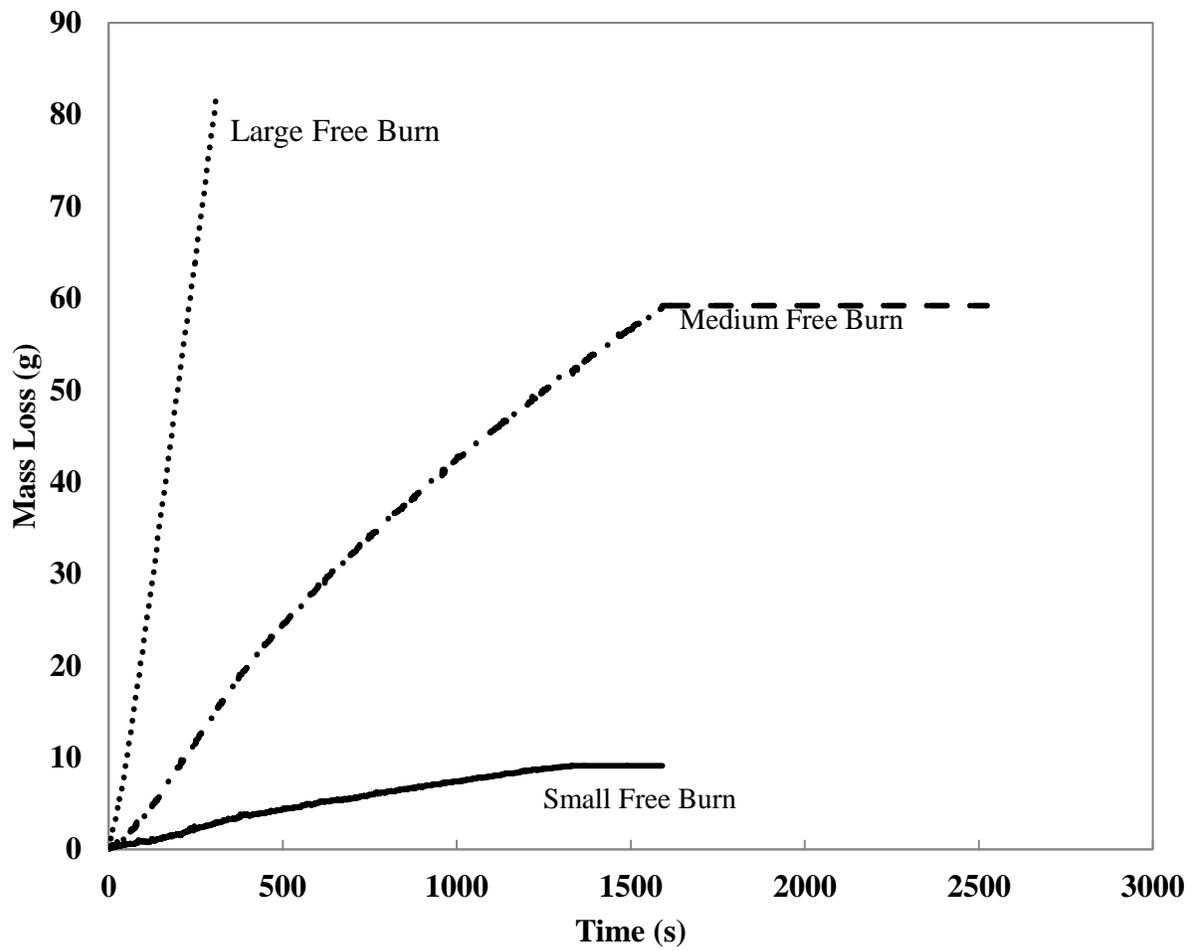


Figure 4-1: Mass Loss vs. Time for Free Burn Trials

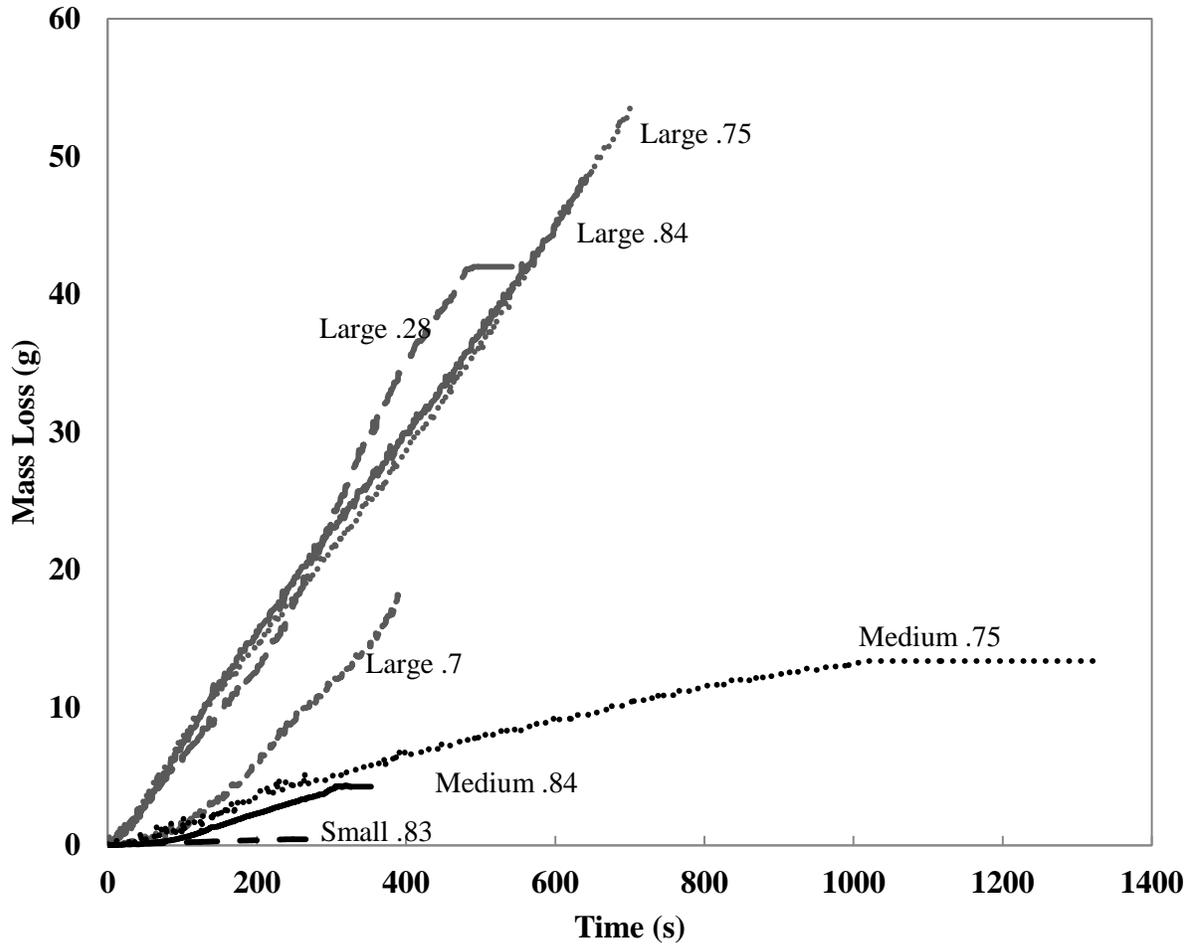


Figure 4-2: Mass Loss vs. Time for Snow Trials

From this data it was necessary to obtain mass loss rate information; the mass loss rate is the slope of the mass loss vs. time. This line was plotted as a 6th order polynomial trend line on the mass loss vs. time graph for each trial. To obtain the slope or mass loss rate, the derivative of the 6th order trend line was calculated; the resulting equation was plotted using the time increments as a mass loss rate vs. time graph for each trial. Figure 4-3 shows the mass loss rate vs. time graph for the free burns whilst Figure 4-4 displays the data for the snow trials. In addition a mass loss rate per area vs. time graph is in Figure 4-5 for the free burns, and Figure 4-6 for snow trials.

The per-area graphs allow for the containers to be more directly compared. Individual graphs and equations are located in the appendix.

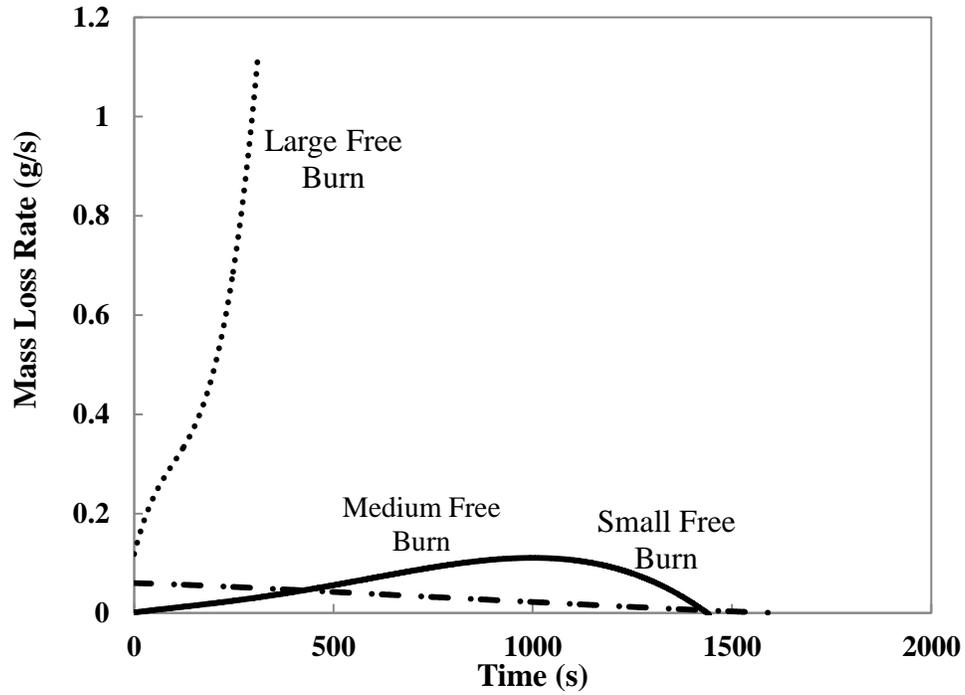


Figure 4-3: Mass Loss Rate vs. Time Free Burns

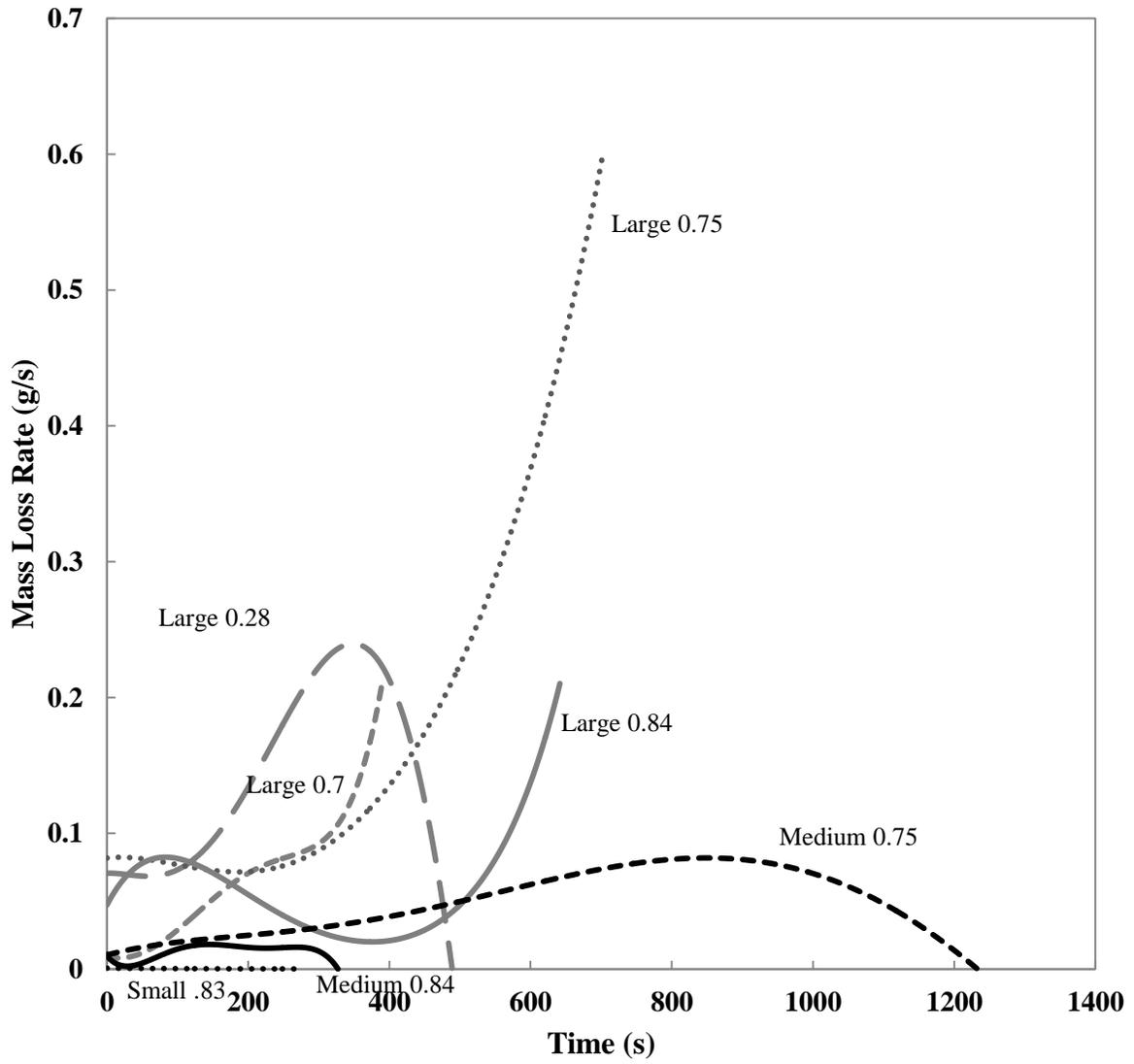


Figure 4-4: Mass Loss Rate vs. Time for Snow Trials

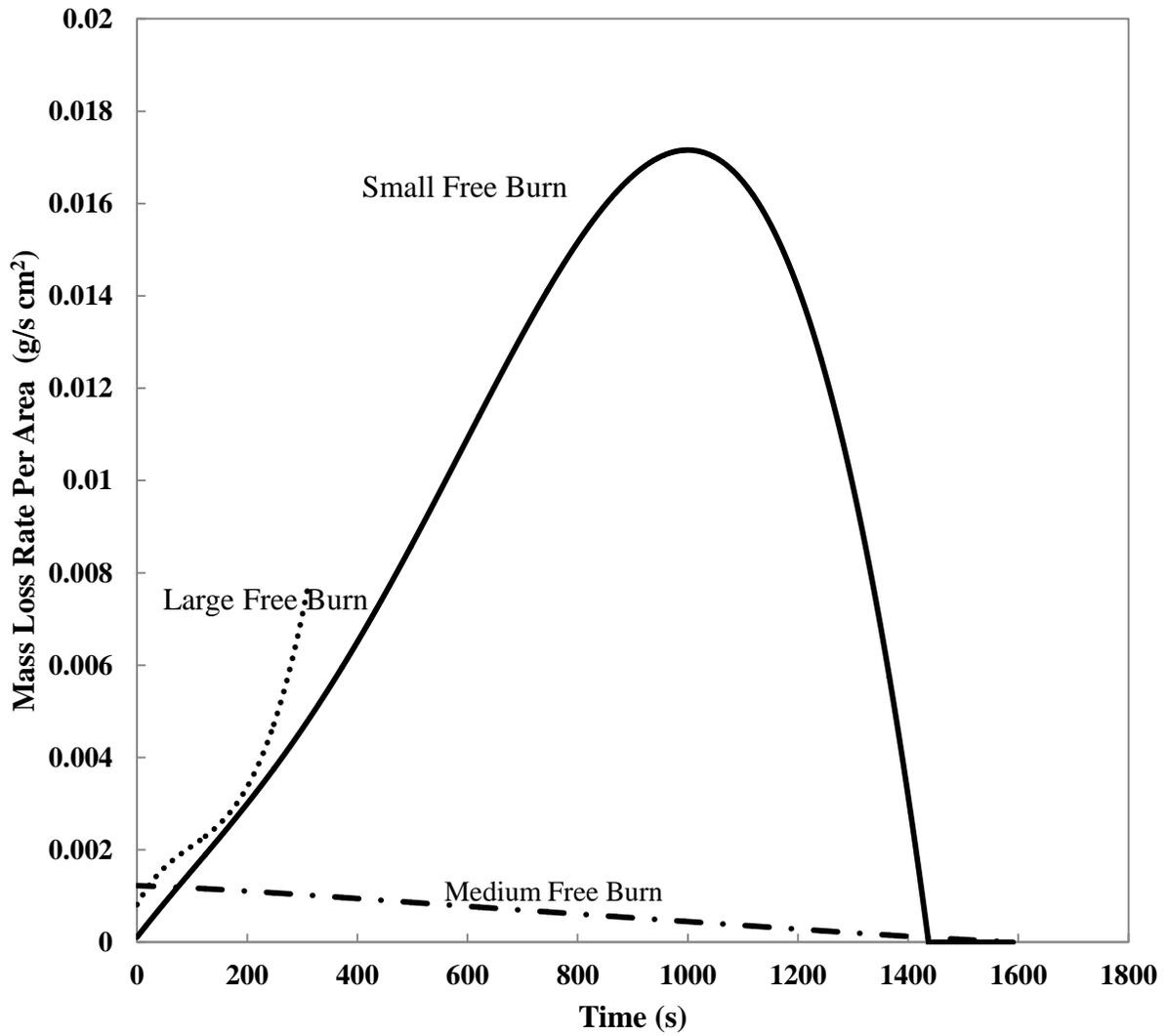


Figure 4-5: Mass Loss Rate Per Area vs. Time Free Burns

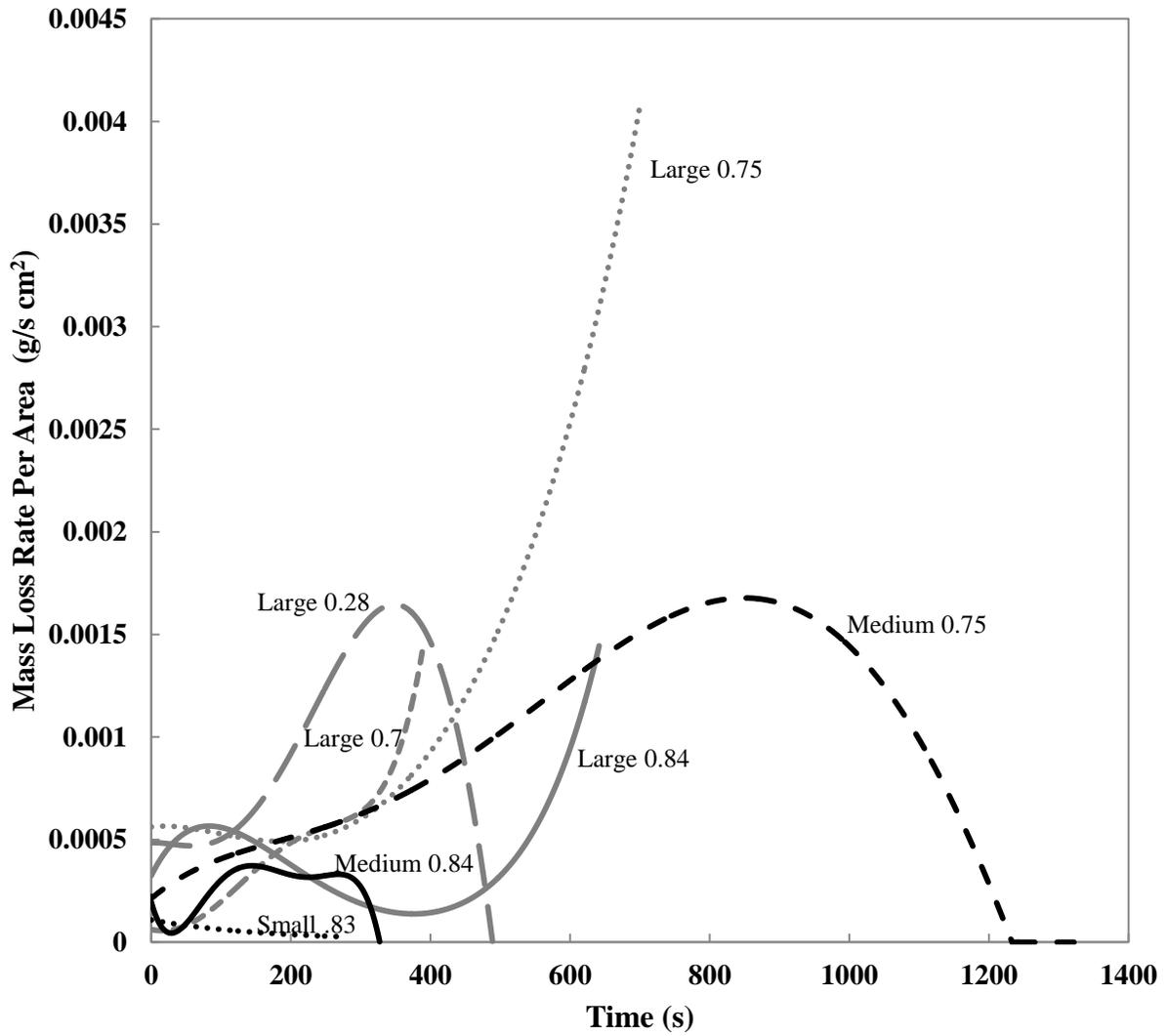


Figure 4-6: Mass Loss Rate Per Area vs. Time for Snow Trials

5.0 Analysis

5.1 Critical Oil Ratio and Boilover

Table 5-1 shows the oil to weight ratio and if the trial included ignition. Ignition occurs if the oil maintains a flame for at least 30 seconds. For the medium and small containers the critical burn ratio, which is the minimum oil to snow weight ratio required for ignition, was found. For the medium container this critical oil ratio was determined to be between 0.7 and 0.75, this is because the 0.70 oil to snow ratio did not ignite while the oil to snow ratio 0.75 and greater did. For the small container the critical burn ratio was determined to be between 0.75 and 0.83, data is shown on Table 5-1. The trials conducted on the larger container were not tested at an oil to snow weight ratio that did not ignite. The critical burn ratio is below 0.28, but since it is so far below that of the small and medium containers, as well as industry standards, it would be unnecessary to test further.

Table 5-1: Ratios, Ignition, and Methods of Extinguishment

Container	Ratio (g Oil / g Snow)	Ignition	Method of Extinguishment
Large	0.28	Yes	Self
Large	0.70	Yes	Manual
Large	0.75	Yes	Manual
Large	0.84	Yes	Manual
Medium	0.70	No	N/A
Medium	0.75	Yes	Self
Medium	0.84	Yes	Self
Small	0.75	No	N/A
Small	0.83	Yes	Self

Table 5-1 also shows the method of extinguishment for each of the ignited trials. For each of the small and medium ignited trials the containers self-extinguished. However, in every experimental trial performed in the large container, except for the 0.28 oil to snow weight ratio, the fire was manually extinguished because boilover occurred. This is a vigorous burning phase where the melted snow below the oil reaches its boiling point and steam starts mixing with the oil layer. This propels oil droplets into the flames which increases flame height and burn rate (Buist, In-situ Burning). The boilover produced a large flame that almost reached the protective barrier, the large container then had to be manually extinguished to insure lab safety. An example of boilover is exhibited in Figure 5-1. This impeded the results from the experiments because the premature extinguishment affects the mass loss and the overall mass loss rate trend.



Figure 5-1: An example of the boilover phase

5.2 Free Burn Analysis

Free burn trials, or baseline trials without any snow or ice, were conducted in each container size. Figure 4-3: Mass Loss Rate vs. Time Free Burns from the Results section, shows the mass loss rate per time of each free burn trial. In order to compare these values to accepted values published in the Society of Fire Protection Engineers Handbook, the regression rate was calculated with units of millimeters per minute. This was done by dividing the rate by the density to obtain a volume loss per time. This volume per time was then converted to the regression per time by dividing the area of the respective container. The average regression rate was obtained over the entire combustion time period. Each obtained regression rate was plotted with its corresponding equivalent circular diameter from Table 5-2, onto Figure 5-2 which shows the

regression rate versus diameter for various fuels with the data obtained from Society of Fire Protection Engineers Handbook.

Table 5-2: Container Sizes and Equivalent Diameter

Size	Width (cm)	Area (cm ²)	Pool Diameter
Small	2.54	6.45	2.87
Medium	6.99	48.79	7.88
Large	12.07	145.56	13.61

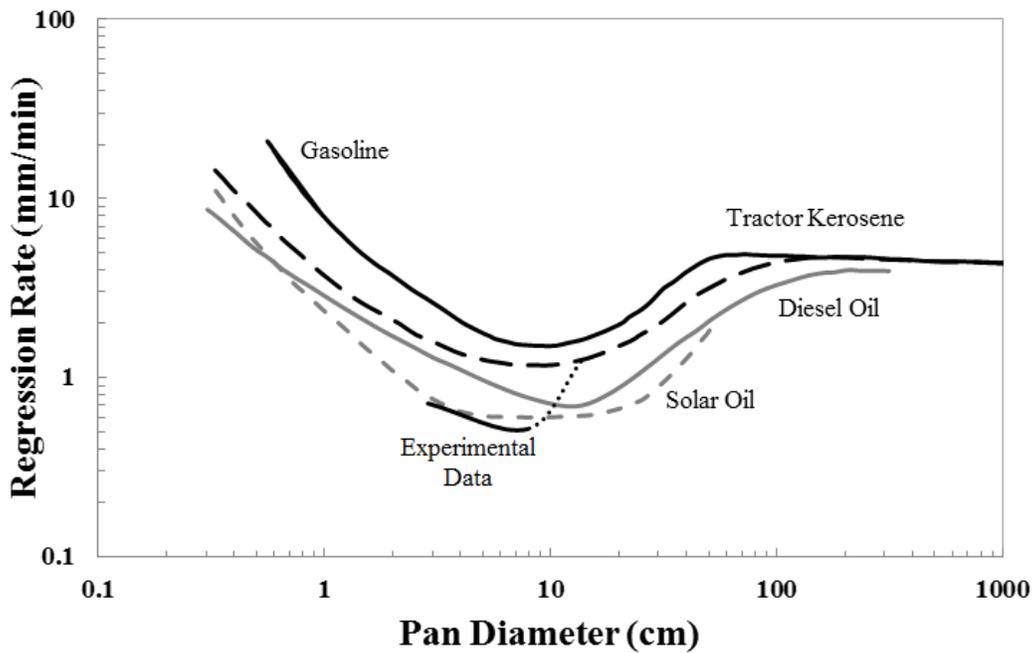


Figure 5-2: Regression Rate vs. Pan Diameter

The experimental data on Figure 5-2 is composed of three points, one for each container; small, medium and large. The solid black line from the small to medium container follows with the trend of the other fuel lines. The dotted line is from the medium container to the large container regression rate, and seems to defy the overall trend, however this can be explained. The large container free burn was manually extinguished, rather than allowed to burn itself out as occurred in the small and medium containers. This resulted in an inaccurate regression rate being obtained for the large container, if it had been allowed to burn to self-extinguishment the regression rate would likely fall in line with the general trend.

5.3 Burning Stages

Throughout the trials different stages of burns were visually identified, these were broken down into six stages for the self-extinguishing trials and three for the trials that experienced boilover, here you find illustrations of these stages as well as pictures from the experiential large 0.28 ratio trial. Stage 1 is illustrated by Figure 5-3, it shows the mixing of oil and snow prior to ignition, at this point the oil would pool on top of, or diffuse through the snow, with the amount of diffusion dependent on the snow packing density (porosity).

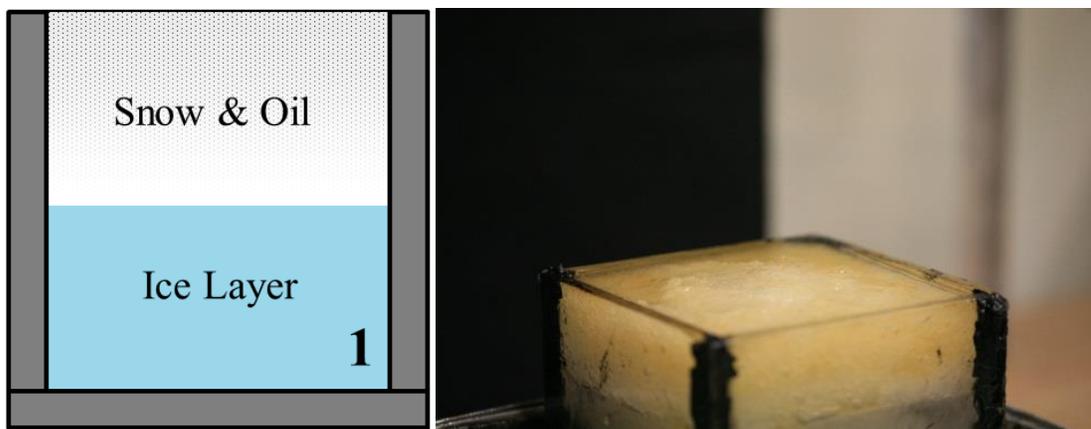


Figure 5-3: Stage 1 Prior to Ignition

In stage 2, shown in Figure 5-4, the oil has been ignited and begun burning. At this point the snow has begun to melt, and a water layer containing snow has formed on top of the ice. In addition a slide oil film can be seen at the top of the container. This film is vital to the oil combustion; the thicker it is the faster combustion could take place.

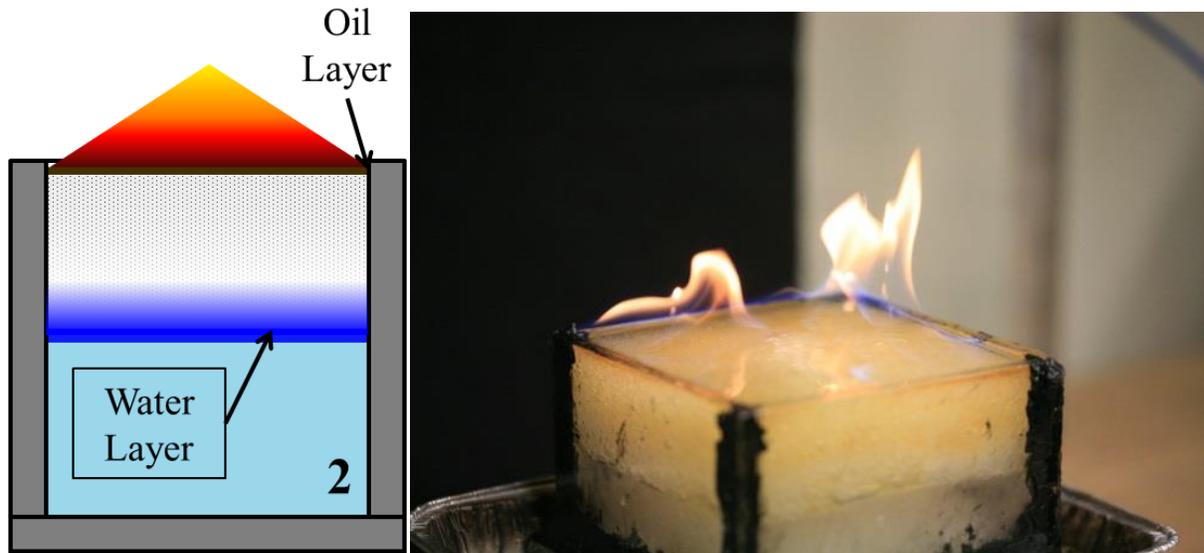


Figure 5-4: Stage 2 Initial Combustion

Stage 3 Figure 5-5, shows the peak mass loss rate of a self-extinguishing trial, or in the case of a boilover, the rapidly increasing mass loss rate and the point at which the fire was manually extinguished. This stage shows a very thick oil layer whose development was aided by the growing water layer, which forces the oil to the top as the water layer increases in height into the snow. In addition, it can be seen that although the oil layer has receded into the container, it is still close enough to the top edge of the container to entrain the oxygen necessary for combustion.

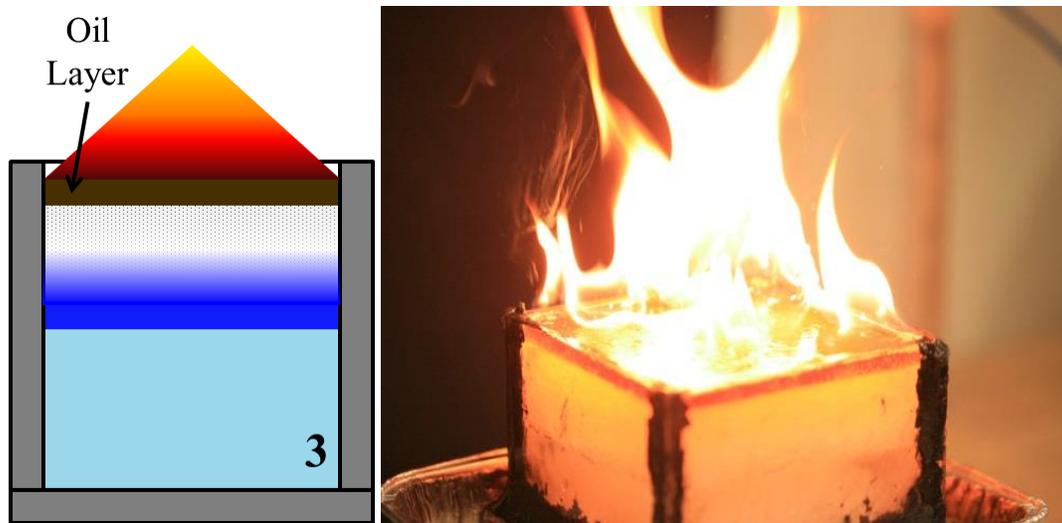


Figure 5-5: Stage 3 Rapid Combustion/Peak Mass Loss Rate

However, as the fire progresses to Stage 4, Figure 5-6, the oil layer further recedes into the container. Though the layer is still thick at this point, it has regressed too far into the container and oxygen limitations begin to play an effect. This is true for the majority of trials; it could be argued that the large container at this point is not yet oxygen limited due to the large diameter allowing more air entrainment. For the medium and small trials the oxygen limitations are clearly seen at this point. As the fire continues to burn it reaches Stage 5, shown in Figure 5-7, in which the oil has further regressed into the container and is thinner. At this point the fire becomes oxygen limited, and in the case of the large container the thinness of the oil layer further adds limitations to combustion. Stage 6, displayed in Figure 5-8, simply shows the post extinguishment container, the oil level is very low and the thickness of the oil layer is much thinner than it was at the peak mass loss rate of Stage 3.

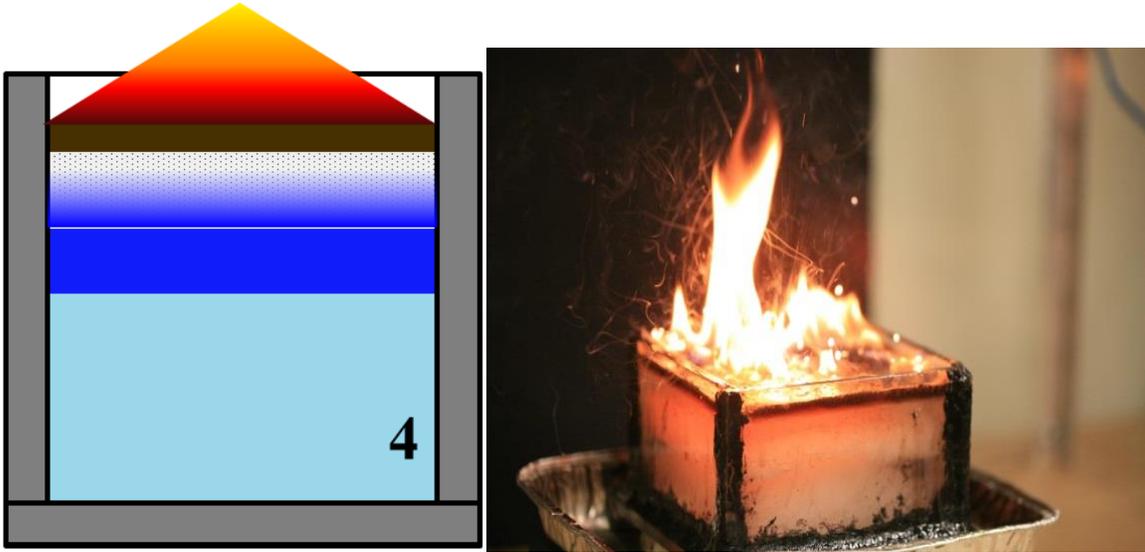


Figure 5-6: Stage 4 Reduced Combustion Rate

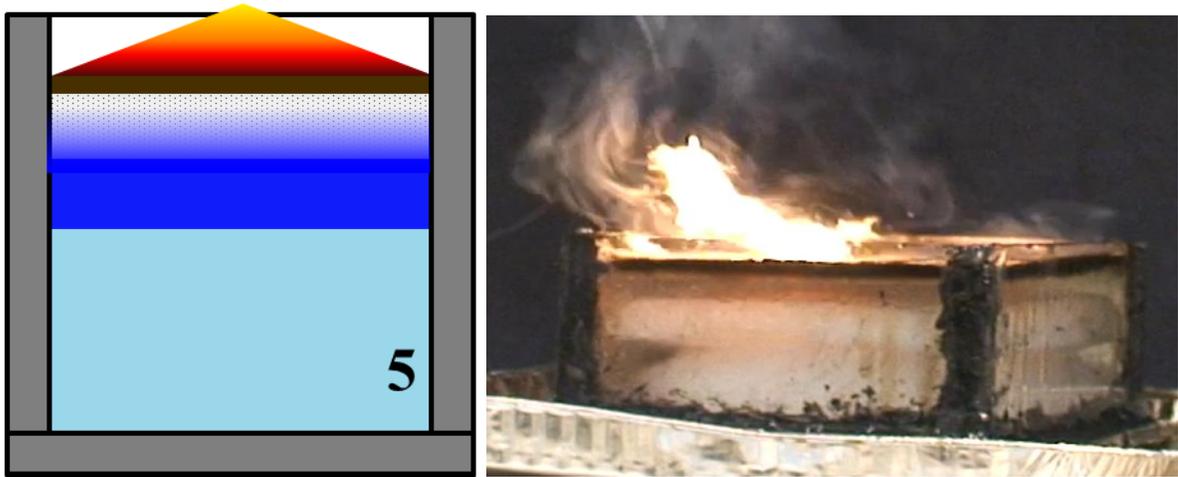


Figure 5-7: Stage 5 Oxygen and Fuel Limited Combustion

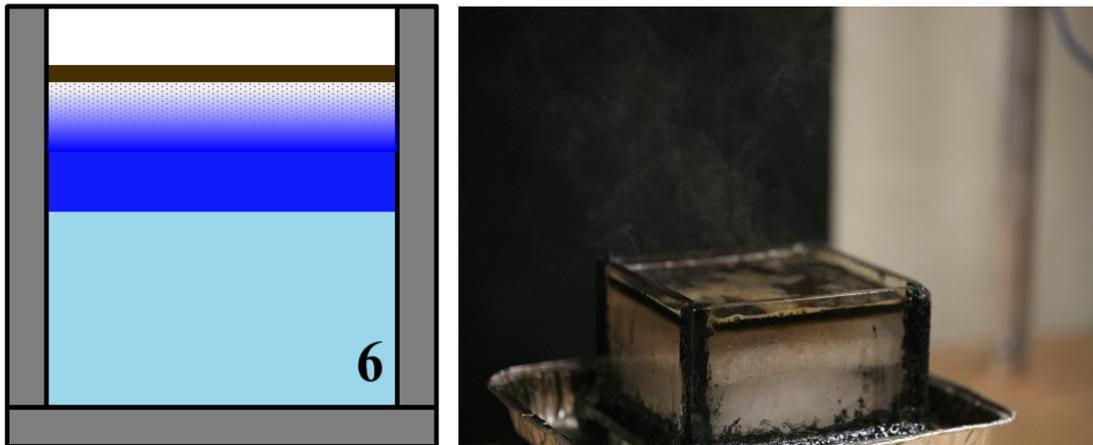


Figure 5-8: Stage 6 Self Extinguished

5.4 Large Container Trends

The stages previously explained can be seen in the mass loss rate graphs of the snow trials, such as Figure 5-9 which displays the large trial mass loss rates vs. time for the 0.28, 0.75, and 0.84 oil to snow ratio trials, as well as displaying their respective snow packing densities. It can be seen that although the 0.28 trial had the lowest ratio of oil to snow of the three trials depicted, it reached Stage 3 in the shortest amount of time. For the 0.28 trial, which can be seen self-extinguishing where the mass loss rate reaches 0, the 3rd stage is characterized by the rapid increase in mass loss rate occurring from a time of 120 to the peak rate at approximately 340 seconds, these and the subsequent times are marked on Figure 5-9. For the 0.75 trial, and the 0.84 trial, both of which reached boilover, the third stage does not end with a peak mass loss since the fire was extinguished. The third stage for these two trials begins are approximately 250 seconds for the 0.75 ratio, and 450 seconds for the 0.84 ratio. Both of these times are much

greater than the 120 seconds it took the 0.28 trial to begin stage 3 of the burning process. This can be attributed directly to the snow packing density, or porosity. The 0.28 trial had much denser snow, which allowed for greater pooling of oil, and required less time to melt snow and generate a substantial oil layer. It is the oil layer's development that is required for the aforementioned stage 3's rapid combustion rate. The more porous snow (lower snow packing density) present in the 0.75 and 0.84 trials resulted in more diffusion of oil into the snow. This lead to a greater amount of time and energy required to melt snow, generate a water layer, and eventually have that water layer aid in pushing the oil up into the distinct, thick oil layer that was required for the rapid combustion.

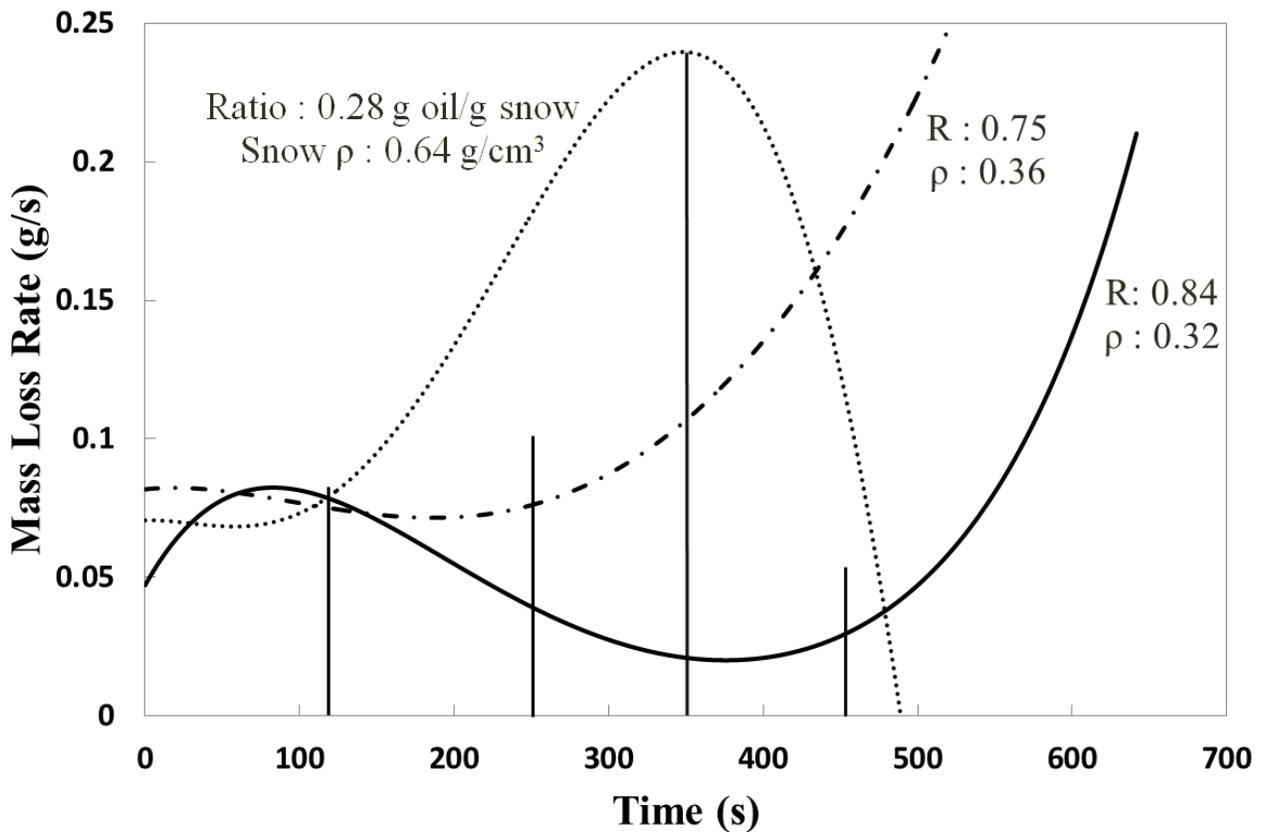


Figure 5-9: Mass Loss Rate vs. Time for Large Container Snow Trials

5.5 Burn Efficiency

Table 5-3: Efficiency shows the oil to snow weight ratio, snow packing density and burn off efficiency of all the ignited containers. The burn off efficiency of the small and medium free burns at 54% and 63% respectively, the large container is not shown because it was manually extinguished. The small container had a greater percentage of oil burned off in comparison to the medium container. This is because the smaller container had a higher regression rate, shorter burn time, and lower oil weight. The final oil layers for the free burns were above the known critical oil layer, the minimum amount of oil pooled in order to have ignition. As the oil layer lowered the opening to the container limited the amount of oxygen entering that allows for combustion, this caused the free burn containers to self-extinguish. The free burn trials were conducted in order to provide a baseline for comparison for the snow and oil experiments which did not seem to follow this trend.

Table 5-3: Efficiencies

Size	Ratio (g Oil / g Snow)	Snow Packing Density (g/cm ³)	Efficiency (%)
Large	0.28	0.64	41
Medium	Free Burn		54
Medium	0.75	0.45	33
Medium	0.84	0.20	21
Small	Free Burn		63
Small	0.84	0.34	9

The oil and snow trials had a trend of the greater the surface area of the ignited oil the greater the efficiency. This can be seen in the trial above where the small oil and snow trial had a burn efficiency of 9% while the medium container with the same snow to oil weight ratio also had an efficiency of 21%. This trend also included the self-extinguished larger container. The larger pool diameter allowed for more oxygen to enter the container and facilitate combustion. The final oil layers for the containers also seem to follow this trend. The 0.28 ratio large container trial had the greatest efficiency; it also had one of the lowest final oil layers out of all the self-extinguished trials.

The snow packing density also has an effect on the burn efficiency in our experiments, albeit to a lesser extent than the pan diameter. This is because the lower the packing density the less oil by weight was being used even if the trial would utilize the same oil to snow weight ratio, however this only occurred in the experiments and would not occur in real-world in-situ burning as the snow is already present and the oil is not intentionally measured and poured. The snow packing density also affects the initial oil layer pooled on top of the snow. The higher the packing density the less the oil can diffuse through the snow giving the oil a higher pool height.

6.0 Conclusion

The focus of this study was to determine how snow affects the burn of a pool of oil in order to simulate the removal of oil by in-situ burning in an arctic region. It was determined that the presence of snow made the burn less effective because initial heat transfer is focused on the oil as well as the melting of the snow.

The parameters focused on in this study were the oil to snow weight ratio, the snow packing density, and the container diameter. Out of all the parameters specified the container diameter seemed to have the highest effect on the burn off efficiency, critical oil ratio and mass loss rate. The critical fuel ratio was determined for the small and medium container and is highly dependent on the container diameter. The trend determined is that as the surface area increases the minimum oil to snow ratio required for ignition decreases. The snow packing density also had an effect on the mass loss rate; this is because the higher the porosity the more oil could diffuse through the snow which would reduce the amount of oil being pooled. This led to a longer time and greater heat loss to the snow occurring before the distinct oil layer required for rapid combustion could develop. This also affects the overall amount of oil being burned, because a container could have a lower oil to snow weight ratio but have more oil for containers with differing snow packing densities.

7.0 Future Work

Each container trial for each snow weight ratio has only been conducted to burn once. The results have been showing that a second trial could have provided more insight in the behavior of oil burning on snow. To understand the behavior of mass loss rate trend two or more trials for each individual run should be done in order to explain the behavior better.

The oil mixed with snow trials had difficulties with igniting the fuel in the containers. The fuel was unsuccessful to ignite because the low packing density of the snow caused the fuel to diffuse and the initial oil layer would not be as high. In order to achieve the desired ratio for each individual run the mass ratio of oil to snow was arrived to by varying both of the mass of oil and the mass of snow. Since the density of snow was not constant the mass loss rate did not show a consistent behavior. The density of the snow should be kept constant and mass of oil should be varied. By doing so, and having a constant container diameter, constant snow packing density and a constant ice mass value it would show that any changes on the mass loss rate is because of the oil burning behavior. Performing more trials by varying oil to snow ratio and a constant snow packing density would aid in identifying the specific effect of snow packing density on combustion.

8.0 References

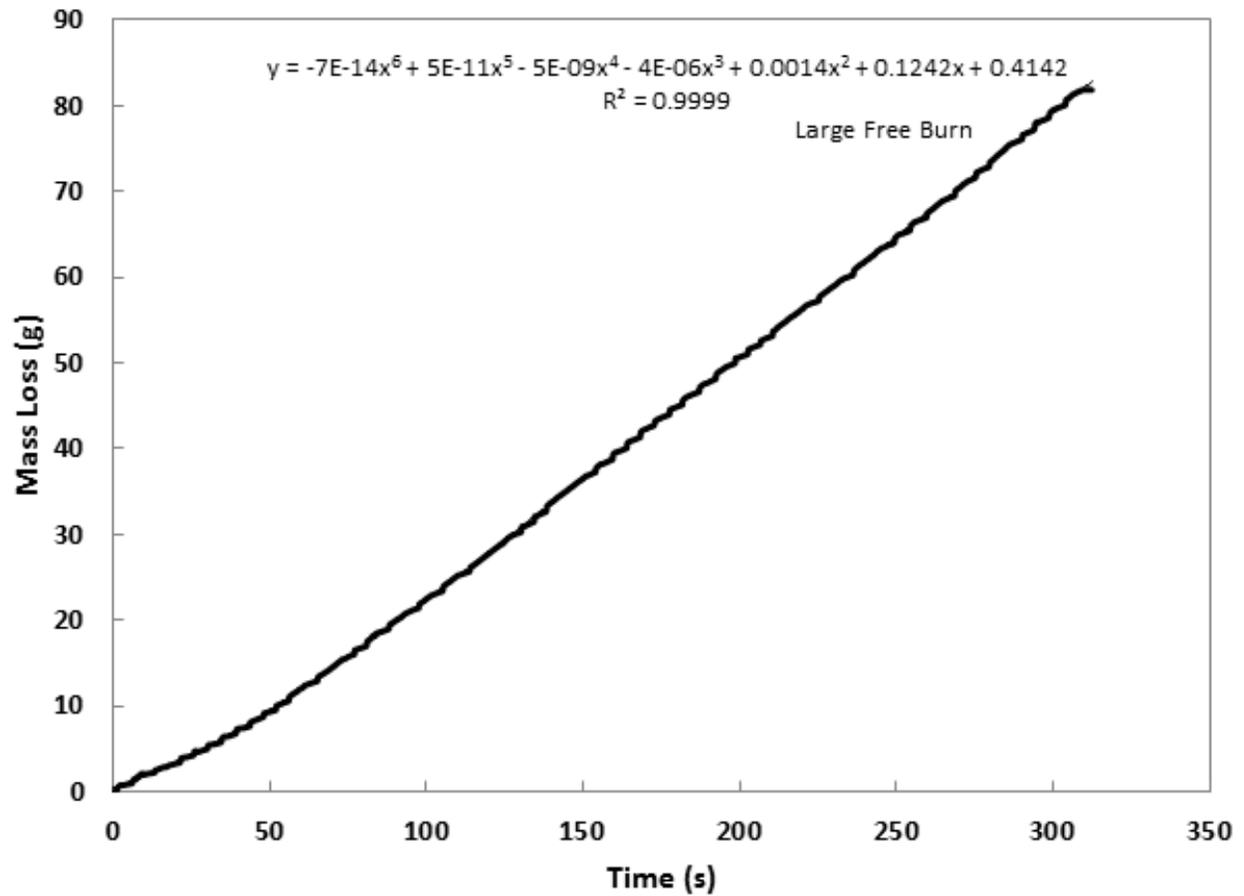
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Appendix

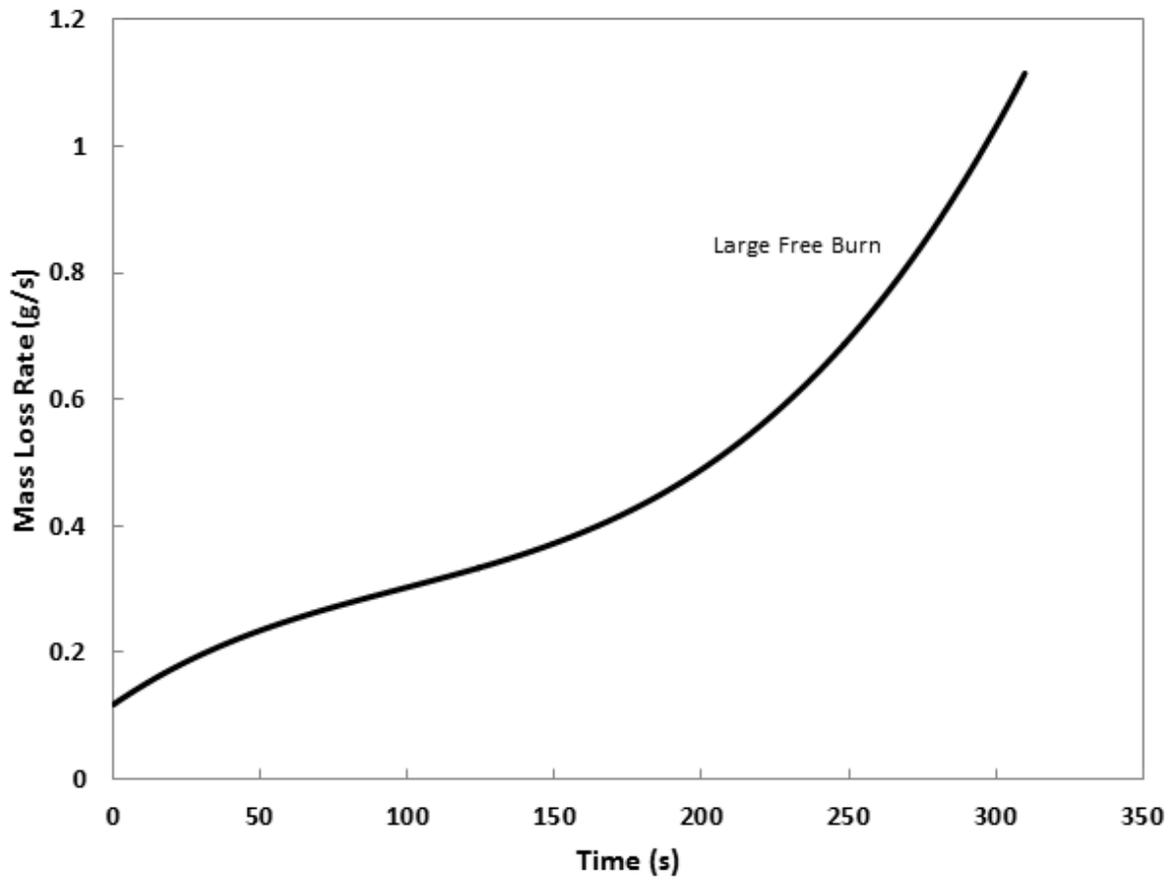
A Free Burn - Baseline Graphs

A.1 Large Free Burn Graphs

Mass Loss vs. Time



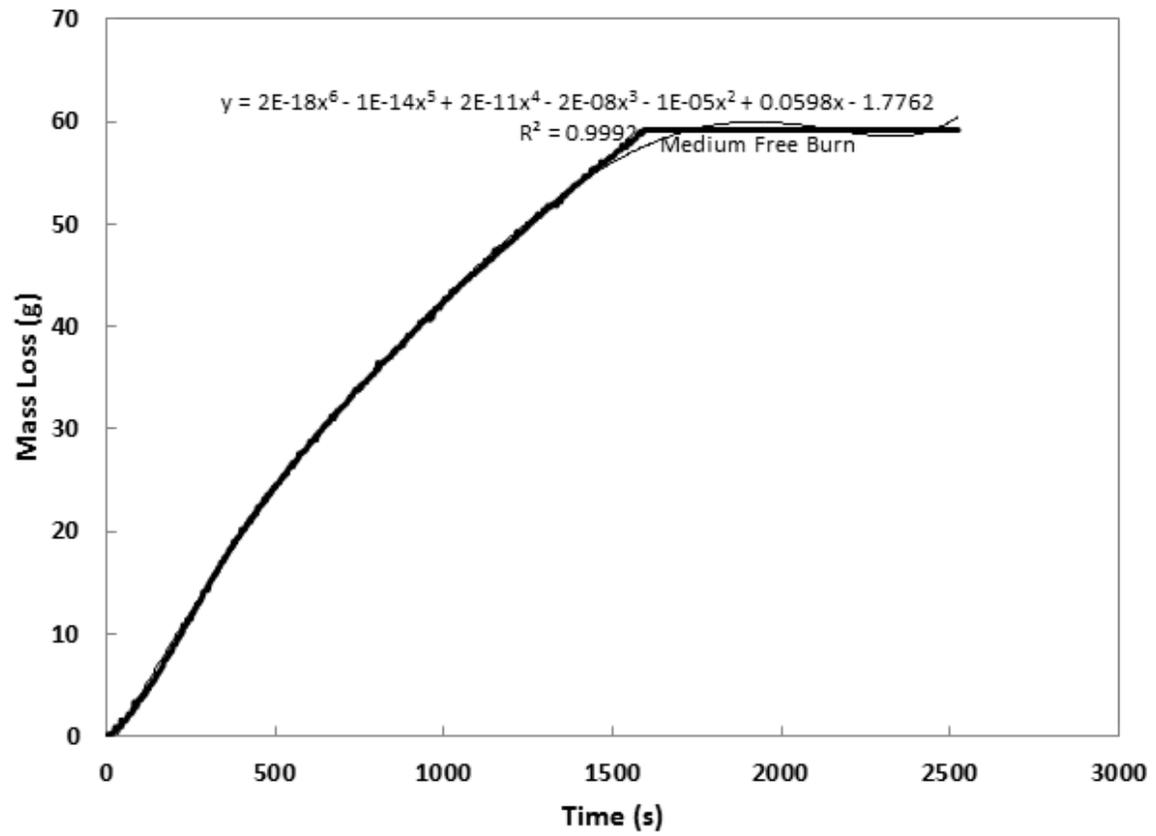
Mass Loss Rate vs. Time



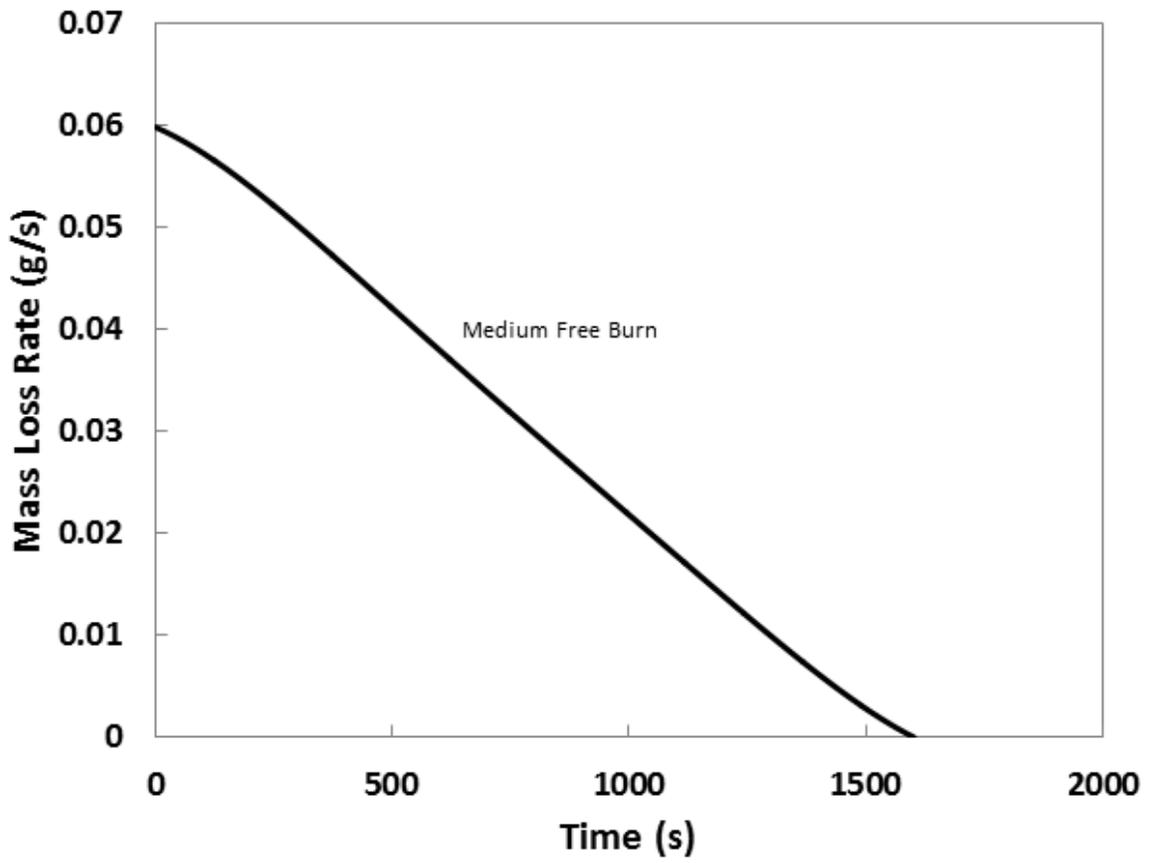


A.2 Medium Free Burn

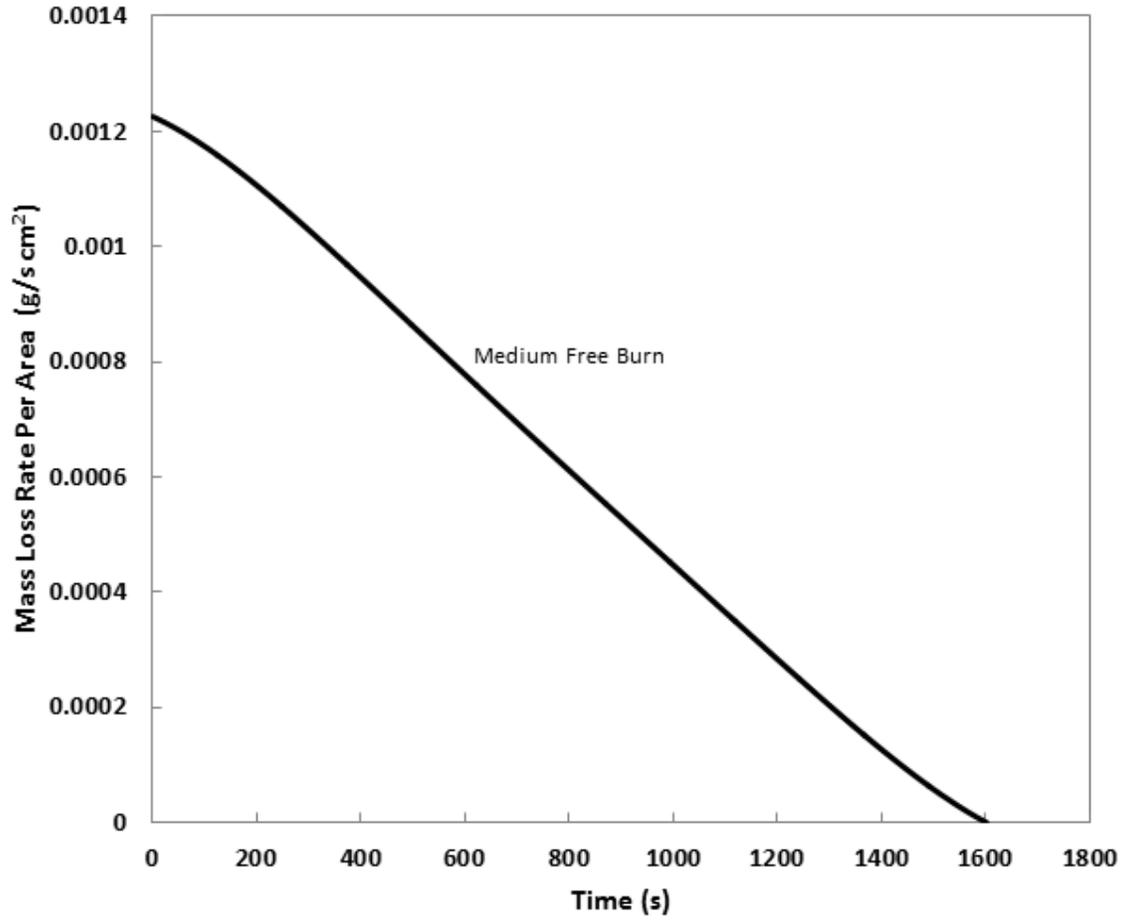
Mass Loss vs. Time



Mass Loss Rate vs. Time

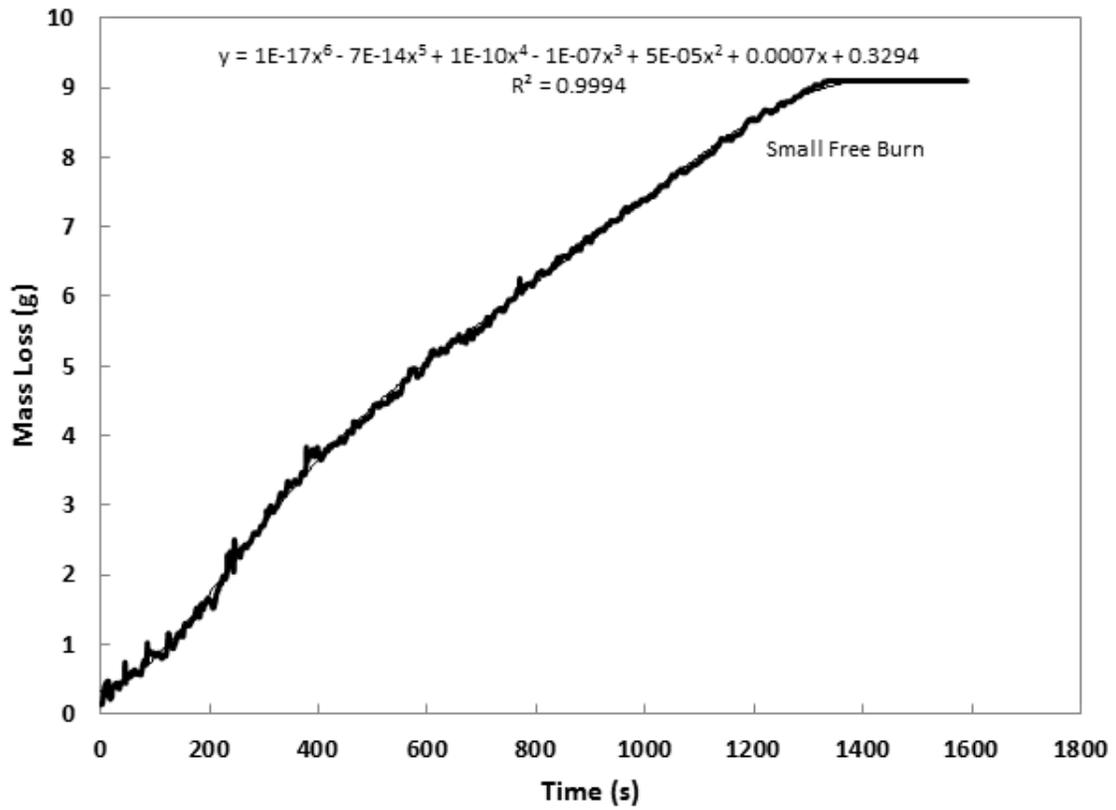


Mass Loss Rate Per Area vs. Time

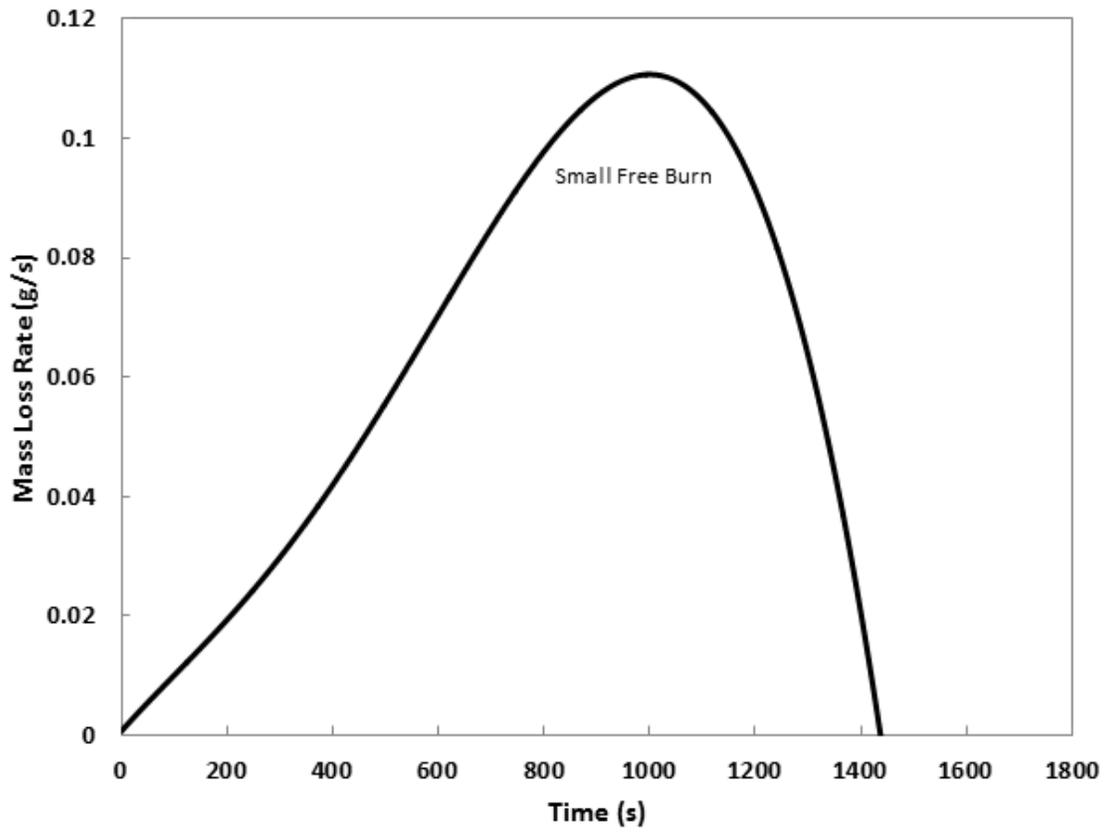


A.3 Small Free Burn

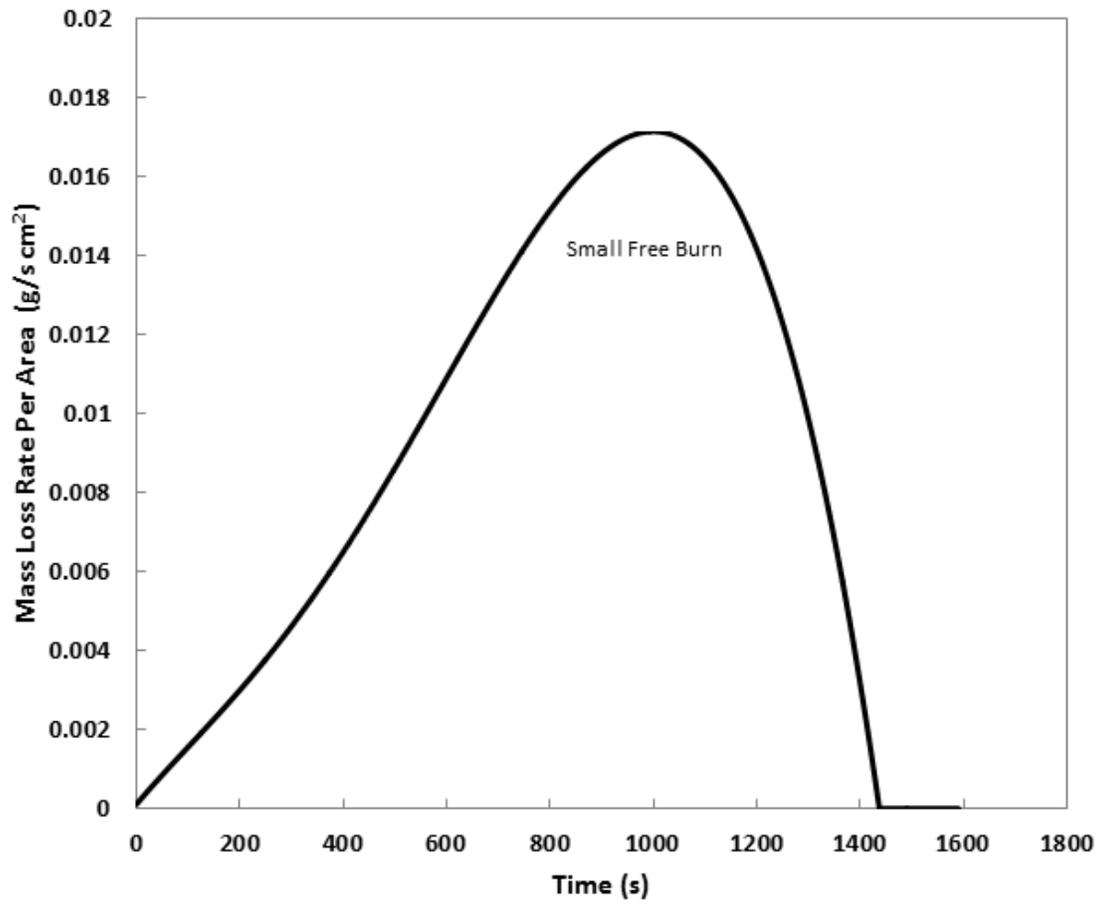
Mass Loss vs. Time



Mass Loss Rate vs. Time



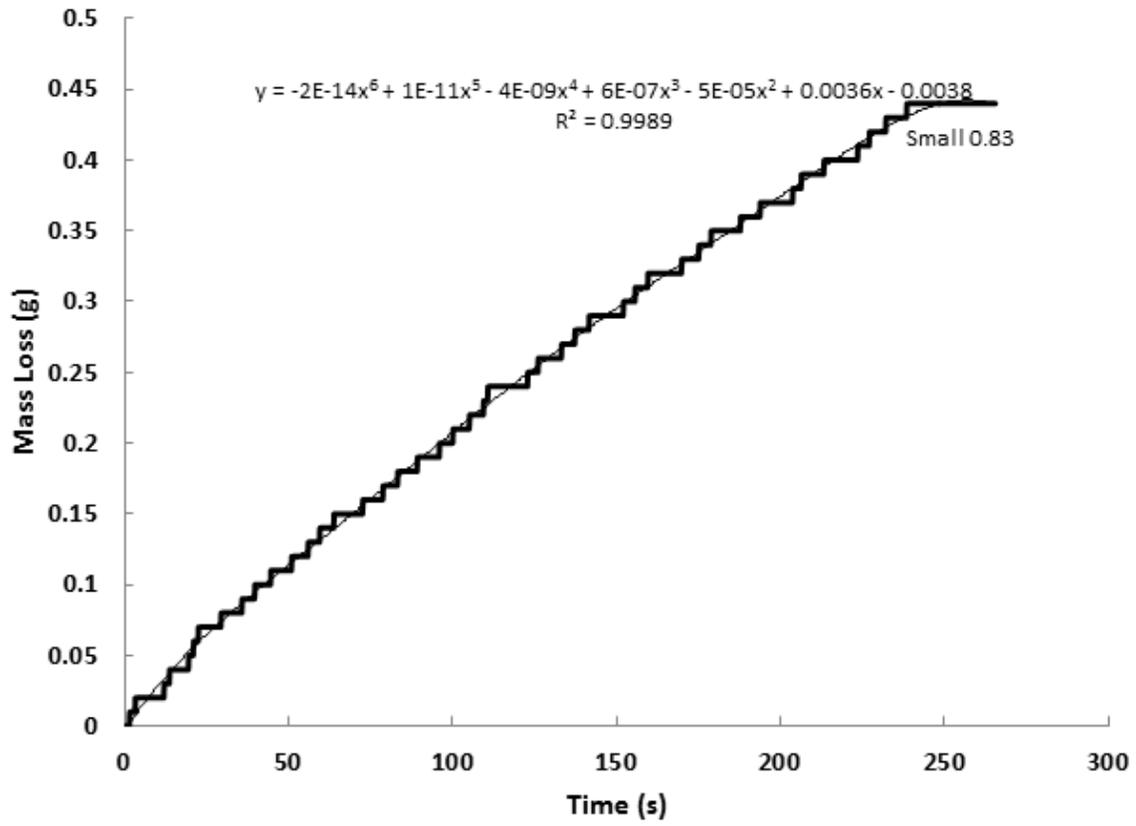
Mass Loss Rate Per Area vs. Time



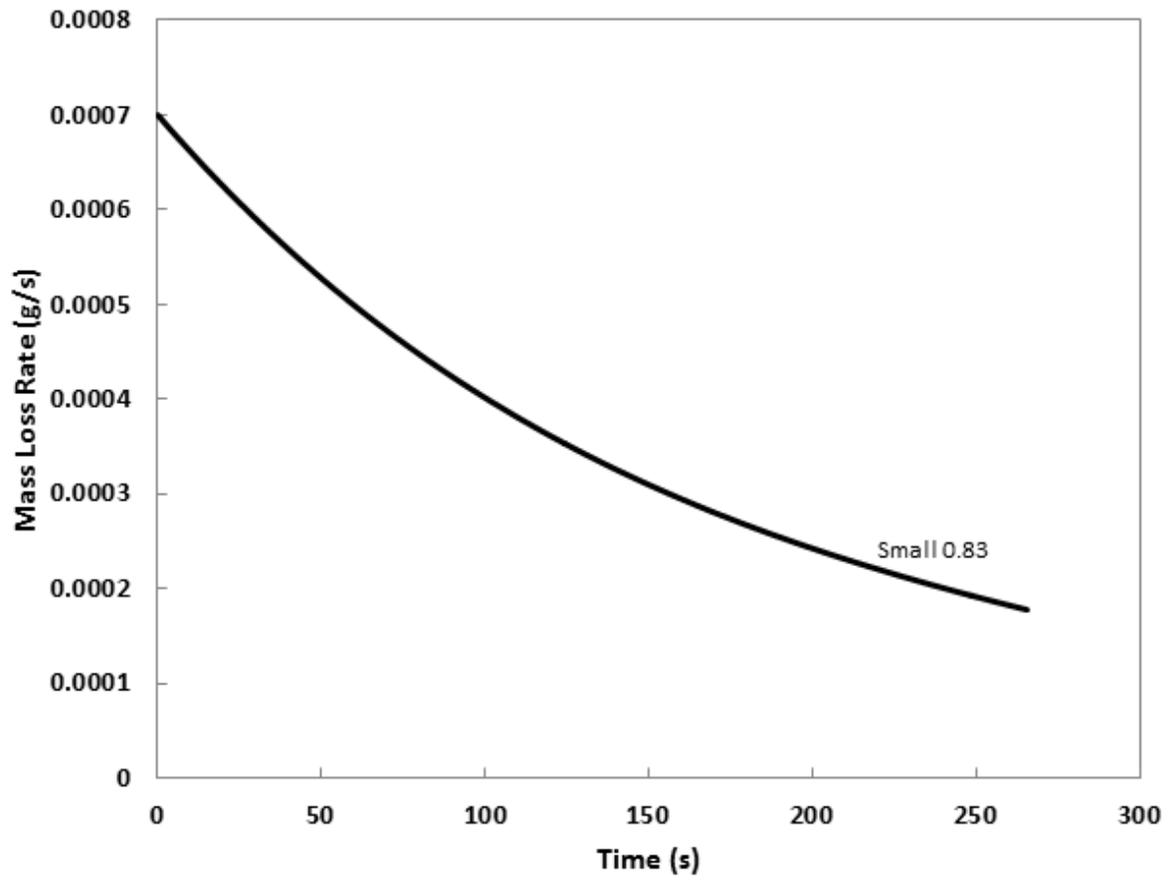
B Small Snow Trials

B.1 Small 0.83 Ratio

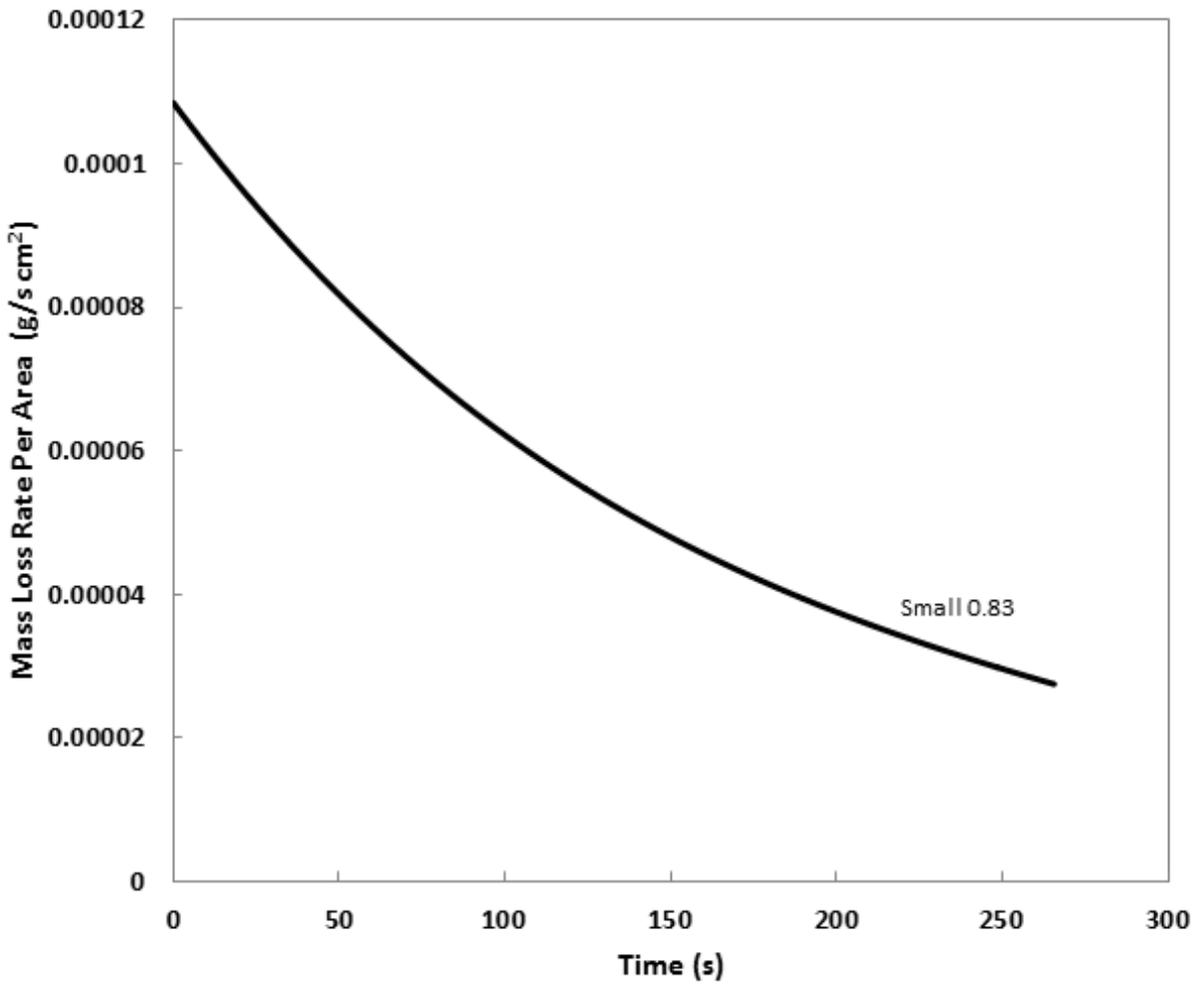
Mass Loss vs. Time



Mass Loss Rate vs. Time



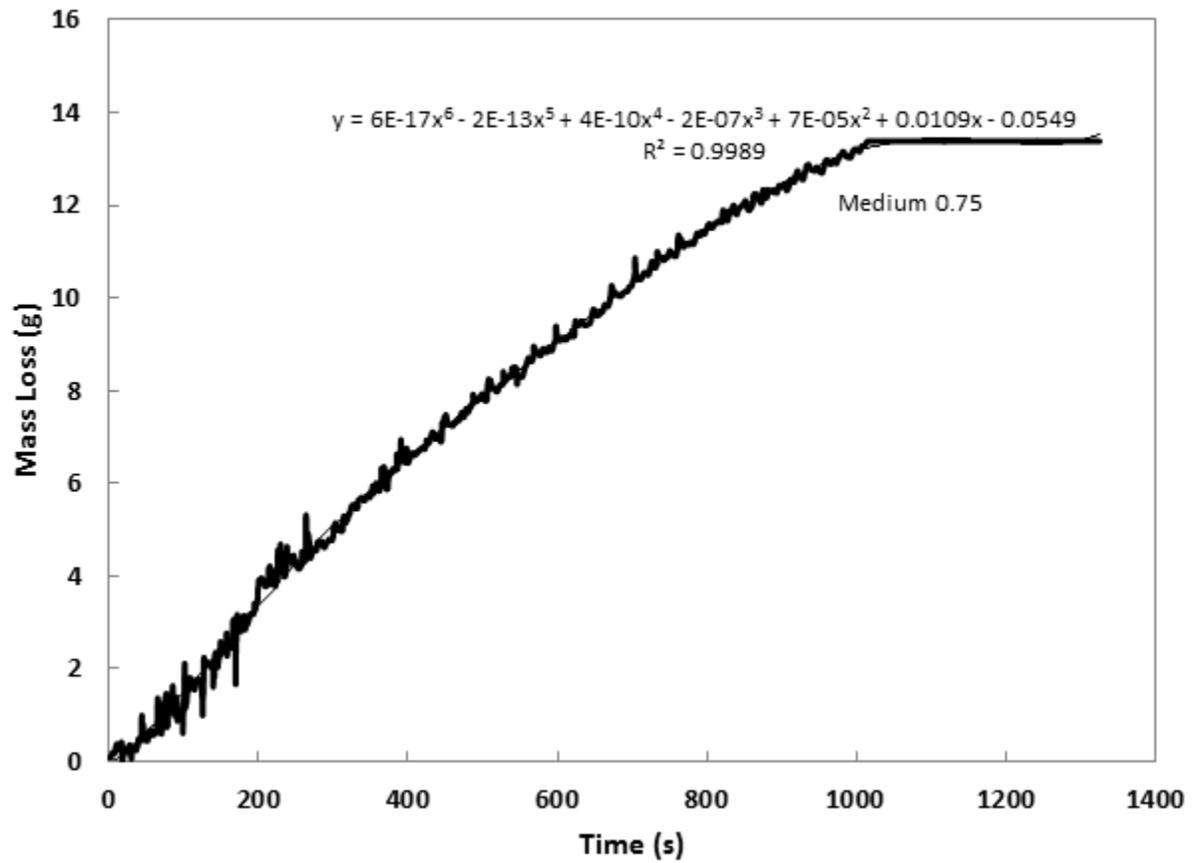
Mass Loss Rate Per Area vs. Time



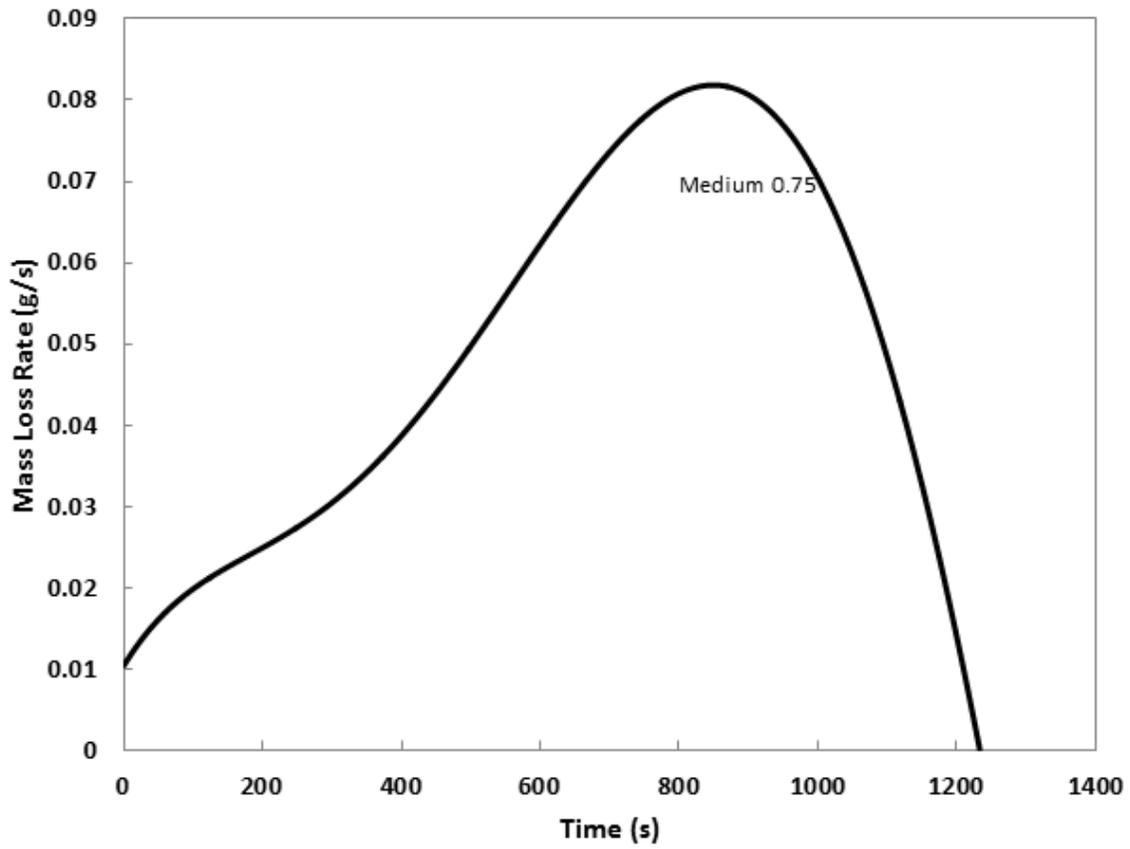
C Medium Snow Trials

C.1 Medium 0.75 Ratio

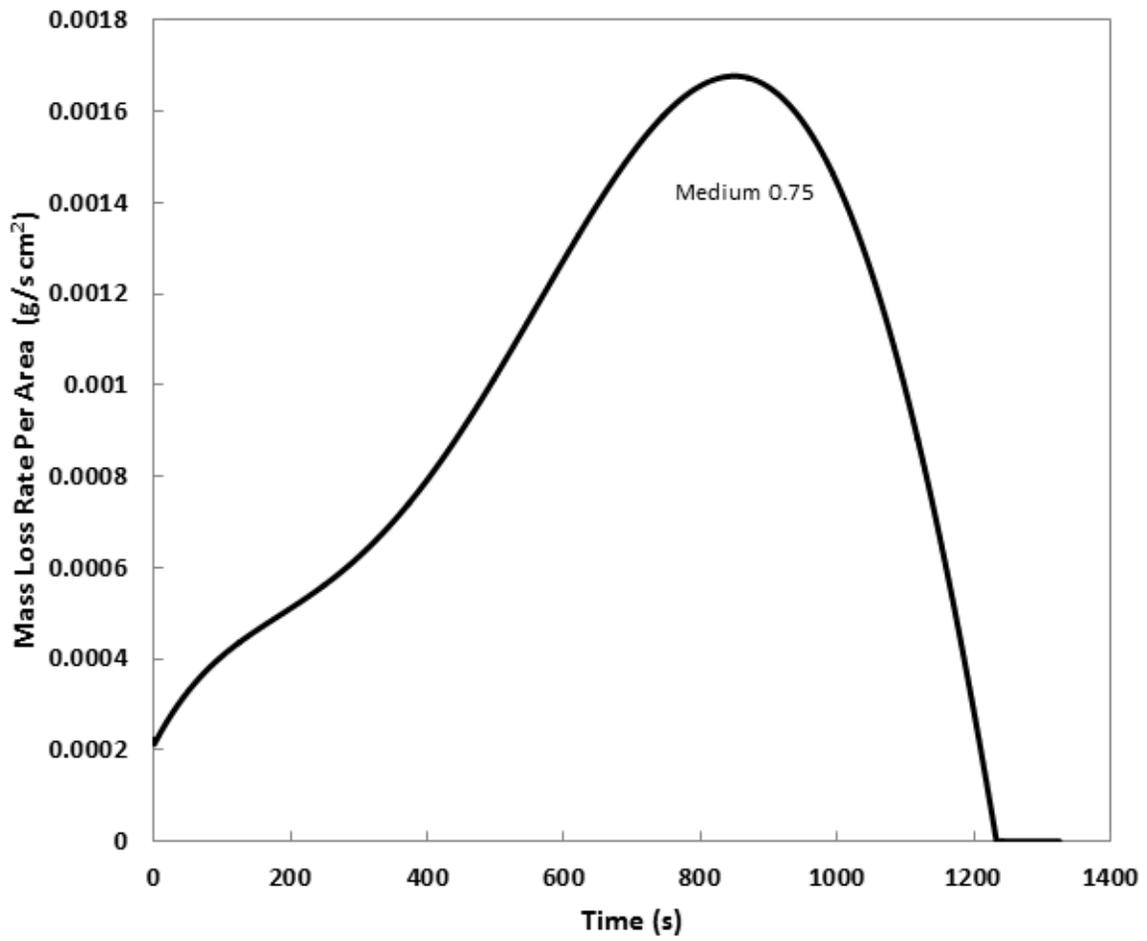
Mass Loss vs. Time



Mass Loss Rate vs. Time

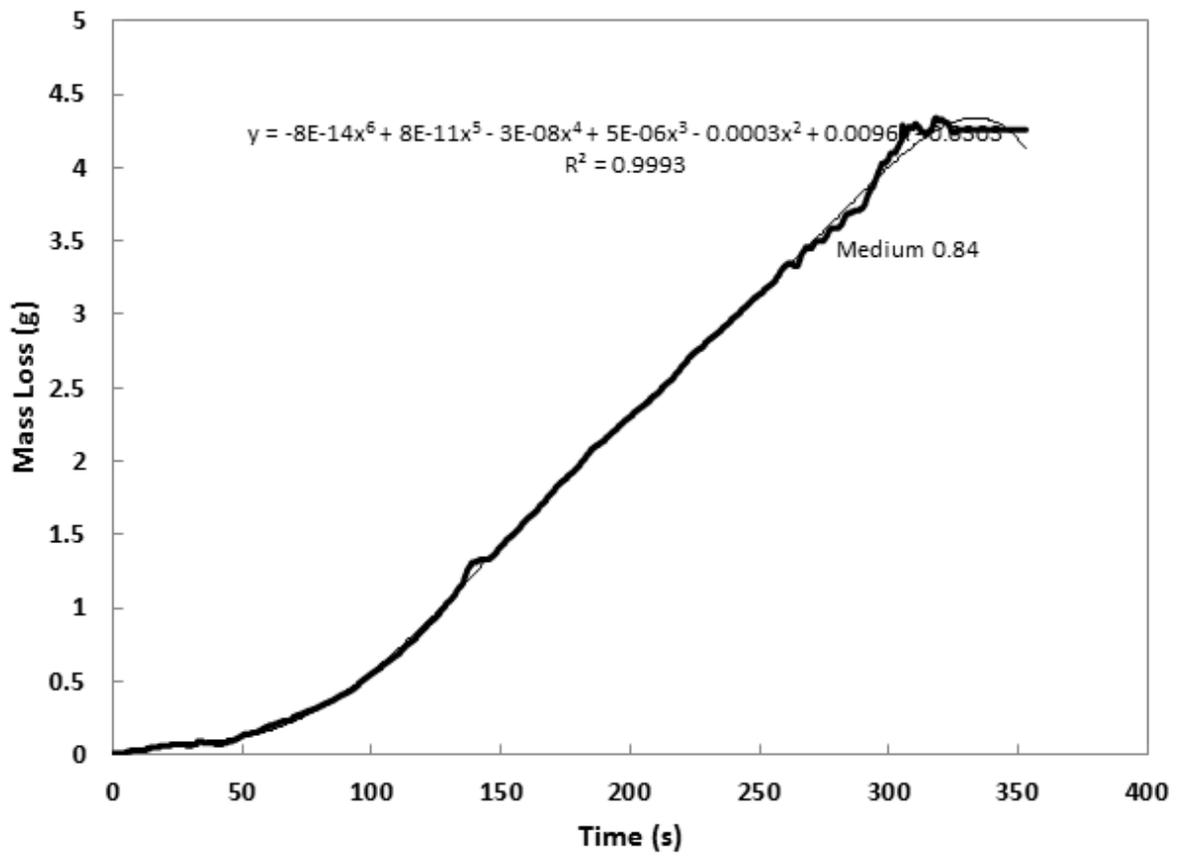


Mass Loss Rate Per Area vs. Time

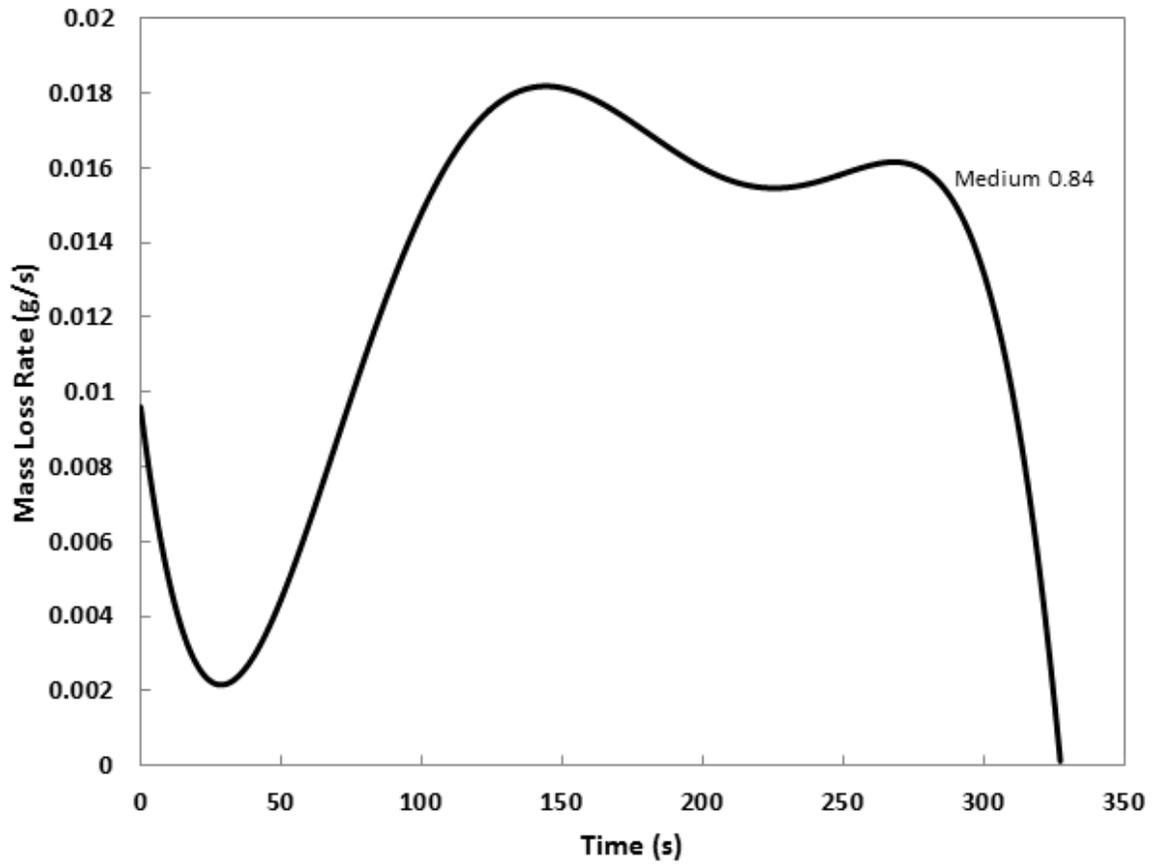


C.2 Medium 0.84 Ratio

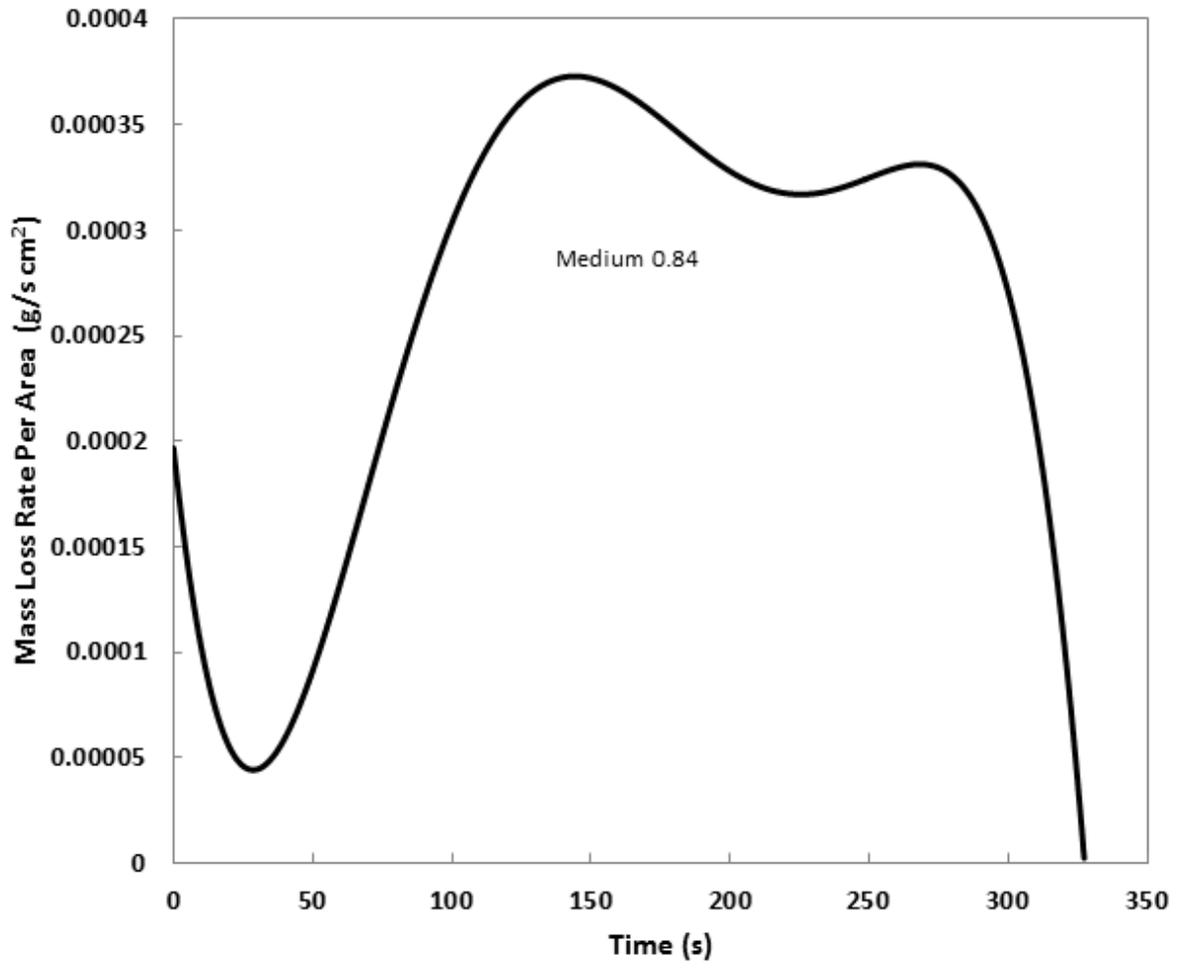
Mass Loss vs. Time



Mass Loss Rate vs. Time



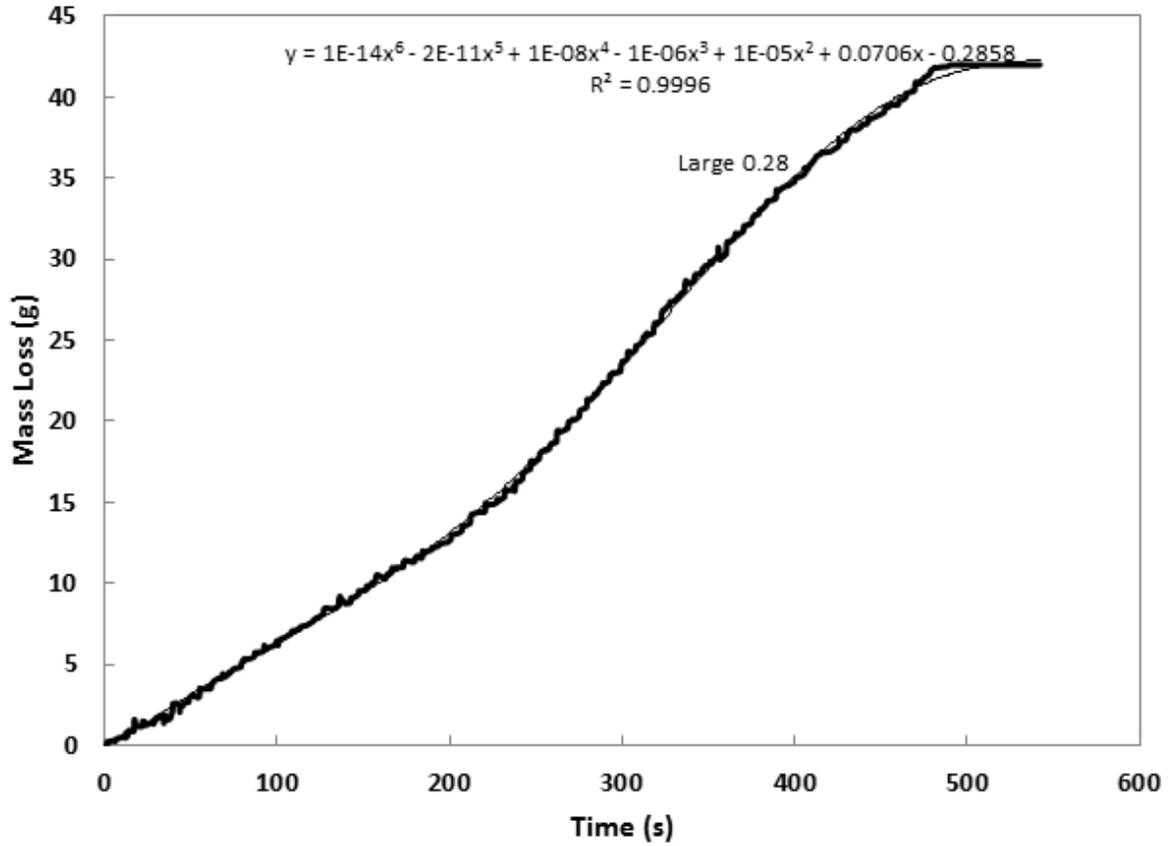
Mass Loss Rate Per Area vs. Time



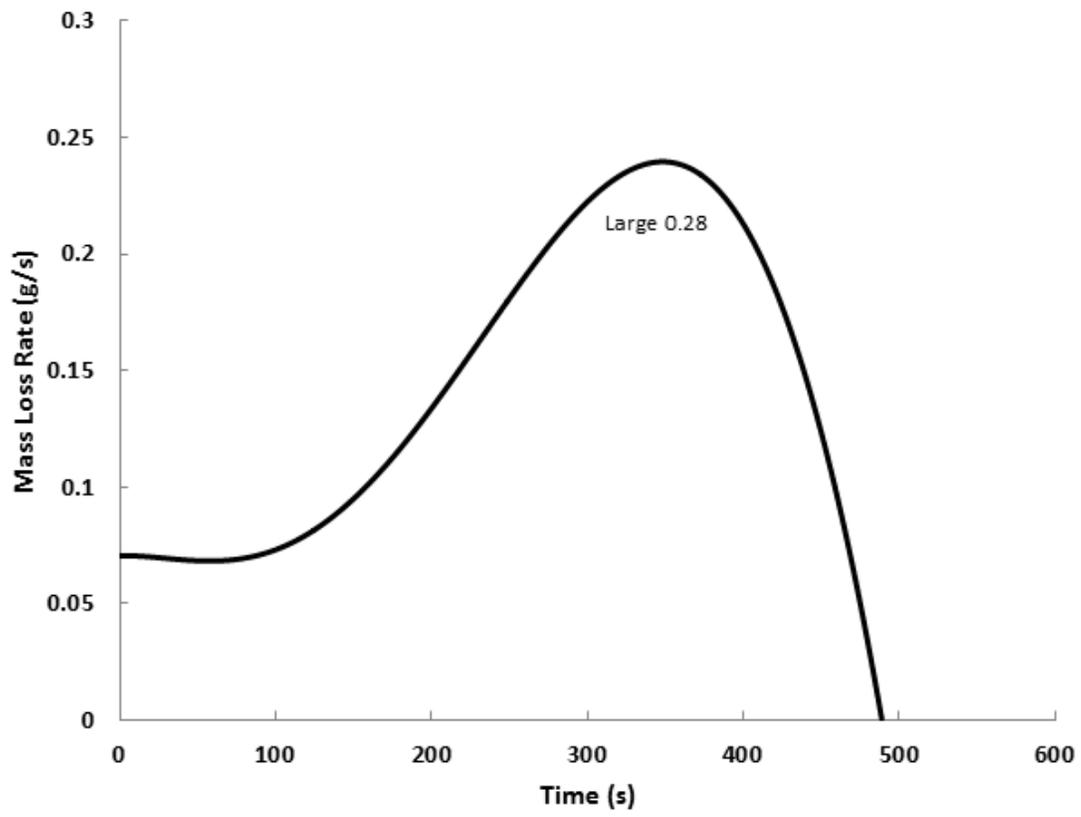
D Large Snow Trials

D.1 Large 0.28 Ratio

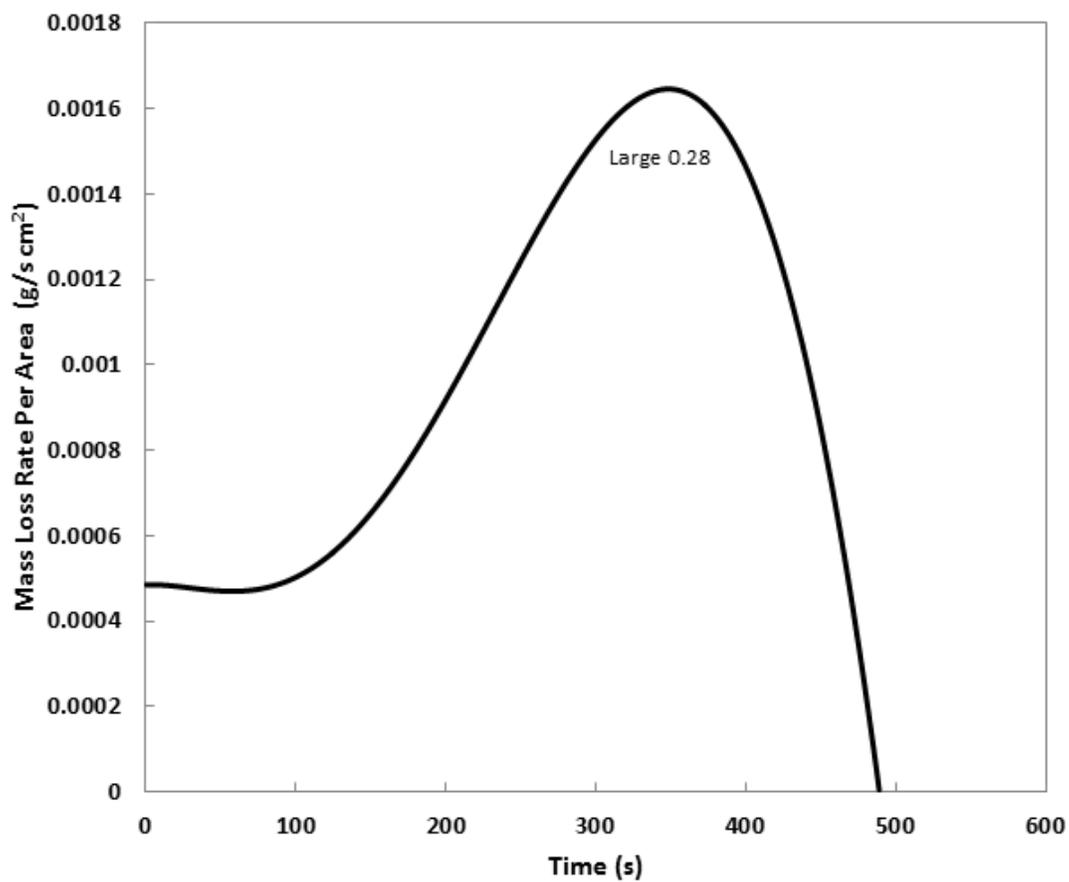
Mass Loss vs. Time



Mass Loss Rate vs. Time

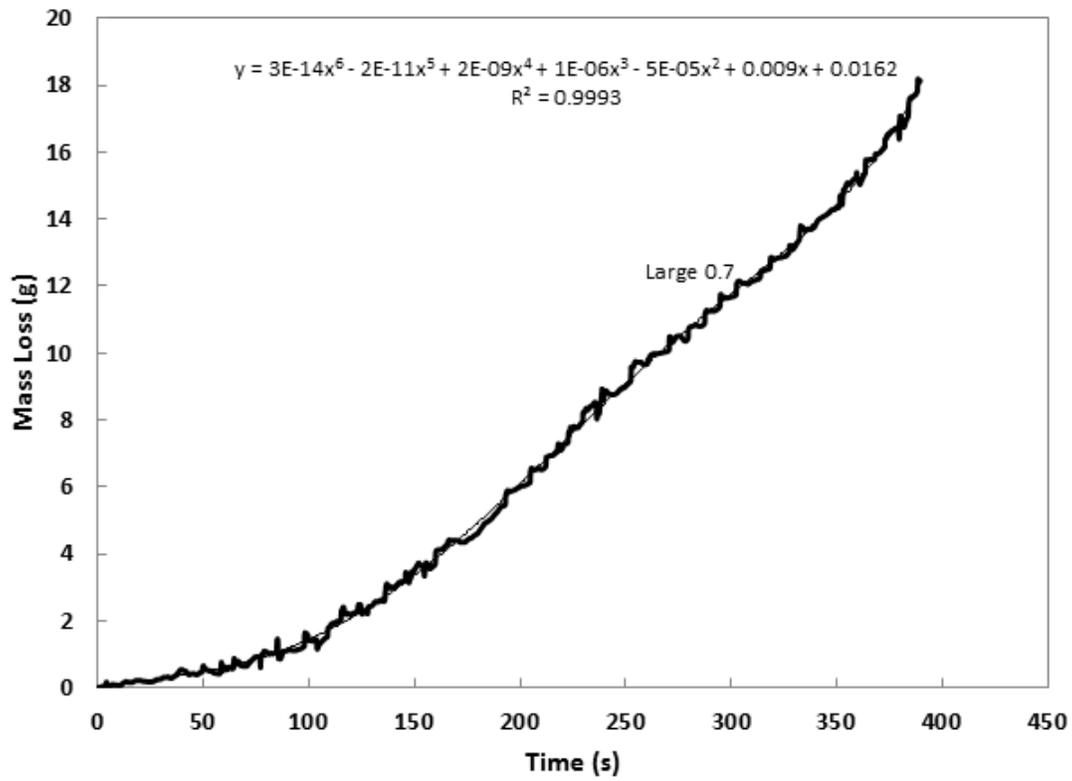


Mass Loss Rate Per Area vs. Time

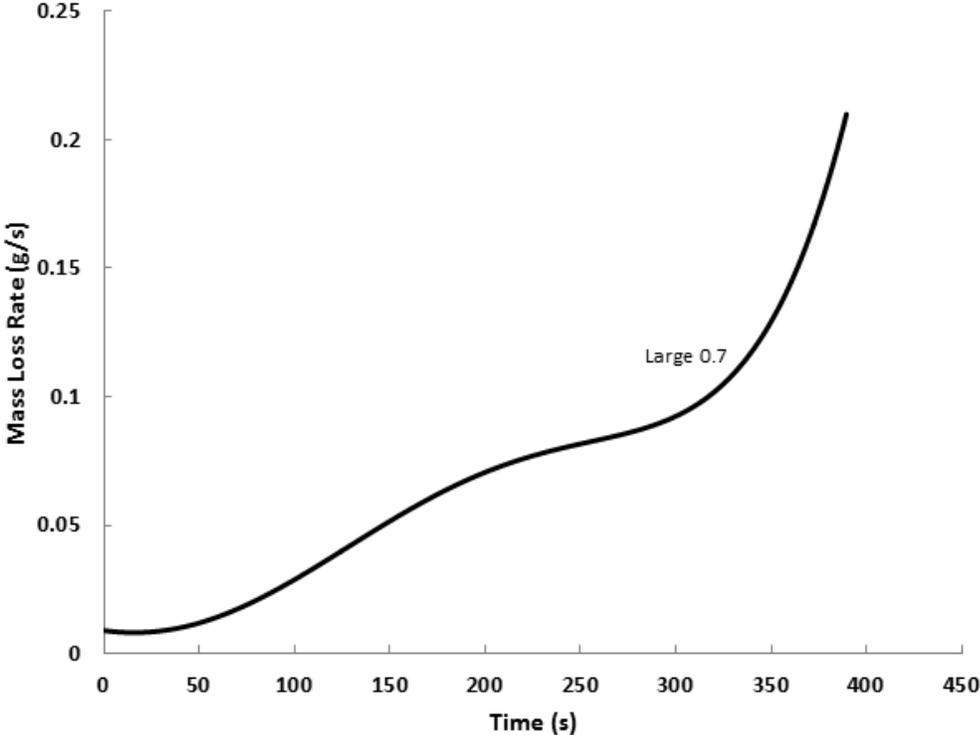


D.2 Large 0.7 Ratio

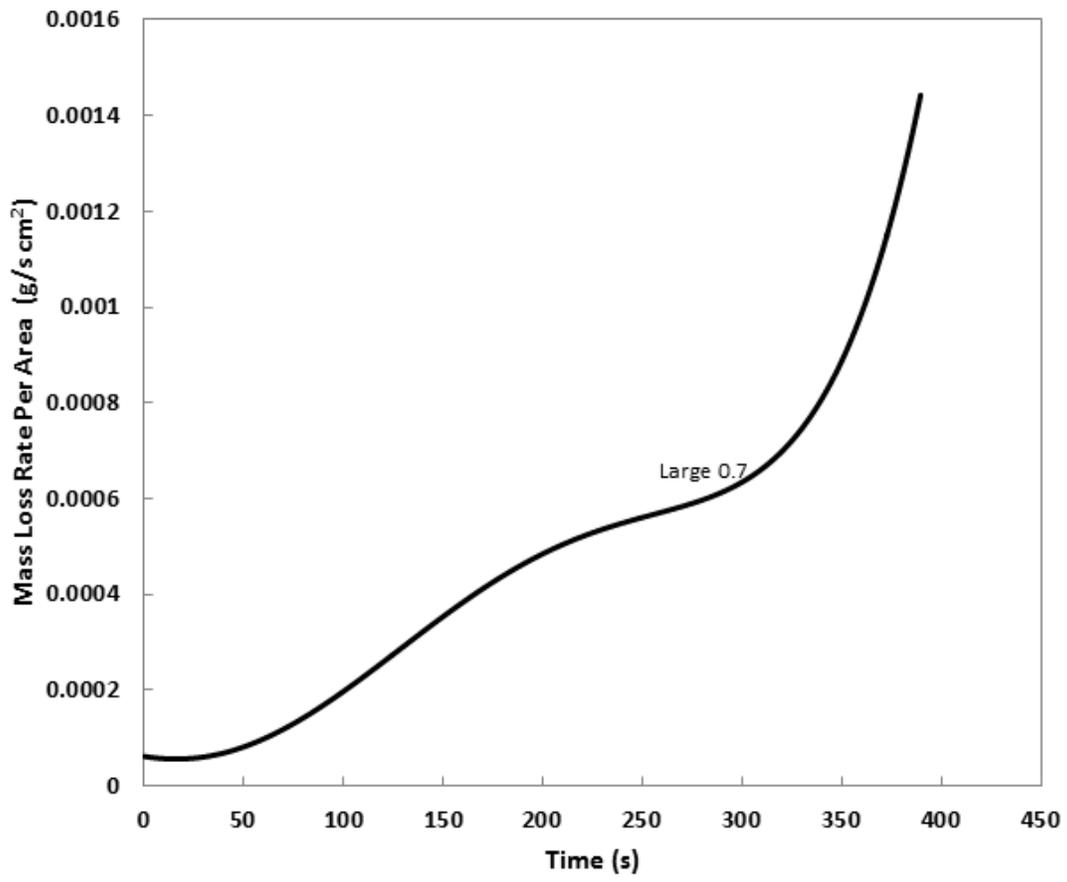
Mass Loss vs. Time



Mass Loss Rate vs. Time

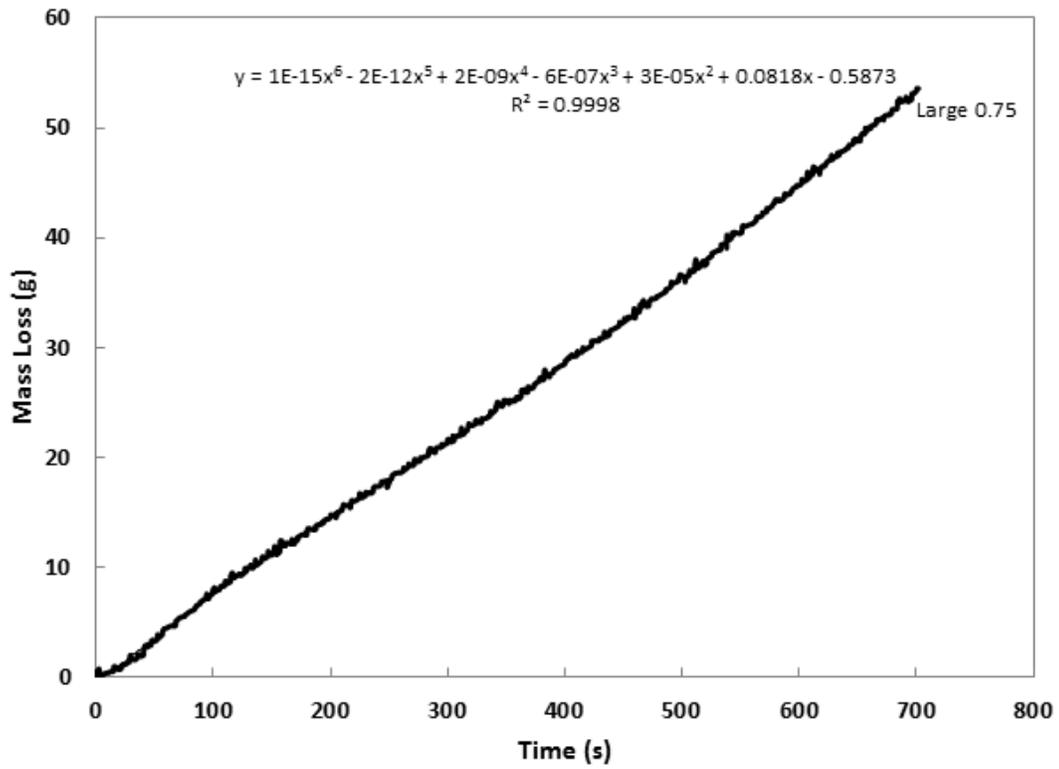


Mass Loss Rate Per Area vs. Time

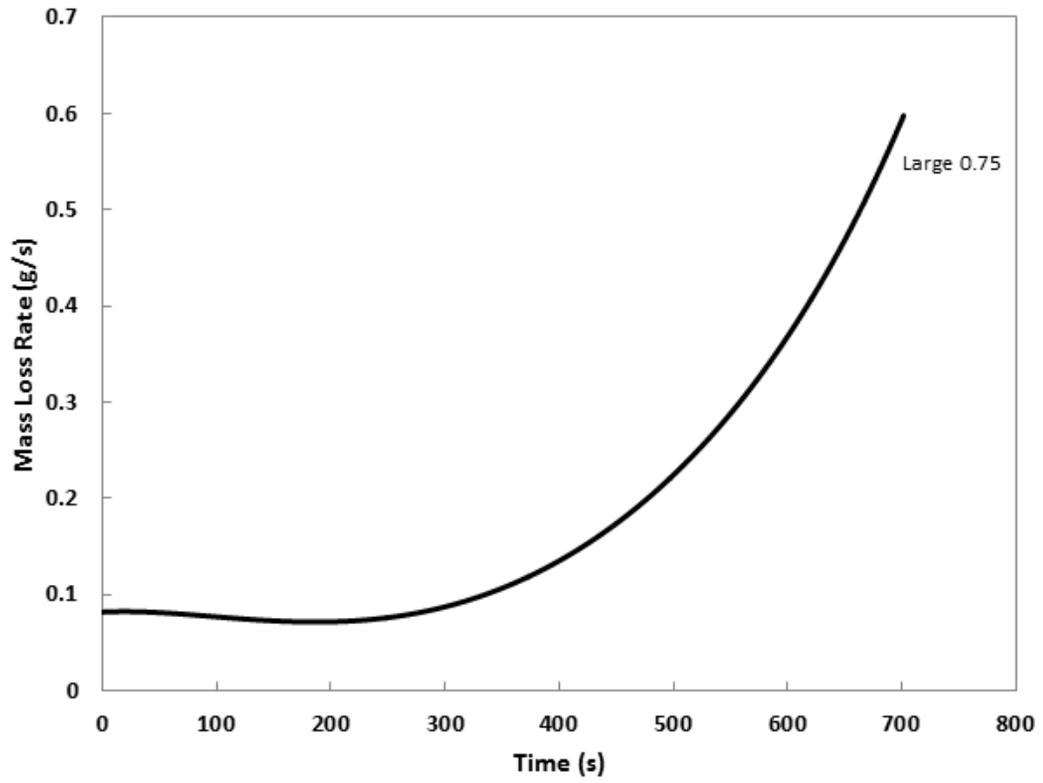


D.3 Large 0.75 Ratio

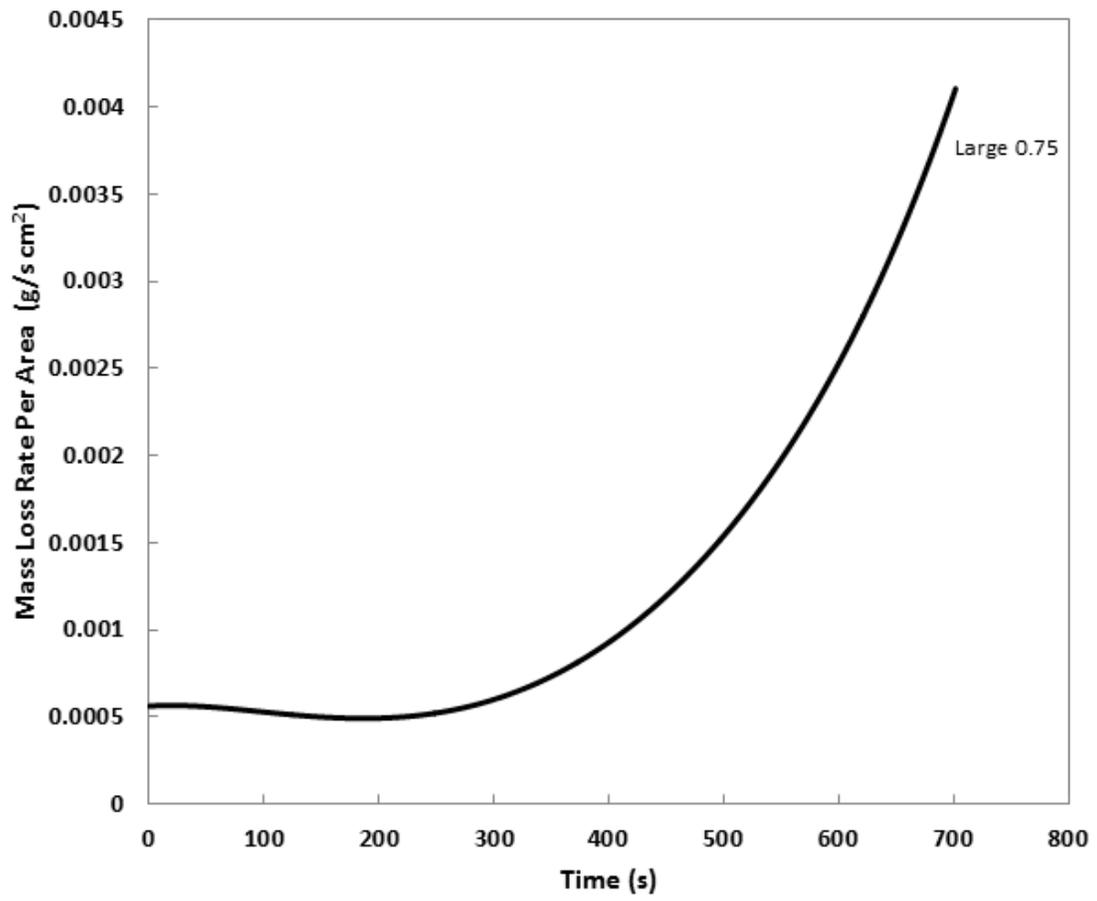
Mass Loss vs. Time



Mass Loss Rate vs. Time

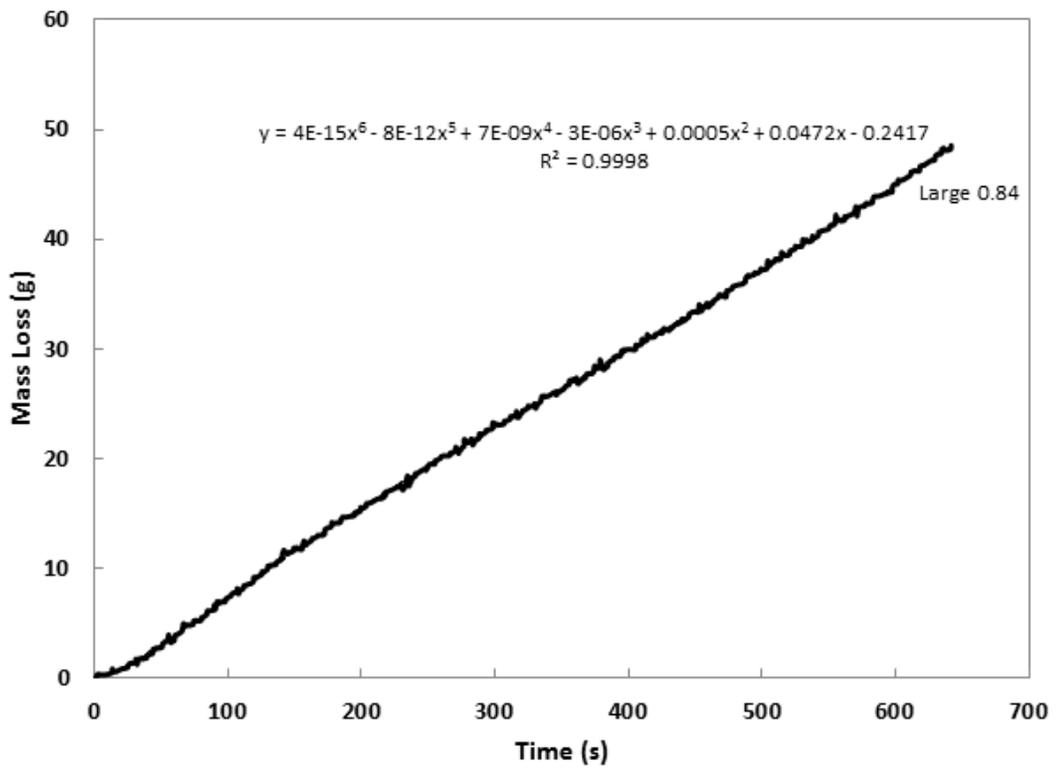


Mass Loss Rate Per Area vs. Time

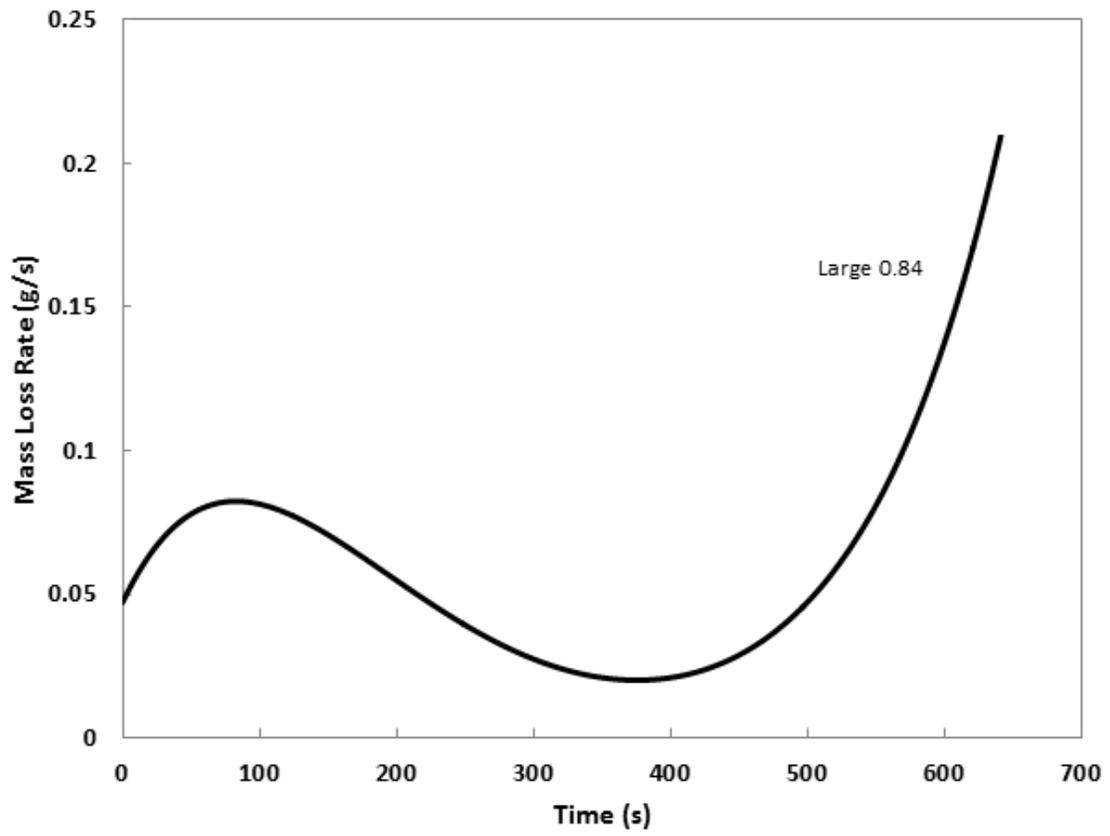


D.4 Large 0.84 Ratio

Mass Loss vs. Time



Mass Loss Rate vs. Time



Mass Loss Rate Per Area vs. Time

