

# **Dust Explosion of Niacin in the Animal Feed Industry**

A Major Qualifying Project submitted to  
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fulfillment of the requirements for the Bachelor of Science

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## Abstract

The objective of this research project is to study how the dust explosion of Niacin is affected by several factors and how different inerts inhibit the explosion of Niacin when mixed together and suspended in air. This is important because the number of explosions in the animal feed industry went from 8.6 to 20.2 explosions per year from 1900 to 1988 (Eckhoff, 2003). Since 2016, there has been an average of 29.3 explosions per year, resulting in 183 injuries and 15 deaths (Keefe & Cloney, 2023). The industry is massive, with over 250,000 employees (IFIF, 2020) and an annual turnover rate of more than \$400 billion (IFIF, 2024).

Anything that can burn in air can become explosive if subdivided enough, with the rate of its reaction increasing exponentially until it becomes an explosion, which can be triggered by a number of sources. A 20-L sphere was used to test Niacin and mixtures of it with inerts to see how its explosion is affected by concentration, turbulence, and the location of the chemical igniters within the sphere. Also, the decomposition of  $\text{NaHCO}_3$  was explored, determining how its endothermic, radical scavenging decomposition affects Niacin's explosion. The in-situ PSD of powder injected into the sphere was measured using a modified 20-L sphere and a Sympatec HELOS/KR-Vario laser.

$\text{NaHCO}_3$  and  $\text{NaCl}$  greatly inhibit the explosion of Niacin because they are radical scavengers with endothermic decompositions, which remove heat and  $\text{H}^+$  and  $\text{OH}^-$  radicals from the reaction.  $\text{MgO}$  and  $\text{CaCO}_3$  did not inhibit the explosion as well, because they are not radical scavengers and only act as heat sinks for the reaction. Decomposing  $\text{NaHCO}_3$  into  $\text{Na}_2\text{CO}_3$  increases the explosion severity greatly, but less so when  $\text{CO}_2$  is added to the sphere before the explosion. Moving the chemical igniters from the center of the sphere reduces the explosion severity because the flame gets quenched by the cold walls of the sphere. Increasing the ignition delay time linearly decreased the explosion severity exponentially. The dust particles became heavily fragmented when injected into the sphere because of the high force exerted on the particles.

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## Introduction

### Objective

The objective of this research project is to study how the dust explosion of Niacin is affected by several factors and how different inerts inhibit the explosion of Niacin when mixed together and suspended in air.

### Rationale

The animal feed industry produces nutrient-rich food and supplements for all types of livestock, such as cattle, pigs, chickens, and more. This industry is massive, with the International Feed Industry Federation saying it “generates an estimated annual turnover of over US \$400 billion” (IFIF, 2024) and directly employs “more than a quarter of a million skilled workers, technicians, managers and professionals” (IFIF, 2020). This large number of people employed and the high value of the field gives a great incentive for preventing explosions in the workplace.

Additionally, dust explosions are a common threat in the industry and others working with powdered substances. Between the years of 1900 and 1988, dust explosions in the United States increased in their frequency, injuries caused, and material loss across three sections of time. Table 1.1 displays statistics of grain dust explosions across most of the 20th century in the United States. This depicts that dust explosions have historically been a persistent threat in the animal feed industry.

**Table 1.1:** Grain dust explosions in the United States from 1900-1988 (Eckhoff, 2003)

Loss Category	1900-1956		1957-1975		1979-1988	
	Total	Per Year	Total	Per Year	Total	Per Year
Number of Explosions	490	8.6	192	10.1	202	20.2
Fatalities	381	6.8	68	3.6	54	5.4
Injuries	991	17.4	346	18.2	267	26.7
Estimated Damage to Facility (U.S. \$ millions), not inflated	70	1.3	55	2.9	169	16.9

In recent years, dust explosions have remained a prevalent problem. Since 2016, the United States has experienced an average of 29.3 explosions each year, with 26 people being injured and 2 people being killed. 48.4% of these explosions happened in factories working with food products, including animal feed. This threat to life, limb and material makes preventing dust explosions incredibly important.

**Table 1.2:** Dust explosion statistics from 2016-2022 in the United States (Keefe & Cloney, 2023)

Year	Explosions	Injuries	Fatalities
2016	31	22	3
2017	28	43	6
2018	37	30	2
2019	37	27	1
2020	26	23	1
2021	20	17	1
2022	26	21	1
<b>Average</b>	<b>29.3</b>	<b>26.1</b>	<b>2.1</b>

Niacin is used in the animal feed industry for many purposes, but it is very dangerous to work with due to its low energy required to ignite it. The minimum ignition energy is 7 mJ (Jubilant Ingrevia Limited, 2021). This amount of energy could be discharged as static electricity from a person touching a door handle (Eckhoff, 2003), dropping a tool onto the ground, or any number of sources. This makes using Niacin incredibly risky, so studying how its explosions are modified by different factors is important.

## Background

### What is a dust explosion?

Firstly, an explosion is “an exothermic chemical process that, when occurring at constant volume, gives rise to a sudden and significant pressure rise” (Eckhoff, 2003). Any solid material that can burn in air can also explode if subdivided small enough. A good example is a log of wood on a campfire. To light a log on fire in a campfire, it needs to sit on the flame for a long time before it can catch on fire, but it will likely burn for hours. To speed up its burn process, you take the log and put it into a woodchipper. These wood chips are much smaller, but have the same mass as the original log. These wood chips can now be lit with a match, but will likely burn for a few minutes. If you take the wood chips and grind them into a powder, like sawdust, you still have the same mass of wood as the wood chips or the log. The difference now is you can light this pile of sawdust with almost anything, but it will burn up very quickly. If you take a handful of sawdust, throw it in the air, and light it with a match, it will burn up almost instantly and the result is an explosion.

Dust explosions can be ignited from many sources. Some of these sources are smoldering or burning dust, open flames, electrical arcs, and mechanical impacts. Smoldering or burning dust can occur in a lot of ways, but a common way is dust accumulating on hot surfaces or hot pipes. The porous nature of dust layers gives oxygen “access to the particle surface throughout the deposit and makes the heat conductivity of the deposit low” (Eckhoff, 2003), which could result in an explosion. Open flames could be sourced from burners, boilers, blowtorches, anywhere that a flame is exposed to the air. Electrical arcs can occur from short circuits, static electricity discharges, or simply turning a lightswitch on or off. Mechanical impacts create a lot of heat from friction, which could start an explosion. This could be from a mechanic using a hammer, an accidental drop of a tool, or any sort of impact.

Dust explosions aren't a “one-and-done” event though, since they could trigger a secondary explosion too. The blast wave from the first explosion could knock a bulk-deposit of dust into the air, which becomes another hazard. The energy from the first explosion could ignite this new

dust cloud, triggering the secondary explosion. Secondary explosions can be more dangerous too, depending on the amount of dust disturbed by the first explosion (Eckhoff, 2003).

### Main factors that affect dust explosions

Dust explosions are highly variable and their activity can be changed by a number of means. One way is through the concentration of dust within the air. This concentration is normally expressed as  $\text{g/m}^3$ , grams of dust per cubic meter of air. In general, each type of dust has a range of concentrations in which it can explode. For a lot of organic dusts, this is a slim range, only about one order of magnitude in width.

Additionally, the chemical composition of the dust affects its explosibility. In a factory setting, it's highly unlikely that dust will solely be one compound suspended in air. It's likely to be several types of powders mixed together. Not every dust is explosive though, and some compounds inhibit the explosion of more reactive compounds. But like in all fields of chemistry, there are exceptions to this too. Serrano et. al. (2023) showed that some binary mixtures of dust increased in their explosion severity when the concentration of the inert was below 25%. This was not the case for all mixtures though, with some decreasing in severity with the introduction of any inert.

The size of particles in the air also affects the explosion. The smaller the particles, the stronger the explosion. This is because the number of active sites on a mass of flammable solid increases exponentially with each degree of subdivision, since the surface area of the dust per unit of volume increases exponentially. This is portrayed in the log example given previously. The more active sites, the more spots that a flame can start. This reduces the minimum ignition energy and increases the explosion severity. Once a dust's particle size is small enough, intermolecular forces become more influential than gravity. This can cause dust to agglomerate, which makes the effective particle size of the dust bigger and the surface area smaller. The agglomeration of dust makes the explosion less powerful.

The turbulence of the air influences the explosion of dust too. Increased turbulence leads to more molecule interactions in the air, which can make more powerful explosions. In an animal



feed factory, this could be from fans used to circulate air, trucks or other vehicles driving through, or other means of moving air. Turbulence affecting dust explosions can decrease exponentially though, which reduces the risk of dust explosions. Murillo (2016) used a 20-L sphere to study the effects of turbulence in dust explosions and after 100 ms of time after dust was injected into the sphere, the turbulence dropped by 80-90%.

## 20-L Sphere

The 20-L sphere Murillo (2016) used is the same used for this research project. This sphere is a double-walled steel sphere with cooling water flowing between the walls and it is the standardized device used to study dust explosions across the world. The main factors that are studied using the 20-L sphere are:

The maximum pressure within the sphere across a series of tests ( $P_{\max}$ ). For example, if a test is conducted at 250 g/m<sup>3</sup> of dust and the pressure in the sphere reaches 3.3 bar and another is conducted at 500 g/m<sup>3</sup> and the pressure reaches 5.2 bar, the  $P_{\max}$  is 5.2 bar.

The maximum rate of pressurization within the sphere in a series of tests  $(dP/dt)_{\max}$ .  $(dP/dt)_{\max}$  is determined in the same way as  $P_{\max}$ . However,  $(dP/dt)_{\max}$  is dependent on the size of the vessel that the explosion takes place in. If an explosion in the 20-L sphere has a  $(dP/dt)_{\max}$  of 150 bar/s, an explosion of that same caliber will not have the same pressure rise in a 100 m<sup>3</sup> storage drum in a factory.

To correct for this,  $K_{\max}$  is used.  $K_{\max}$  is used by organizations to determine proper explosion safety parameters and  $K_{\max}$  is dust-specific, not vessel-specific. Each dust has a  $K_{\max}$  value which classifies it as one of four categories, ST 0 to ST 3.

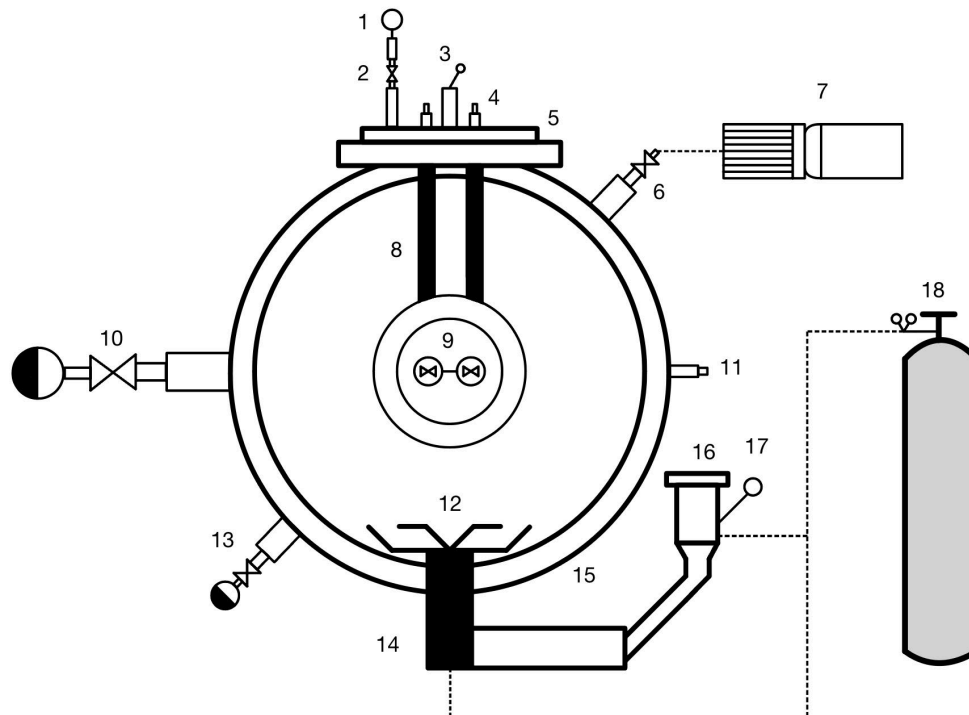
**Table 1.3:**  $K_{max}$  categories and their descriptions (Cesana & Siwek, 2022)

Category	$K_{max}$ (m·bar/s)	Description
ST 0	0	Not explosive
ST 1	0 - 200	Weak explosion
ST 2	201 - 300	Strong explosion
ST 3	> 301	Very strong explosion

$K_{max}$  is determined by the software associated with the 20-L sphere using this equation:

$$K_{max} \left( \frac{m \cdot \text{bar}}{s} \right) = \sqrt[3]{0.02(m^3)} \times \left( \frac{dP}{dT} \right)_{max} \left( \frac{\text{bar}}{s} \right) \quad (1)$$

The 20-L sphere is not commonly used to find the  $K_{max}$  of dusts because of its large size difference compared to industrial vessels. Instead, a 1 m<sup>3</sup> vessel is used. This is because the flame generated from explosions in the 20-L sphere is quenched more rapidly because it reaches the cool walls of the sphere faster.

**Figure 1.1:** Schematic of the 20-L sphere apparatus

**Table 1.4:** 20-L sphere apparatus parts' names

Number:	Abbreviation:	Piece:	Number:	Abbreviation:	Piece
1	P-1	Pressure gauge	10	V-4	Valve to exhaust
2	V-1	Valve to pressure gauge	11		Pressure recorder
3		Sphere safety switch	12		Dispersion nozzle
4		Electrode connection point	13	V-5	Valve to cooling water
5		Sphere lid	14	V-6	Air-controlled inlet valve
6	V-2	Valve to vacuum pump	15		Sphere walls
7		Vacuum pump	16		0.6 L compartment
8		Electrode cylinder	17	P-2	Pressure gauge
9	V-3	Inlet valves to sphere	18		Compressed air cylinder

P-1 is used to show the pressure inside the sphere. V-1 is used to protect the pressure gauge from the power of the explosion. The sphere safety switch disables the sphere when open, making an explosion impossible if the user is not prepared for one. The electrode connection point is where wires are connected to set off the chemical igniters that initiate the explosion. The vacuum pump is how the pressure in the sphere is regulated. The electrode cylinders are where chemical igniters are attached to initiate the explosion. The V-3 valves are where air can be let into the sphere if the pressure is too low or where other compressed gas cylinders can be connected. V-5 is where water is pushed between the walls of the sphere, keeping it cool throughout a series of tests. Powder is put into the 0.6 L compartment, which gets pressurized to 20 bar before V-6 injects it into the sphere.

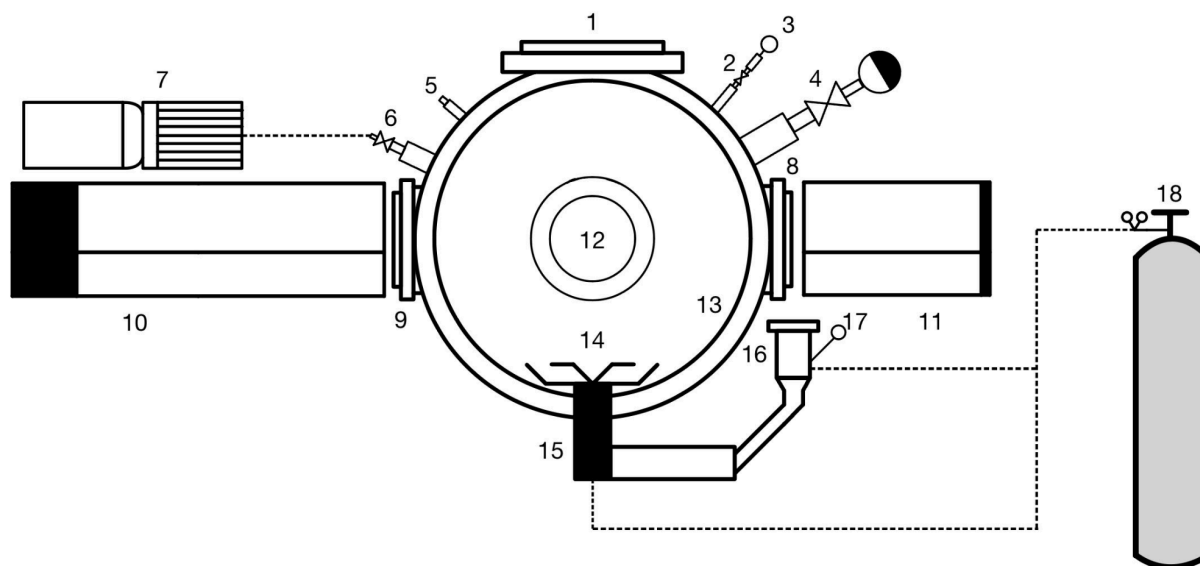


**Figure 1.2:** Picture of the 20-L sphere apparatus used

### In-Situ Particle Size Distribution

Powder that is injected into the 20-L sphere is fragmented severely because of the high pressure in the 0.6 L compartment. This makes the behavior of its explosion act differently than if the powder had not fragmented. The powder's PSD before injection is called ex-situ and its PSD after is called in-situ.

It is not possible to measure a powder's in-situ PSD using a traditional 20-L sphere. To see this, modifications were needed in order to visualize its behavior. First, a new 20-L sphere was used with windows on the sides. A laser was shined through the windows to measure the light diffraction caused by the particles of dust. The laser used was a Sympatec HELOS/KR-Vario.

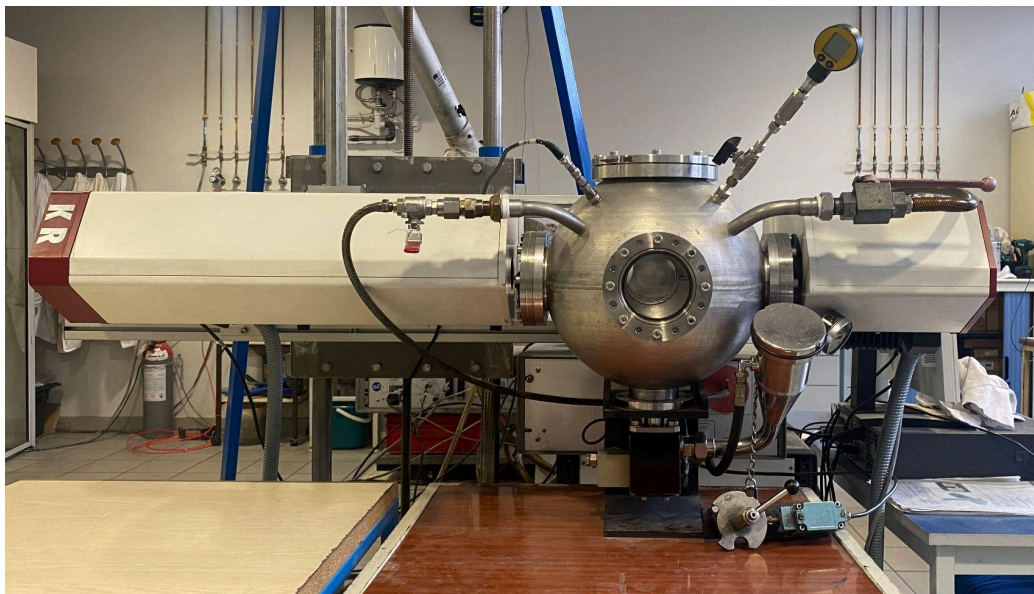


**Figure 1.3:** Schematic of the in-situ PSD analysis apparatus

There are no electrode cylinders in the 20-L sphere used for PSD analysis because no explosions can be done in this sphere for safety concerns. The laser's ends were positioned very close to the windows on the sphere to prevent any light from outside or the room reaching the lenses.

**Table 1.5:** In-situ PSD analysis apparatus parts' names

Number:	Abbreviation:	Piece:	Number:	Abbreviation:	Piece
1		Sphere lid	10		Left-part laser
2	V-1	Valve to pressure gauge	11		Right part laser
3	P-1	Pressure gauge	12		Sphere front window
4	V-2	Valve to exhaust	13		Sphere walls
5		Pressure recorder	14		Dispersion nozzle
6	V-3	Valve to vacuum pump	15	V-4	Air-controlled inlet valve
7		Vacuum pump	16		0.6 L compartment
8		Sphere right-side window	17	P-2	Pressure gauge
9		Sphere left-side window	18		Compressed air cylinder



**Figure 1.4:** Picture of the in-situ PSD analysis apparatus used

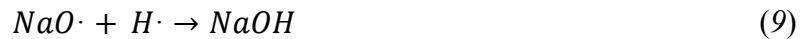
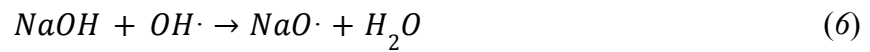
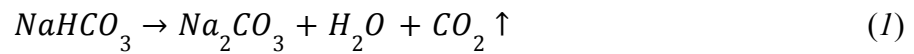
### Compounds Used in the Experiments

Niacin is an organic powder and was the main compound used in the experiments. Also known as Vitamin B-3, it is an ST 2 compound, making it very explosive, with a  $(dP/dt)_{\max}$  of 912 bar/s  $\pm 10\%$  when tested as a pure compound. In the animal feed industry, it is used mainly in cow and bull feed. Panda et al. (2017) studied the effects of adding Niacin to a cow's diet from the last 2 weeks of gestation to early lactation. They found that adding 12 g of Niacin to a cow's daily diet increases milk production by 11 lb over the course of a lactation cycle. It also protects them from metabolic diseases like ketosis, which are rampant among lactating cows. The control group which was not supplied any niacin, had an average of 16.7 mg/dl of acetone in their blood. The group given 6 g of niacin per day had an average of 10.2 mg/dl and the group given 12 g of niacin a day had an average of 6.83 mg/dl. This significant drop in acetone levels reduced the likelihood of a cow developing ketosis. They also experienced a lot less heat stress.

Sodium bicarbonate ( $\text{NaHCO}_3$ ) is an inert in dust explosions that was studied.  $\text{NaHCO}_3$  starts to decompose 170 °C, but is faster at 200 °C (Pasquali et al., 2007). The decomposition has a physical and chemical effect on explosions when  $\text{NaHCO}_3$  is mixed with an explosive dust. Increased number of moles in the sphere after the decomposition gives the physical effect of acting like a heat sink for the explosion. This takes heat away from the explosive material,

reducing the flame propagation and ultimately, the severity of the explosion. Also, the reaction itself is endothermic, further acting as a heat sink.

NaHCO<sub>3</sub>'s chemical effect on dust explosions is radical scavenging. When an organic dust explodes, many different compounds are made, most of which need to react with an H<sup>+</sup> or OH<sup>-</sup> radical to form and release energy. NaHCO<sub>3</sub>'s decomposition consumes these radicals, which limits the explosion's severity since they can no longer react with the organic material. Yang et al. (2022) studied the decomposition of NaHCO<sub>3</sub> and showed the process as follows:



This 9-step process includes the consumption of 5 H<sup>+</sup> or OH<sup>-</sup> radicals being consumed per molecule of NaHCO<sub>3</sub>. The explosion of organic powders is severely dampened by the decomposition as a result.

Sodium chloride (NaCl) is an inert in dust explosion as well that also features some radical scavenging. The decomposition of NaCl happens at 807 °C and is also an endothermic reaction (Yang et al., 2022). This results in Na<sup>+</sup> and Cl<sup>-</sup> ions being made, which reacts with H<sup>+</sup> or OH<sup>-</sup> radicals in the explosion. NaCl's radical scavenging is not as strong though, since only 2

molecules can be removed from the explosion per molecule of NaCl, compared to 5 for NaHCO<sub>3</sub> (Cao et al., 2015).

Calcium carbonate (CaCO<sub>3</sub>) is another inert that was tested. CaCO<sub>3</sub> thermally decomposes above 840 °C into CaO and CO<sub>2</sub> molecules. This is endothermic and it acts like a heat sink. However, neither of the products of the decomposition are radical scavengers, so its inerting effect is purely physical. Magnesium oxide (MgO) was tested too. MgO does not decompose in a dust explosion because of its extremely strong intermolecular forces. Its melting point is 2,852 °C (Haynes & Lide, 2011). It acts purely as a heat sink itself, instead of having an endothermic reaction to take heat away.



## Methodology

### Tests in the 20-L sphere

To conduct tests, first the mixture that was being tested was prepared. When it was made, roughly 5g of extra powder was mixed in case of spills. The sphere was rebuilt before the tests, since it needed to be cleaned and allowed to dry overnight if tests were done previously. All pieces were dried with a paper towel before being rebuilt, if needed. The cooling water pump was turned on V-5 was opened, allowing cooling water to flow between the inner and outer walls of the sphere. If the water reached 35 °C, some water was removed and replaced with cold water.

Next, chemical igniters were prepared. The exposed wire on the ends of the ignitor were threaded through the eyelets in the electrode cylinders and bent upwards to ensure physical contact with the cylinders. The rest of the wires were wrapped around the exposed part and the cylinders to further the physical contact. This is necessary because the electrical charge that activates the igniters runs through the cylinders. The opening to the igniters were oriented downwards. If multiple igniters were used, the exposed parts of each wire were intertwined tightly and fastened to the electrode cylinders in the same fashion as a single igniter. The pattern of the wires being intertwined did not matter, a white wire can be paired with another white wire or a red one. After the chemical igniters were attached, the lid was put on the sphere, locked in place, and the electrodes were put on the electrode connection points. The electrodes can also be placed on either connection point.

Next powder was put into the 0.6 L compartment. Slightly more powder than was required for the test was used (0.01 - 0.05 G). This was because some powder gets stuck in the tube connecting it to the sphere, so this helps reduce error. A spatula was used to push the powder down far into the 0.6 L compartment while the side was hit with the lid of the compartment to get as much dust to enter the sphere after the test was started.

Next, the vacuum pump was turned on and V-2 was opened. Once the sphere reached 0.350 - 0.370 bar, V-2 was closed and the vacuum pump was turned off. The sphere was inspected for

leaks after. If the pressure was increasing too quickly, bolts and connections were tightened and the valves were inspected for any airflow. The sphere's pressure inside always still increased, since it was never perfectly airtight. A "rule of thumb" followed was that the sphere should not have a change in pressure greater than  $\sim 0.0003$  bar/s. Any residual water in the sphere would turn into a vapor when the sphere is depressurized, so the pressure would increase slightly faster after cleaning it.

After all leaks were addressed, The pressure was increased to 0.395 bar. At 0.4 bar, the 20 bar of pressure in the 0.6 L compartment would increase the pressure in the sphere to atmospheric pressure without an explosion. The test was then launched in KSEP, the software paired with the sphere. This would pressurize the 0.6 L compartment, inject the dust, and ignite the chemical igniters. After, the caps to the igniters were vacuumed out, along with any residual dust from the sphere and the 0.6 L compartment. This process was repeated until all tests were completed for the series. 7-8 tests could be done without needing to clean the sphere. If low concentrations of dust were used, (less than  $500 \text{ g/m}^3$ ) 9-10 tests could be done before cleaning the sphere.

To clean the sphere, all valves were closed, the cooling pump was turned off, the compressed air tank closed, and the line connecting the compressed air tank to the sphere was bled. The lid, 0.6 L compartment, dust dispersion nozzle, and sublid were removed. V-6 was removed with the 0.6 L compartment still attached. The stopper in V-6 was removed from the valve. All pieces were cleaned with water, scrubbing each piece with a sponge. The electrical components of V-6 and the lid were not cleaned to prevent damage. When cleaning the lid, V-1 was closed to prevent damage to the pressure gauge. The inside walls of the sphere were cleaned with a sponge as well. All pieces were dried with paper towels and left to dry overnight before the next series of tests were completed.

## In-Situ Particle Size Distribution Analysis Methodology

To conduct the in-situ PSD analysis, the first step was to clean the sphere and laser. The analysis is very sensitive to change, so everything needed to be cleaned as perfectly as possible. The sphere and 0.6 L compartment were vacuumed to remove any dust inside. The side and top

windows of the sphere were cleaned with a paper towel wetted with ethanol. Both sides of the side windows were cleaned, ensuring there were no smudges or dust on the glass. The lenses were cleaned with a lens cleaning tissue wetted with ethanol as well, also ensuring there were no smudges or dust. If there was anything on the glass, it would interrupt the laser's path and cause errors in the laser's PSD analysis. The dispersion nozzle so that its side arms are perpendicular to the laser's path through the windows. This helps prevent the windows from being instantly covered in dust, blocking the laser.

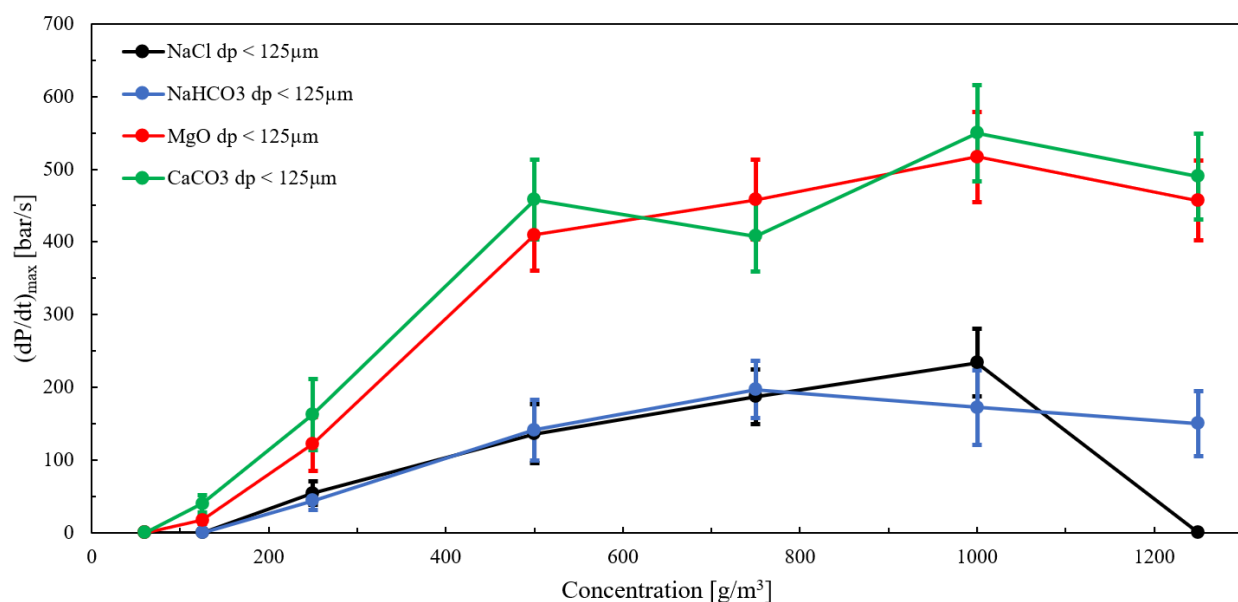
The lid was screwed on and 0.43 - 0.47 g of the powder being tested was put in the 0.6 L compartment. The sphere was depressurized to 0.3 bar and V-3 was closed. The sphere was depressurized so much to allow time to address any leaks and start the laser. Any leaks that were present were fixed in the same manner as in the 20-L sphere tests.

Next, the laser was turned on, the Windox 5.7 software was opened, and the appropriate lens was selected. There were 3 lenses, R1, R3, and R5, each with a PSD it was able to detect. Fine dust could be detected by the R1 and R3 lens, but the R5 was used for coarser dust. The clarity of the lens was tested, ensuring the opacity is below 2%. The higher the opacity was, the less clear the windows were. A high opacity could have made the laser stop calculating the results from the test. A reference test was done before each trial, removing any effects of any dust still in the sphere. After the reference test was completed, the pressure was raised to 0.395 bar and the actual measurement was started. A "test check" was done in KSEP to inject the dust into the sphere. The laser would measure the light diffraction caused by the dust and start calculating the results. 2-3 minutes later, the result would display in the Windox 5.7 software.

## Results and Discussion

### 50/50 wt% Niacin/Inert Mixtures' Explosion Severities

Niacin was mixed with each inert in a 50/50 wt% ratio. The purpose of these tests were to see how well the inerts inhibit the explosion of Niacin at different dust concentrations inside the sphere. When this factor is tested, the mixtures with a lower  $(dP/dt)_{\max}$  show a stronger inhibiting effect than those with higher  $(dP/dt)_{\max}$ . These trials were conducted using a 60 ms ignition delay time and 10 kJ ignition energy.



**Figure 3.1:** Explosion severities of 50/50 wt% mixtures of Niacin and inserts at different dust concentrations

NaHCO<sub>3</sub> is the best inhibitor of the 4 inserts tested, with a  $(dP/dt)_{\max}$  of 197 bar/s  $\pm$  20%. The decomposition of NaHCO<sub>3</sub> is the main reason for this, because of both a strong physical and chemical effect. The radical scavenging of the inert puts it above the others with its ability to quench the flame of the explosion. NaCl was also extremely good at inhibiting the explosion, having a  $(dP/dt)_{\max}$  of 234 bar/s  $\pm$  20%. This is close to the value for NaHCO<sub>3</sub> because of the very high ignition energy. If the ignition energy were lower, the explosion could have started at a more localized point, making the radical scavenging of NaHCO<sub>3</sub> much more effective than the

radical scavenging of NaCl. Both  $\text{CaCO}_3$  and  $\text{MgO}$  did not act as effective inhibitors, with a  $(dP/dt)_{\max}$  of  $550 \text{ bar/s} \pm 12\%$  and  $517 \text{ bar/s} \pm 12\%$  respectively. Their reduced effectiveness is because they lack the chemical effect that  $\text{NaHCO}_3$  and  $\text{NaCl}$  have.

**Table 3.1:**  $(dP/dt)_{\max}$  of each mixture and their severity reduction compared to pure Niacin

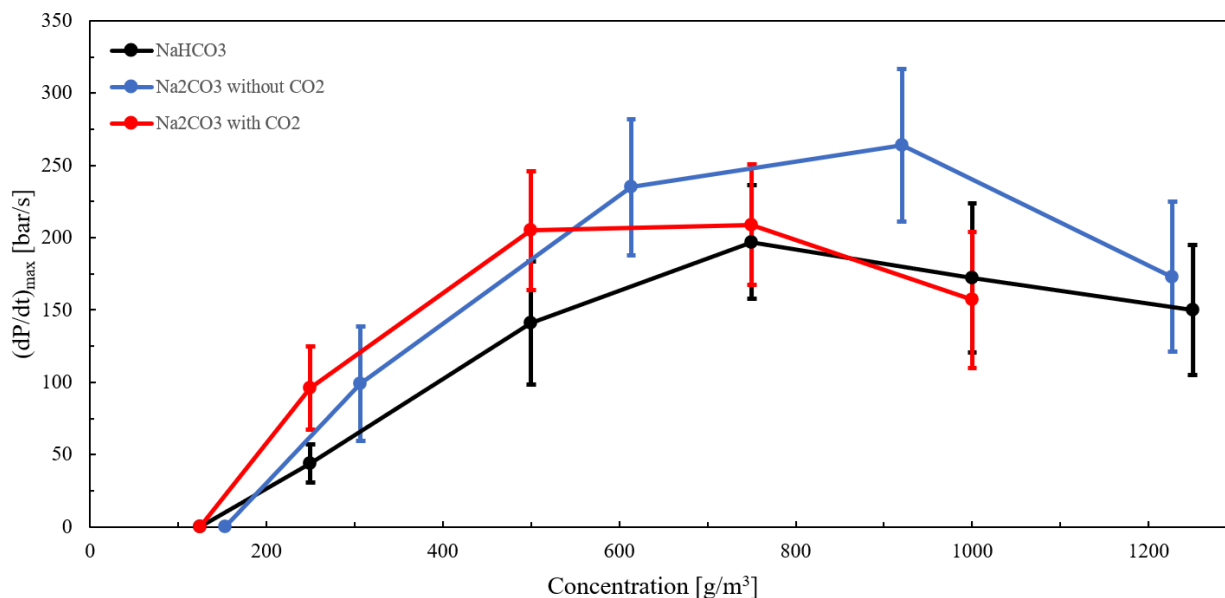
Compound	$(dP/dT)_{\max}$ (bar/s)	Uncertainty ( $\pm\%$ )	Explosion Severity Reduction
Pure Niacin	912	10	
$\text{CaCO}_3$	550	12	39.7
$\text{MgO}$	517	12	43.3
$\text{NaCl}$	234	20	74.3
$\text{NaHCO}_3$	197	20	78.4

## $\text{NaHCO}_3$ Decomposition

The decomposition of  $\text{NaHCO}_3$  has a lot of parts that affect the explosion of Niacin, with radical scavenging, increasing the amount of molecules present in the sphere, and being endothermic and taking energy away from the flame. Trials were conducted to see how the explosion would be affected if some of these factors were removed.

$\text{NaHCO}_3$  ( $d_p < 125 \mu\text{m}$ ) was heated in an oven at  $200 \text{ }^\circ\text{C}$  overnight to decompose it into  $\text{Na}_2\text{CO}_3$ . It was mixed with Niacin ( $d_p < 20 \mu\text{m}$ ) so that  $\text{Na}_2\text{CO}_3$ 's wt% was equivalent to the amount produced from its decomposition in the explosion. For every gram of  $\text{NaHCO}_3$  used, 0.63 g of  $\text{Na}_2\text{CO}_3$  is produced. For a trial requiring 20 g of powder, 16.3 g were used, 10 g of Niacin and 6.3 g of  $\text{Na}_2\text{CO}_3$ . A  $\text{CO}_2$  tank was also attached to V-3 to put the amount of  $\text{CO}_2$  produced by the decomposition of  $\text{NaHCO}_3$  as well. The ignition delay time was set to 60 ms and the ignition energy was 10 kJ.

It was expected that the explosion severity of a Niacin/ $\text{Na}_2\text{CO}_3$  mixture without  $\text{CO}_2$  would be the highest. This mixture removes a portion of molecules from inside of the sphere ( $\text{CO}_2$ ) and the endothermic first step of its decomposition. When  $\text{CO}_2$  is added to the sphere, the only portion not included is the first decomposition step.

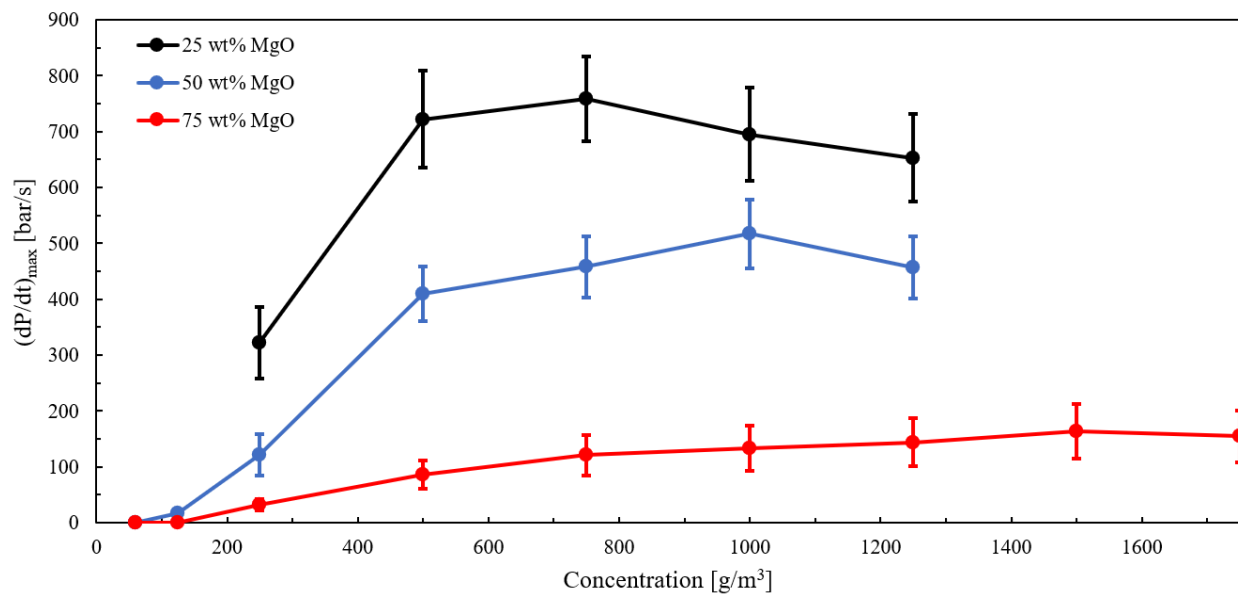


**Figure 3.2:** Explosion severities of  $\text{Na}_2\text{CO}_3$  compared to  $\text{NaHCO}_3$

At lower concentrations, the trials with  $\text{CO}_2$  had higher values for  $(dP/dt)_{\max}$  than those without  $\text{CO}_2$ , but still within the uncertainty of the tests. At higher concentrations, the tests without  $\text{CO}_2$  became more severe and followed the hypothesis. When  $\text{CO}_2$  is not added, the concentration of radicals in the sphere is higher and leads to a higher explosion severity.

### $(dP/dt)_{\max}$ vs. Inert Concentration

To test how the concentration of niacin within the dust affects its explosion, 3 binary mixtures of  $\text{MgO}$  ( $d_p < 125 \mu\text{m}$ ) and Niacin ( $d_p < 20 \mu\text{m}$ ) were prepared, with  $\text{MgO}$  being 25 wt%, 50 wt%, and 75 wt% in the samples. The ignition delay time was set to 60 ms and the ignition energy was 10 kJ.

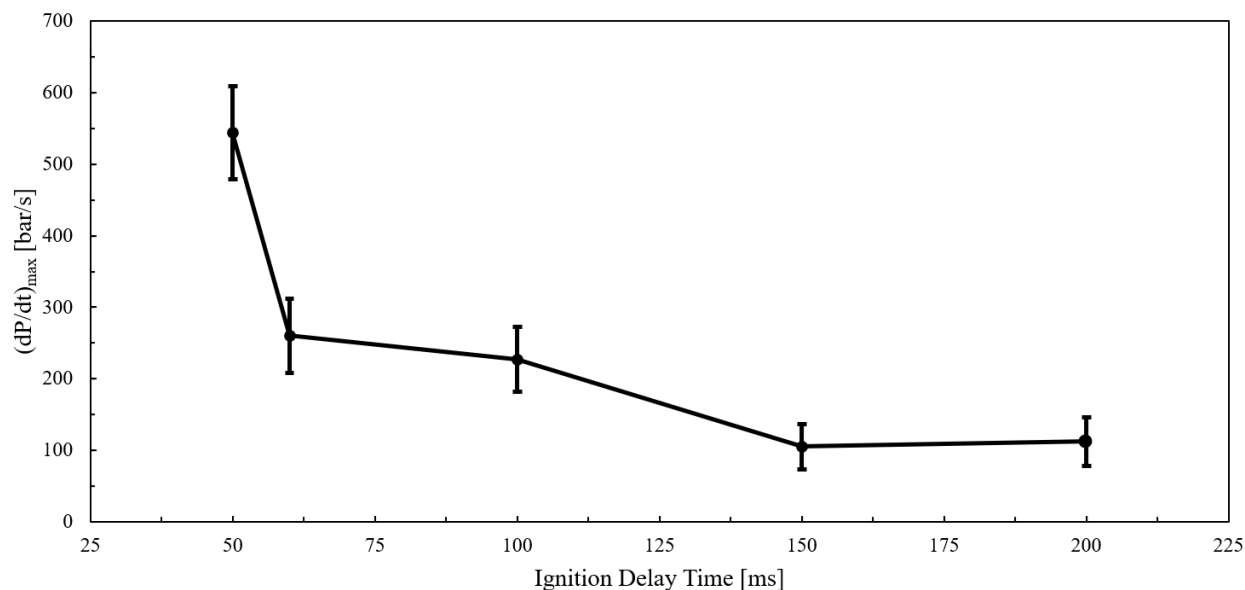


**Figure 3.3:**  $(dP/dt)_{\max}$  at different MgO concentrations and different dust concentrations

As the concentration of MgO increased, the overall explosion severity decreased dramatically. The sample that was 25 wt% MgO had a  $(dP/dt)_{\max}$  of 758 bar/s  $\pm$  10%. Also, the maximum rate of pressurization happened at a lower concentration than the other trials, at 500 g/m<sup>3</sup>. The tests at 50 wt% MgO had a  $(dP/dt)_{\max}$  of 517 bar/s  $\pm$  12%, peaking at 1,000 g/m<sup>3</sup>. At 75 wt% MgO, its peak happened much later at 1,500 g/m<sup>3</sup>, only at 164 bar/s  $\pm$  30%.

### $(dP/dt)_{\max}$ vs. Ignition Delay Time

The turbulence inside of the sphere is incredibly high just after the dust is injected, but it drops quickly. Higher turbulence leads to more particle interactions, which increases the explosion's severity. To conduct these tests, a 50/50 wt% mixture of Niacin ( $d_p < 20 \mu\text{m}$ ) and MgO ( $450 \mu\text{m} < d_p < 630 \mu\text{m}$ ) was made. The ignition delay time varied between 50 ms and 200 ms and the ignition energy was 100 J. A lower ignition energy was used to allow the turbulence inside the sphere to reduce faster.



**Figure 3.4:**  $(dP/dt)_{\max}$  of a Niacin/MgO mixture at different ignition delay times

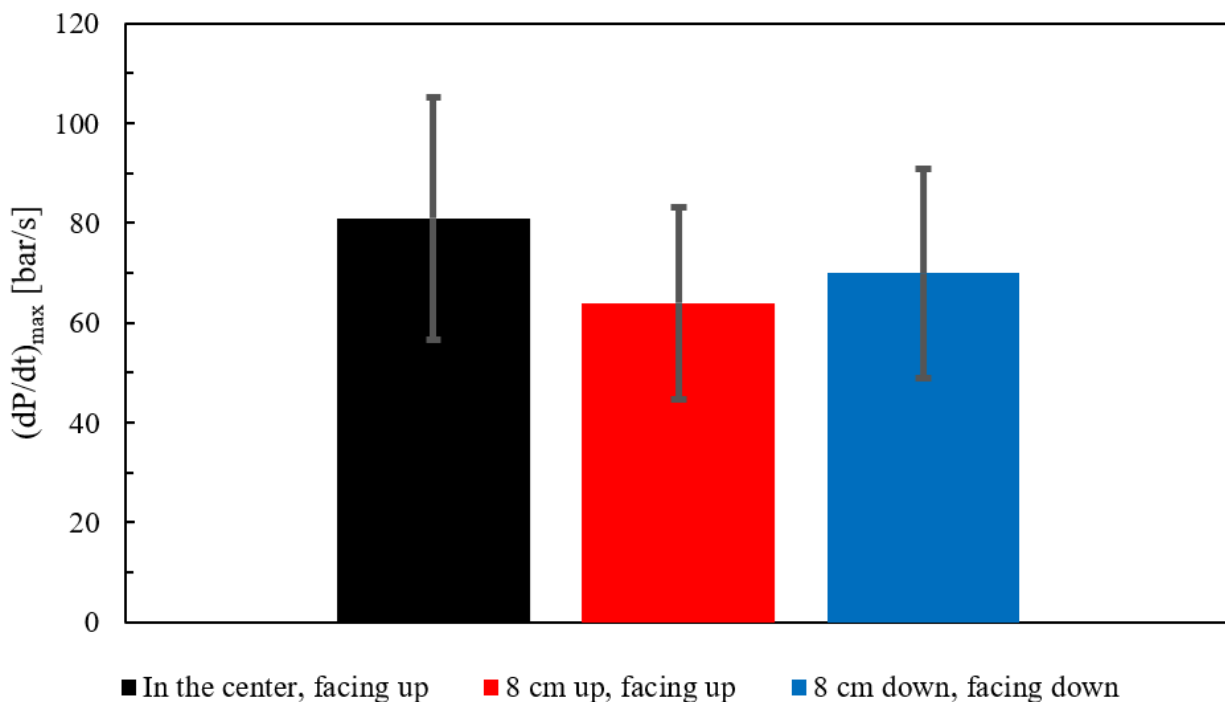
At earlier ignition delay times, the explosion severity is incredibly high. But after 60 ms, the severity decreased somewhat linearly. This follows a similar pattern to that presented by Eckhoff (2003), where the explosion severity decreased proportionally with a decrease in turbulence.

## Location of the Chemical Igniters

After a significant amount of time, the reduction in turbulence within the sphere could cause the dust to settle to the bottom. Larger, more dense molecules would settle faster than smaller and lighter ones, since they are less likely to follow the air's pattern since they have a higher Stoke's Number value.

These tests were done with a 50/50 wt% mixture of MgO ( $450 \mu\text{m} < dp < 630\mu\text{m}$ ) and Niacin ( $dp < 20 \mu\text{m}$ ). This mixture was used because MgO is over twice as dense as Niacin and its particle size is much bigger as well. After the turbulence drops, MgO is more likely to settle than Niacin. This would make the concentration of Niacin in the top-half of the sphere higher than the bottom-half, which would make explosions originating in the top-half more powerful as well. The trials were conducted using a 200 ms ignition delay time and ignition energy of 100 J.





**Figure 3.5:** Explosion severity of tests when moving the location of chemical igniters

When the chemical igniter was moved away from the center of the sphere, it decreased the explosion severity by between 15-20%. This is likely because of flame quenching. When the flame of the explosion reaches the cold walls of the sphere, a lot of its heat is transferred to the walls and causes the flame to collapse. When the chemical igniters are moved from the center, the explosion starts closer to the walls and the opening of the igniters are pointed toward the walls. This made the flame be quenched by the walls sooner, before all of the Niacin could be ignited, reducing the explosion severity.

### In-Situ Particle Size Distribution

When the PSD was tested, Niacin ( $dp < 20 \mu\text{m}$ ) and each inert ( $dp < 125 \mu\text{m}$ ) was injected into the sphere alone to test how its PSD changed after injection. Then, Niacin was mixed with each inert in a 50/50 wt% ratio, then tested as well. Mixtures were tested to see if there is any visible agglomeration of the dusts. The laser used measures the PSD every 5 ms for 300 ms after the opacity of the air in the sphere reaches 1% or higher.

**Table 3.2:** Average dust PSD values for pure compounds

Compound	d10 ( $\mu\text{m}$ )	d50 ( $\mu\text{m}$ )	d90 ( $\mu\text{m}$ )	d99 ( $\mu\text{m}$ )
Niacin	1.87	3.26	5.48	8.78
NaHCO <sub>3</sub>	3.22	7.19	10.61	18.33
NaCl	2.66	6.98	16.35	25.66
CaCO <sub>3</sub>	2.03	4.84	7.33	12.57
MgO	2.45	8.20	18.11	27.41

All of the pure compounds were fragmented heavily by their injection into the sphere. Niacin's smaller size is because its starting particle size was smaller than the inerts, starting at  $< 20 \mu\text{m}$  instead of the inerts'  $< 125 \mu\text{m}$ . NaCl and MgO were larger after injection than the others because of the intermolecular forces in the compounds. Both of them have ionic bonds instead of the covalent bonds of CaCO<sub>3</sub> and NaHCO<sub>3</sub>.

**Table 3.3:** Average dust PSD values for 50/50 wt% mixtures with Niacin

Mixture's Inert	d10 ( $\mu\text{m}$ )	d50 ( $\mu\text{m}$ )	d90 ( $\mu\text{m}$ )	d99 ( $\mu\text{m}$ )
NaHCO <sub>3</sub>	1.73	4.53	7.34	9.00
NaCl	2.64	6.11	9.29	11.30
CaCO <sub>3</sub>	3.28	4.97	6.63	7.43
MgO	2.63	7.25	11.42	13.70

The mixtures were fragmented much more than the pure compounds, with the d99 particle size for each being reduced by between 40-50%. This is likely because the smaller Niacin particles could slam into the larger inert particles, breaking them apart more after injection. Since the particle size did not increase with the mixtures compared to the pure compounds, no intermolecular forces could be ascertained.

## Conclusions

- **What effects do each of the inerts have on the explosion of Niacin?**
  - NaHCO<sub>3</sub> and NaCl are the stronger inhibitors because of the radical scavenging from both compounds
  - CaCO<sub>3</sub> and MgO are not as good because they only have a physical effect of acting like heat sinks, not a chemical one of being radical scavengers
- **How does removing the decomposition of NaHCO<sub>3</sub> affect the explosion of Niacin?**
  - It increases the explosion severity because one step of its full decomposition is no longer possible and another step is slowed
  - Adding CO<sub>2</sub> decreases the concentration of radicals, which decreases the severity of the explosion
- **How does concentration, ignition delay time, and the location of the charges affect the explosion of Niacin?**
  - The higher concentration of Niacin, the higher the explosion severity, when mixed with MgO
  - The longer the ignition delay time, the lower the explosion severity because the reduction in turbulence reduces the number of particle interactions
  - The location of the charges has minimal effect on the explosion
    - The small difference can be due to the flame being quenched when exposed to the cold walls of the sphere, since the flame reaches the walls faster when the charges are not in the direct center of the sphere
- **What is the effect of injecting dust into the sphere at 20 bar?**
  - The dust gets fragmented severely, meaning the dust's effective particle size at the point of ignition is much smaller than the powder
  - Mixtures with Niacin make the inerts become more fragmented, which could make the radical scavenging effects of NaCl and NaHCO<sub>3</sub> more effective
  - This makes the surface area per unit mass higher, which increases the explosion severity

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