PLATFORM DEVELOPMENT AND OPTIMIZATION FOR TESTING RESPIRABLE COAL AND SILICA DUST IN SIMULATED UNDERGROUND COAL MINE CONDITIONS

by

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Submitted in Partial Fulfillment
of the Requirements for the Degree of
Master of Science in Mineral Engineering
with Specialization in Geotechnical and Geomechanical Engineering

NEW MEXICO TECH
SCIENCE • ENGINEERING • RESEARCH UNIVERSITY

New Mexico Institute of Mining and Technology
Socorro, New Mexico
December 2022

This thesis is dedicated to my parents. Thank you for all your love and support.

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ABSTRACT

In mining, respirable dust is a tremendous hazard for mine workers. These tiny particles can be produced in high concentrations by daily mine activities such as blasting, crushing, drilling, or transporting material. In underground coal mines, particle concentration can be a critical danger since workers are in confined spaces with limited artificial ventilation, high humidity in the air, hot temperature, and other site conditions that may lead to more complex particle identification and higher dust particle concentrations. Therefore, necessary controls should be implemented to reduce exposure and guarantee safe work environments for miners. Between respirable dust materials generated in coal mines, respirable coal mine dust (RCMD) and respirable crystalline silica (RCS) are abundant and can lead to the development of deadly lung diseases such as coal workers' pneumoconiosis (CWP), silicosis, and pulmonary massive fibrosis (PMF). Although many people in the industry have made significant efforts to research, mitigate, and control RCS and RCMD exposure, lung diseases caused by these materials remain a problem that has cost several lives. However, plenty of work can still be done to prevent dust exposure and create better working conditions for workers in the mining industry. This research aims to build infrastructure and conditions to test humidity, concentration, and dust distribution inside a chamber to provide a platform for testing new and current monitoring systems, personal protective equipment (PPE), and mitigation techniques/equipment that can help reduce the exposure of RCMD and RCS in underground coal mines. Two dust chambers were built to simulate underground coal mine conditions. A Humidity control station (HCS) was designed, constructed, and tested to supply variable humidity conditions for testing inside the chamber. Coal samples were reduced to respirable size to supply the chamber with airborne dust produced by an aerosol generator. The samples were tested with a particulate matter sensor and an aerodynamic particle sizer to determine the best internal area to place equipment inside the chamber. The detailed production procedure is covered in this document, and recommendations are made to improve the platform and for future research related to dust testing with similar conditions.

Keywords: Respirable Coal Mine Dust (RCMD); Respirable Crystalline Silica (RCS); Coal Workers' Pneumoconiosis (CWP); Dust Chamber; Humidity Control Station (HCS).

ACKNOWLEDGMENTS

This study is funded by the National Institute for Occupational Safety and Health (NIOSH) [#75D30119C06390 & #75D30120R67845].

I would like to express my thanks to my academic advisor Dr. Navid Mojtabai for providing me with the opportunity of admission for my MS degree at New Mexico Tech and for his guidance and support throughout my program.

I want to thank my research advisor Dr. Pedram Roghanchi. His guidance and constant high expectations have helped me to push myself to become a better worker during my master's program.

I want to thank my committee member, Dr. Mehrdad Razavi, for his support throughout my program and his commitment to delivering excellent education.

I would like to thank Vanessa Salinas for her constant support and precise comments on several activities that helped me to enhance my work and correct mistakes along the way.

My sincere thanks to NMT graduate students Eurico Madureira, Nataly Vanegas, Maria Lozano, and Maria Camila Acevedo for their collaboration on experiments.

I would like to thank NMT graduate student Milton Das and NMT associate professor Gayan Rubasinghege for their intellectual collaboration in the design of the Humidity Control Station.

Lastly, I sincerely want to thank my family, that always has been a motivation and a source of guidance for me.

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LIST OF ABBREVIATIONS AND SYMBOLS

AG	Aerosol Generator
APS	Aerodynamic Particle Sizer
ARD	Arizona Road Dust
BL	Bottom Left
BM	Bottom Middle
BR	Bottom Right
COPD	Chronic Obstructive Pulmonary Disease
CPDM	Continuous Personal Dust Monitor
CWP	Coal Workers' Pneumoconiosis
DDF	Dust-Related Diffuse Fibrosis
DI	Distilled Water
DOE	Design of Experiment
DPM	Diesel Particulate Matter
DI	Distilled Water
FTIR	Fourier-Transform Infrared Spectroscopy
HCS	Humidity Control Station
LOD	Limit Of Detection
LPM	Litters per Minute
MDP	Mixed Dust Pneumoconiosis
MSHA	Mine Safety and Health Administration
NIOSH	National Institute of Occupational Safety and Health

NMT	New Mexico Tech
PDM	Personal Dust Monitor
PEL	Permissible Exposure Limit
PM	Particle Matter
PMF	Progressive Massive Fibrosis
PPE	Personal Protective Equipment
RCMD	Respirable Coal Mine Dust
RCS	Respirable Crystalline Silica
RH	Relative Humidity
TC	Total Concentrations
TEOM	Tapered-Element Oscillating Microbalance
TL	Top Left
TM	Top Middle
TR	Top Right
XRD	X-Ray Diffraction

The dissertation is accepted on behalf of the faculty Institute by the following committee:

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I release this document to the New Mexico Institute of Mining and Technology.

Alexander Antonio Medina Gomez November 18, 2022

CHAPTER 1

INTRODUCTION

The mining industry is a significant industry that has brought many benefits to society and has helped to develop multiple sectors over the years [1], [2]. As in other industries, workers could be involved in various activities that may lead to several health and safety hazards, increasing the risk of injuries and illnesses [3]–[8]. One of these risks is exposure to respirable dust particles in working areas. Dust is produced during daily mining activities, such as cutting, grinding, and handling materials [9]. Both underground and surface mining can have tremendous dust production in everyday activities. However, underground mines' conditions can be more dangerous due to limited artificial ventilation, confined spaces, and other environmental conditions [10]–[13]. Given underground mine conditions, the air is likely to contain more respirable dust concentrations than in surface mining. Therefore, more engineering and administrative controls must be implemented to safeguard the miners' health in underground operations.

In the United States, coal is highly used in the industrial, transportation, residential, and commercial sectors due to its availability across the mineral deposits in the country. However, the primary use of coal in the country is to produce energy [14]. A reliable and constant energy source is critical to comply with the country’s demands. Coal mines will continue extracting this material for a long time until a transition to renewable energies is completed. Even with that, there are still chances of using coal for certain activities in the coming years.

In mining, dust is widely dispersed across projects since companies use techniques that typically generate dust while extracting minerals from the ground [15]. Dust can be described as small solid particles in the air[16]; these particles can have different sizes, yet, respirable airborne particles can generally range from close to 0 to 10 µm [17].

In underground coal mines, respirable dust fraction is called respirable coal mine dust (RCMD). RCMD is a heterogenous complex mixture that has more than 50 different elements and their oxides [17]–[19]. Its mineral content depends on the geology and rock type of the mine. The most common minerals associated with RCMD are kaolinite, illite, calcite, pyrite, and quartz [18]. Other materials and particulates, such as limestone, marble, silicate minerals, carbonates, and diesel particulate matter (DPM), among others [17], can be present in underground coal mine operations [17]. Some of these materials, such as crystalline silica and DPM, are carcinogens [20]. It is estimated that around 40 to 95% of RCMD in an underground mine is pure, primarily coal, and the other components include some particles produced from diesel equipment, rock dusting practices, cutting the roof and floor, and other everyday activities in underground coal mines [18], [19], [21].

Quartz can be extremely dangerous when it becomes respirable, depending on the minerals with which it is combined to [19]. Among the thousands of minerals, quartz is considered one of the essential minerals in forming rocks and soil and represents about 12% of the earth's crust volume [22], [23]. Respirable crystalline silica (RCS) are tiny particles produced by daily construction or mining activities like cutting or grinding [24]. RCS is a critical component of RCMD. The continued exposure and cumulative inhalations of RCMD and RCS can lead to multiple lung diseases, including coal worker's pneumoconiosis (CWP), mixed dust pneumoconiosis, silicosis, dust-related diffuse fibrosis (DDF), and progressive massive fibrosis (PMF) [15], [21], [22], [25].

To control and know how much respirable size material is allowed in work environments, OSHA and MSHA define the permissible exposure limits (PEL), or dust standards, to enforce regulations establishing the legal limits of workplace exposure to pneumoconiotic agents [26].

Exposure to concentrations higher than the PEL of RCS and RCMD is a severe issue that has affected for years miners' health [27]. These tiny particles represent undesired conditions that should be identified, minimized, and mitigated with the hierarchy of controls (elimination, substitution, engineering controls, administrative controls, and PPEs) [28]. Otherwise, inhalation of these hazardous materials could have potentially fatal consequences for miner's life.

Effective monitoring systems are the best way to identify exposure to RCMD and RCS when the miner is in danger. Real-time monitoring systems in underground coal mines let us know the amount of material mine workers are exposed to during their shifts and can generate alerts when the concentration is too high. There are two main ways to measure hazardous materials in the field; the first one is with traditional sampling methods, and the second one is with continuous personal dust monitors (CPDM).

Traditional sampling methods can give accurate results and alarm miners about high-concentration spots. However, results could take days or even weeks.

On the other hand, when mine workers wear a CPDM during the entire shift, the equipment provides values for the 30 minutes RCMD mass concentration and the cumulative concentration at the end of the day. CPDMs and similar near-real-time measurement technologies are the keys to preventing diseases associated with coal dust and other materials in underground coal mines. When miners can have real-time alerts to an invisible enemy like dust, they can decide whether to continue working in the same location or move away to avoid breathing these hazardous materials.

Since a long time ago, multiple institutions, companies, and individual researchers have investigated the main reason for an increase in cases of lung diseases associated with mining activities and how to reduce this problem, as mentioned in [21], [29]–[37]. The mining industry knows about the mine workers' risk of developing lung diseases due to continuous exposure to airborne respirable dust particles [38]. Thus, public and private institutions have destinated funds to research and potentially mitigate workers' dust exposure in the mining industry.

This research aims to create infrastructure and conditions to provide a platform to test airborne mine dust particles under controlled simulated mine conditions, focusing on RCMD and RCS. Some conditions considered were humidity, temperature, concentration, airflow, and pressure. The goal was to build a reliable platform to simulate underground coal mine conditions and potentially test the effectiveness of monitoring systems for readings on RCMD and RCS.

The contents of this document are distrusted as follows.

Chapter 1: This chapter introduces the main topic of this thesis, including the necessity of coal in society, definitions of RCMD and RCS, PEL monitoring systems, and finally, the main aim of the research.

Chapter 2: A literature review oriented to the main aim of the project, including topics such as exposure effects of RCMD and RCS, dust control techniques, RCMD and RCS quantification, monitoring systems, and finally, underground coal mine conditions for simulating conditions.

Chapter 3: Detailed explanation of the development and construction of the dust chambers and humidity control station used in the project. In addition, the chapter provides an explanation of sample preparation, equipment, and experiments performed during the research.

Chapter 4: Summary of the finalized products and samples for experiments, and results and recommendations of experiments explained in chapter 3.

Chapter 5: Conclusions of what were achieved during the research and recommendations for future research with similar conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 RCMD and RCS Exposure Effects

Long-time exposure to high concentrations of RCMD and RCS can significantly affect and deteriorate human health [39], [40]. Some early symptoms may appear in the short term with no severe damage. Long-term exposure to dusty environments can affect lung functionality, with irreparable injuries that can lead to death in multiple scenarios [41]. Due to the increasing number of lung diseases associated with RCMD and RCS cases, in 2014, the United States Mine Safety and Health Administration (MSHA) came up with a new rule changing the RCMD exposure limits, measurement technology, and sampling protocol.

(Respirable Dust Standards for the Dust Standards, 2016) [42], on August 1st, 2016, the concentration limits or respirable dust standards were reduced from 2.0 mg/m3 of respirable dust in the air, as mentioned in (30 CFR 70.100(a)(1), to 1.5 mg/m^3 at underground coal mines, as mentioned in 30 CFR 70.100(a)(2).

(Respirable Dust Standards When Quartz is Present for the Dust Standards, 2016) [43], as stated in 30 CFR 70.101(a), for respirable dust standards, when quartz is present, the concentration should be at or below 0.1 mg/m^3 (100 micrograms per cubic meter or µg/m3), expressed in terms of an equivalent concentration and measured with an approved sampling device. Also, when the concentration of quartz exceeds the limit, more correction actions should be implemented following 30 CFR 70.101(b).

Inhalation of dust produced by coal mines at levels above the standards can lead to several lung diseases and complications. The most common cases are Coal Workers' Pneumoconiosis (CWP) and silicosis, which are preventable but incurable lung diseases.

Diseases associated with coal mine dust exposure may include chronic airway diseases, such as emphysema, chronic bronchitis, rheumatoid pneumoconiosis, or Caplan's syndrome, CWP. These can be divided into three forms (simple CWP, rapidly progressive CWP, and progressive massive fibrosis (PMF)), mixed dust pneumoconiosis (MDP), diffuse dust-related fibrosis (DDF), and chronic obstructive pulmonary disease (COPD) [41], [44].

On the other hand, silica-associated diseases include silicosis, lung cancer, pulmonary tuberculosis, COPD, and an increased risk of developing rheumatoid arthritis [24], [45].

2.2 Dust Control Techniques, Identification, and Programs

2.2.1 Dust Controls Techniques

RCMD and RCS can be abundant in underground coal mining [21], [29], [41], [46]–[51], and control of airborne particles is critical to reducing worker exposure. Dust in underground mines is mainly controlled with proper air ventilation and water spray systems in multiple activities across the mine [15], [52]. Actions like wetting roadways and conveyor belts, changing filters, maintaining systems, and identifying critical points are highly beneficial in controlling dust liberation and reducing the number of airborne particles in the mine air. All these controls should be daily practices to keep the mine running safely [15], [53].

2.2.2 Hierarchy of Controls

Many mines follow the hierarchy of controls to establish actions to prevent exposure to materials or situations affecting workers' health. Knowing what can be eliminated, substituted, or changed in how miners work is necessary and can significantly help reduce incidences and injuries. In the case of dust, it is a hazard that sometimes cannot be removed entirely or eliminated in underground coal mines; for this, monitoring systems are highly beneficial to alarm the miner when they must move out from dangerous zones and prevent exposure [15]. In addition, as a last resource in the hierarchy of controls, PPEs and administrative controls are always beneficial in high dust production environments, especially when engineering control systems are not feasible or insufficient. For this, the use of NIOSH-approved respirators must be implemented to reduce the intake of airborne materials [15], [54]. However, PPEs should be considering the last line of defense to prevent exposure to these materials [55].

2.2.3 Monitoring Systems

Monitoring systems like personal dust monitors for RCMD and sampler units for silica analysis help to provide dust concentration data and based on that, make decisions to reduce exposure in identified highly dusty production areas like drilling or transporting. When dust readings are above dust standards, mines must implement corrective actions like more monitoring with sampling devices, increasing ventilation in the areas, and using more water spray systems until levels drop below PEL limits [56].

2.2.4 Institutional Programs

Institutional programs like mine workers' screening options help identify medical conditions among miners. Contractors and coal miners working for either underground or surface mines operations can get lung function tests (spirometry), chest x-ray, symptom assessments, and a health assessment questionnaire from NIOSH at no cost. Also, some mines offer the worker's annual black lung screenings totally for free for specific job positions [57]. However, in some cases, workers do not take advantage of these benefits because they fear losing their jobs, even though NIOSH assures that screening is confidential [58].

Overall, dust control techniques like water sprays, scrubbers, ventilation systems, monitoring systems, PPEs, and medical checks are always helpful in reducing and identifying high concentrations in underground coal mines and keeping miners safe. The sum of all the efforts together is the key to making a difference and reducing health diseases associated with mining activities in the future.

2.2.5 Related Dust Studies

Identifying and monitoring particle concentrations in the workplace is critical to prevent exposure to toxic materials. When workers are exposed to airborne dust particles, the particle size concentration is essential to understand the dangers of the materials since some of the finest dust fractions can potentially reach and affect deep regions in the respiratory tract [30]. Developing lung diseases associated with RCMD and RCS is an exposure time problem. The more exposure to highly dusty hazardous environments in coal mines, the less time these previously mentioned diseases can develop.

Brown et al. 2013 [30] divide airborne dust particle fractions into four groups depending on the aerodynamic diameter.

- First, inhalable is the mass percentage of all airborne particles inhaled by the mouth and nose.
- Second, extrathoracic is the mass percentage of inhaled particles that do not pass through the larynx.
- Third, thoracic is defined as the mass percentage of inhaled particles that reach beyond the larynx.
- Forth, Respirable is the mass percentage of inhaled particles that enter unciliated airways.

From these particle classifications, the size of the airborne particles that have 50% penetration for the respirable and thoracic fractions is 4.0 m and 10 m, respectively [30], [59], [60].

Phalen et al. 1988 [61] mentioned that particles with an aerodynamic diameter of 10 µm can penetrate the headway and have the chance to enter the lung airway; likewise, some particles with an aerodynamic diameter of 4 µm can pass through the tracheobronchial airway and fall into the gas exchange region. These particle sizes of RCS and RCMD concern the most for disease prevention because the body cannot eliminate them by itself, and they can cause serious health issues [30], [62].

Lebecki et al. 2016 [63] took samples for dust concentrations at an underground rock coal face with different thicknesses drilling with a heading machine. Gravimetric dust samplers CIP-10R and CIP-10I, placed close to optical dust samplers, were used to collect data from the excavation. For this study, concentrations exceeded the maximum permissible concentration, and corrections actions were recommended.

Baron P.A. [64] discusses the uses of portable aerosol photometers for different real-time information on dust concentration for specific environments. The research mentions that some of these devices can work in potentially explosive atmospheres. These devices usually do not distinguish between different aerosols but can give a volume value. However, high humidity conditions may affect the readings. Many direct-reading aerosol monitors use this technology and could be scaled up to develop an accurate, reliable device for more applications in underground coal mines. More work should be done to reach a point where they meet permissibility requirements to use in underground coal mines and can compete with accepted and approved devices in the industry.

Mishra et al. 2018 [65] conducted a study to design smart helmets for underground coal mines that could potentially work as monitoring devices, which could provide real-time readings for parameters in the air like methane, humidity, and temperature. In underground coal mine conditions, workers' comfort conditions can be negatively affected by clothes, boots, or items they must carry during their shifts [10], [66], [67]. Therefore, any additional heavy or large device may negatively affect comfort conditions. Suppose helmets can work with incorporated monitoring systems. In that case miners will not have to carry another device to the mine to monitor dust conditions, representing many benefits for companies and employees.

Light scattering, optical, gravimetrical, TEOM technology, different low-cost sensors, and other techniques have been used to measure dust concentrations in various industries [56], [68]–[72]; however, not all have permission today to use in underground coal mining.

Thorpe et al. 2013 [72] conducted a study using photometer-type dust monitors, a TEOM 1400, a personal dust monitor (PDM) 3600 (modified to measure inhalable particles), Respicon TM, and a Dustrak DRX to measure inhalable dust particles during laboratory and field tests. Concentration changes were measured with monitoring systems and compared using different materials inside a wind tunnel to simulate natural conditions. Results regarding inhalable particles showed that photometer-type direct-reading dust monitors consistently underestimated inhalable airborne dust concentrations. The modified PDM and the Respicon TM showed more consistent values than a reference IOM sampler.

NIOSH (2010) [73], in its document “Best practices for dust control in coal mining,” provides an excellent guide to understanding the different dust control mechanisms in underground coal mines and the way to measure airborne particles with approved monitoring systems. Also, the second edition, NIOSH (2021) [15], continues the document and provides updated information regarding monitoring samplers and techniques and specific dust control techniques in different zones of the mines.

NIOSH (2002) [22] provides a summary of NIOSH-approved techniques to measure silica and a review of these methods' parameters, considerations, and possible results.

Halterman et al. 2017 [70] conducted a laboratory study in which a PDM3700 and a photometer (personal DataRam, pDR-1500) were used to compare gravimetric measurements. They used five different aerosols (diesel exhaust fume, coal dust, Arizona road dust (ARD), welding fume, and salt [NaCl] in respirable size varying concentrations inside a chamber. The study found a similarity in readings between PDM3700 with the ones measured gravimetrically for most materials. On the other hand, the photometer (pDR-1500) was significantly sensitive to aerosol physical characteristics.

Although this technology is not permitted in underground coal mines, some can be adapted to new devices to offer faster responses, accurate results, and a comfortable option for miners to wear—the more available monitoring systems in the market, the lower the price.

2.3 RCMD and RCS Necessity for Field Monitoring

As mentioned earlier [56], black lung disease was found in almost 30% of miners that worked for 25 years or more in the 1960s; as a result, nine years later, concentration limits were reduced to control the exposure to coal and silica dust. Thanks to those requirements and medical programs, only about 5% of miners that worked 25 years or more had the disease in 2000. However, more than twenty years ago, NIOSH reported an upward tendency in cases of black lung disease in miners who worked for more than a decade and a half in the industry. The reasons are not completely clear. Still, the assumption is that one of the reasons could be related to mining practices [21], [74].

In recent years coal production has been much higher than it was 50 years ago [75]; As a result of high coal production numbers, there is a higher number of workers exposed to high dust concentration environments in coal mining operations. Therefore, more actions should be taken to control this situation and keep miners safe. All these facts have led to implementation of monitoring systems in the field to alarm miners while they are working and help in the decision-making operational mine process. The primary function of monitoring instruments in underground coal mines is to accurately identify and quantify the amount of respirable fraction of RCMD and RCS in the mine air [73]. If more portable, real-time, cheaper, and easier-to-use monitoring instruments are available in the industry, more dust identification could be completed, and miners would have fewer dust exposure situations in their workplaces.

Even though coal mine numbers had decreased since 2015, when 1460 mines reported activities to MSHA[76], many workers are still involved in coal mining activities. In 2015, 24.9% of all hours reported within the mining commodities were by coal mine operator employees and 6.3% by coal contractors. For this same year, the total number of employees in mining sectors between full-time workers and contractors was almost 349,847, with nearly 20% working as coal operators and close to 10% as coal contractors [76]. By 2021, from a total of 12567 mines, 970 of them were active coal mines, as shown in Figure 2[77]. That is an indicator of a high risk of developing diseases associated with RCMD and RCS exposure due to the high number of workers that could be involved in the extraction processes in these active mines.

RCMD and RSC can be present in many active mine operations, including noncoal for RCS, and controls and prevention are fundamental to guarantee a safe working environment for employees in the mining industry. Numbers are still high. Hence, there is a constant need for improvement in the industry involving research in many dust control techniques, equipment, and monitoring systems to control easier, read faster, and keep taking action in controlling hazardous mines materials.

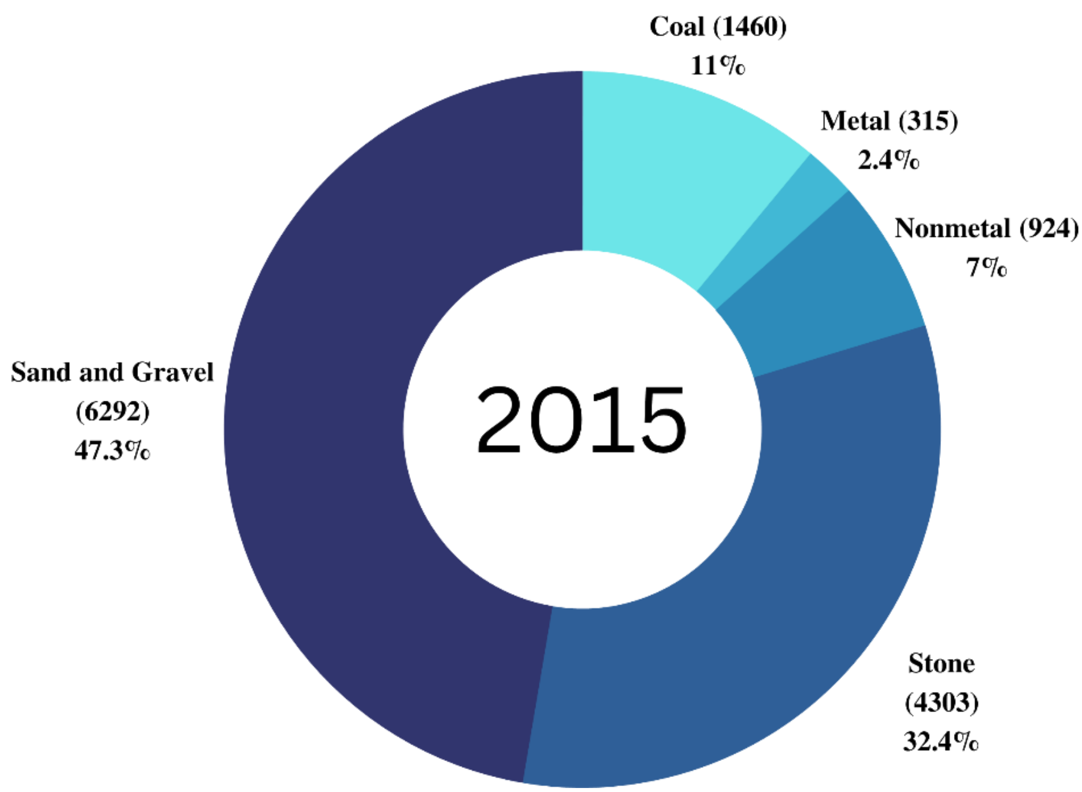

Figure 1. Active mines in 2015 by sectors [77]

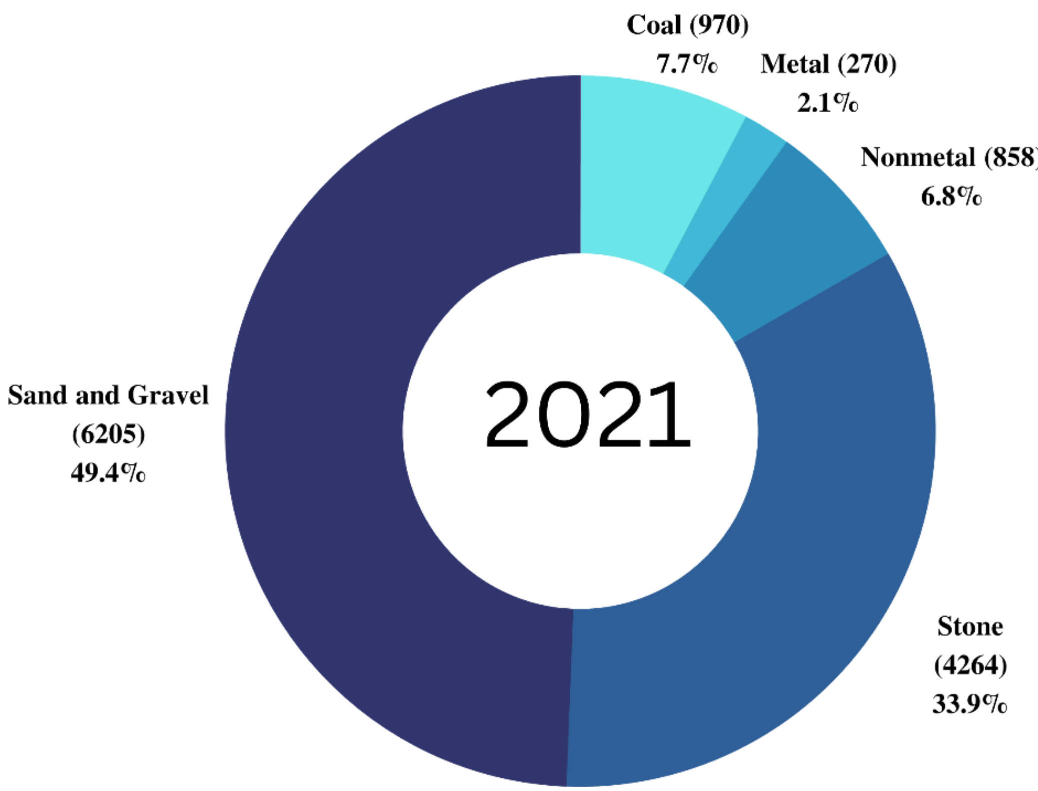

Figure 2. Active mines in 2021 by sectors [77]

2.4 RCMD and RCS Approved Sampling Instruments

Instruments taken to the field should be approved by MSHA and must comply with regulations for underground coal mines. For respirable dust sampling, a gravimetric sampler, a continuous personal dust monitor (CPDM), and a light scattering instrument are the only three MSHA-approved respirable dust sampling instruments for underground coal mines [15].

2.4.1 Continuous Personal Dust Monitor (CPDM)

To measure RCMD, NIOSH-certified personal dust monitor (PDM), PDM3700, is an MSHA-approved safe device for U.S.-based mining applications. Thermo Fisher Scientific company commercializes the device, and since the start of 2016, underground coal mines have been using it to obtain dust samples in compliance with regulations. This device utilizes tapered-element oscillating microbalance (TEOM) technology to get a gravimetric-based measure of respirable dust concentrations in the mine air [15].

The PDM3700 measures in near real-time (every minute) respirable dust concentrations to obtain primary current mass concentration, primary cumulative mass concentration, and percent of limits, as mentioned on the Thermo Fisher website [78], [79].

The latest version, shown in Figure 3, has been a beneficial tool for identifying potential and existing zones with high particles concentration in underground coal mines.

In 2014, a federal regulation lowered the PEL and required miners to wear a personal dust monitor periodically if exposed to zones with potentially high concentrations [56].

The PDM3700 is a portable device that constantly operates at 2.2 LPM with a sampling inlet in conjunction with a cyclone to take particles less than 4.5 µm, mostly the respirable airborne particles. The battery must be charged after every shift, like a cell phone's battery. PDM3700 dimensions are H: 6.75in, D: 3.25in, W: 9.57. It has a screen that provides readings while the miner moves around the mine; the device represents a considerable advance in timing, accessibility, and portability [78].

However, even though the PDM3700 is a big step in providing better tools for miners, some points can still be enhanced, like the sampling time, weight, size, way to program a shift, device interface, noise, and user interaction. In addition, the price could be considered high. Thus, in a scenario where each miner carries one as a personal dust exposure tool defense, this may be considered a significant expense for the companies, limiting the measurements to specific locations in the mine that may not represent the total exposure for all the miners.

For research purposes, PDM3700 can be used in the lab's simulated underground coal mine environment to measure RCMD. However, it is impossible to know the amount of silica in RCMD with the PDM3700 since there is no distinction regarding the material taken in coal mines, mainly coal, with the rest of the components of RCMD; hence, a more extended procedure must be followed.

Figure 3. PDM3700

NIOSH has an ongoing contract with Thermo Fisher to develop the next generation of the PDM3700, targeting three main areas: reducing the size and weight of the PDM

3700, improving the battery life and instrument runtime, and improving the thermal performance of the instrument [80].

2.4.2 Gravimetric Sampler

For measuring RCMD and RCS, current sampling methods generally involved using a gravimetric sampler that mainly consists of a pump with a filter cassette attached to a cyclone (personal sampler), which was designed to use in compliance with 1969 MSHA regulations [73]. The Zefon International Escort ELF pump unit with cyclone shown in

Figure 4 is an approved device for monitoring coal and metal/nonmetal mines. This device consists of a pump and a sampling head. The sampling head should have a nylon cyclone, which separates respirable and non-respirable dust. The cyclone cannot be turned upside down, which contaminates the sample. Metal brackets provide alignment and firmness, and a grit pot holds larger particles that are not respirable. Moreover, it should have a hose that should not be more than 36 inches long with no more than +/- 1/16" of internal diameter. Usually operates at 1.7 to 2.5 lpm, depending on the cyclone type and methods used [81]. For coal mining operations, the pump flow rate should be calibrated at 2 lpm. On the other hand, for metal/nonmetal mining operations, the pump must be set up to work at 1.7 lpm.

Figure 4. ELF pump with cyclone

As mentioned before, gravimetric devices taken to the field have an attached cyclone capable of separating the non-respirable particles in the air unless the sampler has a similar system inside that can separate the particles by itself. Later, the respirable fraction is collected by a 37 mm PVC filter without considering the oversized portion [15]. The separation happens based on the centrifugal force principle. The fast circulation of the particles produced by the cyclone and the selected flow rate captures the particles according to their aerodynamic diameter, forcing the bigger particles to circulate in the periphery. The small ones stay in the middle and get trapped in the cassette filter. The cyclones work with a specific flow rate, which can lead to significant deviations in the desired result if changed [82].

Regarding cyclone types, the most widely used sampler for RCMD is the Dorr-Oliver 10-mm nylon cyclone required by MSHA and the Higgins-Dewell conductive cyclone used in the United Kingdom, which usually works at a flow rate of 2.2 LPM. Both cyclones are certified by ISO/CEN/ACGIH in respirable aerosol sampling convention and have enough conductivity to reduce electrostatic interaction between particles [19], [22]. In addition, the aluminum cyclone, which is used in conjunction with 25mm or 37mm filter cassettes with its holder, operates at 2.5 LPM and can work with 3-piece or 4-piece filter cassettes; this last one permits a better dust distribution deposition in the cassette for further analysis with portable FTIR. Regarding cassettes for approved units, they can be 2-, 3-, or 4-piece cassettes; the 4-piece cassette can work with a portable FTIR using the NIOSH FAST method for field-based monitoring of RCS, as mentioned by Zefon [83].

2.4.3 Light-Scattering Real-time Dust Monitor

Some light-scattering samplers to measure in real-time (1-second to 1-hour intervals) have been approved by MSHA for use in underground mines. However, they are not compliance certified by NIOSH. The personal DataRAM 1000 AN (pDR) provides relative dust concentration in mine environments. Results from this device should be compared with other monitoring systems to alarm miners and compare the accuracy of results since some lectures can have errors because of some common underground coal mine conditions affecting readings in these devices [15].

A clearer comparison and summary of these tree monitoring are summarized in Table 1.

Table 1. Summary of approved monitoring systems [15], [70], [78], [84], [85]

Certified MSHA monitoring instruments.					
Instruments name	***Instruments Type***	***Cyclone***	***Flow rate***	***To read***	***Pros and cons***
PDM3700	Continuous Personal Dust Monitor (CPDM)	A Higgins-Dewell	2.2 LPM	RCMD	The PDM3700 provides a fast and effective solution to measure RCMD every minute in coal mines [78]. Some improvements can be made in battery

					time, size, weight, user interaction, and warm-up time.
ELF PUMP	Gravimetric sampler	Usually is used with the 10-millimeter (mm) Dorr-Oliver cyclone. However, other cyclones can be used.	0.5-3 LPM 2.0 LPM (For coal mining operations)	RCMD and RCS	This sampler is the only approved instrument to determine silica content for compliance purposes. However, silica readings may take a long time since samples should be sent to accredited labs or to MSHA labs for further analysis to determine silica content information. Also, multiple samplers should be placed in the same location due to the variability of readings because of variable conditions in underground coal mines [15], [73].
DataRAM 1000 AN (pDR)	Light scattering	It has no cyclone. It has a sensing chamber where a sensor determines the dust concentrations.	-	RCMD	Readings can be stored in even ranges of seconds, which gives a broad analysis of the dust concentration conditions [84]. However, data readings can be affected by

					different dust compositions, changes in size distributions, and/or changes in humidity in the air [15], [73].

2.5 RCMD Concentration Quantification

The quantification of RCMD amount and concentration in the mine from the collected samples is relatively simple. If the samples were taken through PDM3700, the instrument would show the mass concentration and cumulative exposure on the screen after completing the shift. Later, the device should be connected to a computer using the WinPDM software to export to an Excel sheet, analyze dust concentration minute by minute, and relate periods of high concentration with specific mine areas [78]. On the other hand, RCMD can also be estimated using a gravimetric sampler. In this case, the dust concentration is calculated with the sample's weight and the pump's flow rate during the sampling time. The concentration is usually calculated in milligrams per cubic meter. For this, dust samples should be sent to a certified lab once completing sampling, and with the dust weight and total air volume, the dust mine dust concentration is calculated [73].

2.6 RCS Concentration Quantification

The process gets more complicated for silica quantification and is usually more time-consuming. The sample is taken in the field with the gravimetric sampler. After the shift change, the filter is taken to the lab to verify RCS contents. That is done through analytical methods like XRD methods (NIOSH 7500, OSHA ID-142, MSHA P-2, MDHS 51/2), colorimetric spectrometry (NIOSH 7601), IR methods (NIOSH 7602, NIOSH 7603, MSHA P-7, MDHS 37, MDHS 38) [22], and more recently, the NIOSH FAST method with the portable FTIR for silica analysis. The MSHA P7 infrared method has been used for a long time to determine silica content in coal mines for compliance determination, and the NIOSH 7500 method for metal/nonmetal mines [73]. However, waiting times to get silica concentrations could be even weeks. Therefore, the need to develop a faster reading method.

As mentioned before, currently, there are three existing analytical methods to measure the content of RCS in mine samples. The first two are X-Ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR), which are often more used. Both are indirect techniques, require previous sample preparation, and are approved by NIOSH for measuring RCS. The third method to determine RCS is colorimetric spectrometry, which may be less precise than XRD and FTIR, thus, less used. In both cases, the samples are collected by a personal sampler with a cyclone that removes the non-respirable fraction; later, filters/cassettes are removed at the end of the shift and sent to the laboratory for RCS analysis [22]. The most used measuring techniques are briefly described below.

2.6.1 XRD

X-ray diffraction (XRD) is a technique used to identify crystalline materials' phase identification [86], and for this specific application is used to distinguish the 3 most common polyforms of crystalline silica: quartz, cristobalite, and tridymite. XDR is used for analyzing the samples collected in filter cassettes during sampling in metal and non-metal mines and is an appropriate technique to detect, identify, and quantify RCS [22], [87], [88]. The method's main restrictions depend on the sample's adequate volume in the X-ray beam and the number of crystallites with the correct diffraction orientation [89].

Some methods to analyze silica on samples include NIOSH 7500, OSHA ID-142, MSHA P-2, and MDHS 51/2 [22].

The NIOSH Method 7500 can differentiate between quartz, cristobalite, and tridymite. It requires either a 10-mm nylon cyclone operating at a flow rate of 1.7 LPM, a Higgins-Dewell cyclone at a flow rate of 2.2 LPM, or an aluminum cyclone at 2.5 LPM. The suitable volume should remain between 400 to 1000 liters. The measurement ranges from 0.02 to 2 mg of SiO2 per sample. The XRD equipment requires a Cu Kα source operating at 40 kV and 35 mA, and it has an estimated limit of detection (LOD) of 5 µg of quartz per sample [22], [88], [90].

The OSHA method ID-142 can differentiate only between quartz and cristobalite. It requires a 10-mm Dorr-Oliver nylon cyclone operating at 1.7 LPM. The recommended sampling time is 480 min, representing 816 L at the flow rate mentioned previously. The maximum load could be 3 mg of dust in the filter. The XRD equipment requires a Cu Kα source operating at 40 kV and 40 mA, and it has a LOD of 10 µg of quartz per sample [22], [91].

The MSHA method P-2 can differentiate only between quartz and cristobalite as well. It requires a 10-mm Dorr-Oliver nylon cyclone operating at a flow rate of 1.7 LPM. The suitable volume for the test should remain within 400 to 1000 liters, which means between 235 to 588 min of sampling time, but with a maximum loading of 3 mg of dust. The XRD equipment requires a Cu Kα source operating at 55 kV and 40 mA, with a LOD of 5 µg of quartz [22].

The MDHS 51/2 method can identify only quartz and no other polymorphs. It requires a Higgins-Dewell cyclone operating at a flow rate of 1.9 LPM. The suitable volume for the test needs to be greater than 456 liters, which means more than 240 min of sampling time, with the maximum dust loading in the filter being 2 mg. The XRD equipment requires a Cu Kα source operating at 45 kV and 45 mA, and it has a LOD of 3 µg of quartz, the lowest of the four methods described [22].

The filter required for all four methods mentioned above needs to be of PVC membrane with 37 mm diameter and 5 µm of pore size, except for the MDHS 51/2 method, which requires a 25 mm diameter filter [22].

2.6.2 IR Spectrometry Methods

IR methods have been commonly used to calculate RCS in samples [73], [92]. Some limitations may be seen when measuring lower quartz concentrations. The technique is considered less accurate than XRD; however, it is less expensive and has more potential for improvements in silica analyses.

Some methods to measure crystalline silica with this technique include MSHA P-7, MDHS 37, MDHS 38, NIOSH 7602, and NIOSH 7603 [22].

MSHA P-7 is used to analyze quartz in RCMD samples using Infrared Spectrophotometry. For collection, samples are collected on reweighed filters using MSHA/NIOSH-approved personal respirable dust sampler units (30 CFR Part 74), mainly a 10-mm nylon Dorr-Oliver cyclone, 2.0 LPM. The calibration range is 20-700 μg of quartz, and the method detention limit is 4 μg [93].

MDHS 37 uses a Higgins-Dewell cyclone operating at 1.9 LPM. The method needs a total volume greater than 456 L with less than 1 mg of dust. Ranges of µg quartz are between 10 to 1000, and the detection limit depends on particle size [22].

MDHS 38 uses very similar parameters compared to MDHS but changes the filter preparation and the analytical sample preparation. However, the range of quartz in this method is from 5 to 700 μg. Also, there should be a maximum of 0.7mg of dust in the total volume of air taken for the sample [22].

NIOSH 7602 is an infrared spectrometry technique to analyze and measure silica, respirable crystalline. It uses a cyclone with a pre-weighed filter. Depending on the cyclone, the pump should operate at different flow rates, usually 1.7 LPM (10-mm nylon cyclone) or 2.2 LPM (Higgins-Dewell cyclone). Total air volume should be less than 1000L and more than 400L, with less than 4 mg of total dust in all the samples. The method's accuracy for studies ranges between 10 to 500 µg per sample, and bias can be trivial when matrix effects are accounted for [94].

NIOSH 7603 is an infrared spectrometry technique to analyze and measure quartz in respirable coal mine dust. It uses a cyclone with a pre-weighed filter. Depending on the cyclone, the pump should operate at different flow rates, usually 1.7 LPM (10-mm nylon cyclone) or 2.2 LPM (Higgins-Dewell cyclone). Total air volume should be less than 1000L and more than 300L, with less than 4 mg of total dust in all the samples. The method's accuracy ranges between 4 to 160 µg, and bias might be insignificant after matrix effects are taken into consideration [95].

The filter required all four methods mentioned above must be of PVC membrane with 37 mm diameter and 5 µm pore size.

2.6.3 Colorimetric Spectrometry Methods

For colorimetric spectrometry, NIOSH uses the NIOSH 7601. The method also works as a technique to analyze crystalline silica. However, it is considered less precise than IR or XRD methods. Since the colorimetric approach depends on silicon's measurement, it cannot discriminate between silica and silicates [22]. NIOSH 7601 uses a 10-mm cyclone (1.7 LPM) or Higgins-Dewell cyclone (2.2 LPM) to take the sample. Total air volume should be less than 800L and more than 400L, and the estimated detection limit is 10 µg SiO2 [96].

2.6.4 FAST Method

In order to address the time issue of the P7 method and take action faster in mines, NIOSH developed a field-based method with a portable FTIR to reduce waiting times and analyze samples faster at the mine site without having to have sample preparation. However, it is not used for compliance purposes. A four-piece cassette was developed in collaboration with Zefon International [83] to collect the dust samples with the desired internal dust distribution and further analyze them with commercially available FTIR using the FAST software and obtaining RCS mass and concentration estimate in minutes [15], [97]. For use in the portable FTIR equipment, NIOSH has additionally created filter cassette cradles that position the cassette for analysis. These cradles could be created using a 3D printer, and NIOSH has made the design files for 3-D printing accessible on a public website [15], [98]. RCS from FAST is closer to reality if the sample is collected in a coal mine; for other mines, results can be considered approximated values. The method was made so that no specialized training in analytical techniques is necessary; thus, it is ideal for getting a close approximation in a simulated underground coal mine environment for research purposes. Allowable flow rates and conditions for each cyclone are defined in the FAST software [99].

2.7 RCMD and RCS Lab Testing in Simulated Conditions

2.7.1 The Necessity of Testing in the Lab

When testing RCMD and RCS materials, an underground coal mine would be the most critical condition to test dust behavior and properties. However, even though this could be the most realistic scenario, before taking any new instrument to the field, the equipment should comply with MSHA requirements. This is to avoid that such equipment will not cause a mine explosion or fire in an underground coal mine. There have been many cases in the past [100]. Without this approval, everything must be external until reaching a point where the instrument is reliable and safe enough to apply for further steps. Therefore, the need to test new monitoring equipment simulating underground coal mine conditions in the lab to ensure the instruments can provide accurate information and comparable data to develop new methods or work with current RCMD and RCS dust analytical methods and comply with all MSHA requirements. Mandatory safety standards for underground coal mines are explained in detail in title 30 CFR, part 75 [101].

2.7.2 Additional Sampling Instruments for Testing in the Lab

In addition to MSHA-approved sampler devices and instruments used in NIOSH methods, other tools can be used in the lab to categorize and research RCMD and RCS concentration and properties. The Aerodynamic particle sizer (APS) can provide the collected sample's concentration and mean size values [102], [103]. Commercially available APSs instruments could be used to obtain a spectrum of the particle size distribution between airborne particles inside a testing structure [104]. As mentioned before, not all particle sizes and materials will affect the human body; there are internal self-defense mechanisms in the body that will eliminate some particles. However, the insoluble smallest ones will go to specific locations in the respiratory system where the body cannot eliminate them [30]. That is why it is necessary to know the particle size distribution of the samples and focus on the airborne particle sizes that may affect human health. In addition, for lab analysis, an aerosol generator can generate airborne particles in simulated mine conditions for testing purposes [105]; models can vary depending on flow rates and characteristics of the material needed to be tested. To generate underground coal mine concentration conditions, most models need powdered material in specific particle sizes to operate correctly [106]–[110]. For research purposes, this equipment can aerosolize dust particles and create an environment that can replicate dust patterns in simulated underground mine conditions. Low-cost sensors can work similarly to a PDM3700 under certain conditions and are available in the market for much less money than the PDM3700. An example is an SPS30 sensor developed by Sensirion, which can give fan quadrants of lectures for PM1 (0.3 to 1.0 μm), PM2.5 (0.3 to 2.5 μm), PM4 (0.3 to 4.0 μm), and PM10 (0.3 to 10.0 μm) [111].

2.7.3 Dust Chamber as a Platform for Dust Testing

Chambers have been used in multiple industries for dust studies under different circumstances. Darley et al. 1968 [112] conducted a study to simulate short and long terms plant exposure in simulated natural conditions and with controlled dust distribution patterns. This study used two chamber sizes with dust in micro sizes, controlling light and dust distribution to provide different environments for the plants and project similar behaviors in real conditions.

Another study by Qian et al. 2008 [113] investigated particle resuspension from human activities in a full-scale stainless steel experimental chamber with a floor area of almost 18 m^2 and a volume of 54.4 m^3. The experiments tried different types of flooring and two ventilation configurations. Particles under 10 μm were seeded in the floorings, and airborne particle concentration was measured. A similar study was conducted by Benabed et al. 2022 [114] where a dust chamber was used to measure particle matter (PM) resuspension caused by walking human activity. In this study, increased PM concentrations were observed after minutes of walking on a carpet loaded with dust.

Eades et al. 2018 [115] researched lean explosibility tests with different dust concentrations inside a 38 L explosive chamber simulating underground coal mine conditions.

Noor et al. 2012 [116] used a chamber to verify whether inhaled coal dust significantly alters bone mesostructure due to decreased or increased bone mineral elements and bone turnover markers. For this, thirty-two male Wistar rats were divided into four groups. For some of them, coal dust was aerosolized and supplied to a chamber with a circulated ambient, aiming to generate an environment in that rats could inhale particulate matter 10 (PM10) of coal dust to further analyze changes caused by coal dust in bones.

Marple et al. 1983 [105] developed a hexagonal aerosol test chamber to provide a simulated condition for evaluating aerosol measuring instruments and samplers simultaneously. For this, aerosolized dust was introduced with air inside the chamber and passed through a ten-centimeter honeycomb structure to decrease turbulence. Then velocity was low for particles to fall downwards in a rotating environment that could guarantee better concentration distribution and direct the particles to a final HEPA filter. The research could provide a uniform concentration condition to compare similar data for test sampling units during an experiment.

Depending on what is needed, multiple experiments can be performed inside a dust chamber. Chamber size must consider the type and design of experiments, and adaptations should be included depending on the conditions that want to be achieved.

2.8 Requirements to Simulate Underground Coal Mine Conditions

2.8.1 Testing Body

Usually, to simulate underground coal mine conditions is necessary to find a structure to test materials and modify factors like humidity, pressure, airflow, concentration, and temperature, among other conditions inside it. This body can be a dust chamber, wind tunnel, container, or any infrastructure that can let imitate dust patterns in underground coal mines conditions, as has been used in previous studies [105], [115], [117]–[120].

2.8.2 Humidity, Temperature, and Concentration Conditions

An underground coal mine can be humid and hot. Mostly moist air is found in underground coal mines conditions. However, for lab testing purposes, dry air is also beneficial as a baseline to compare readings since some water mixes could affect concentration estimation in some instruments [15], [73]. Some areas of underground coal mines may be at high temperatures (more than 30 °C) and very humid conditions with more than 90% relative humidity (RH). This can be caused because of reasons like existing geothermal gradient and groundwater conditions, as mentioned by Wang et al. 2012 [121].

Lstiburek, J 2002 [122] mentioned that most people usually might not notice differences in relative humidity levels within the range of 25–60%, which is why this value is frequently mentioned as a baseline [10] and a comfort range of humidity for workers. For underground coal mines, the humidity levels are mostly above 60%, representing undesired conditions in terms of comfort for the workers.

As described by Yonkofski et al. 2018 [123], adding or spraying water stops dust production by temporarily increasing surface humidity and moisture content; consequently, particles agglomerate and reduce airborne dust concentrations. Nonetheless, depending on the material properties, temperature, and relative humidity, always more water will be needed for the surface after some time. Another factor that can increase humidity is water sprayed to control and capture airborne dust. For this, water droplets combine with dust particles in the air, catching the particles and taking them to the ground.

Ventilating conditions are also needed and are an essential part of an underground coal mine design [124]. These mines have different pressure areas, rough surfaces, and confined conditions. In addition, the temperature may affect relative humidity; thus, a value must be selected to create accurate and stable simulated conditions. Conditions may also change depending on the mine parameters, equipment, and the number of people working by shift [10].

The other primary consideration in simulating a mining environment is dust concentration inside the body. A miner can be exposed to many high dust concentration areas during the day; thus, an instrument capable of generating similar dust concentrations is needed. The dust should be aerosolized to generate airborne particles inside the testing structure. Furthermore, particle size distribution should have a broad spectrum like those in coal mining operations to have a realistic proportion of respirable particles within the airborne inhalable particles [30], [53], [105].

An instrument capable of producing a wide range of humidity values is needed to create a platform to simulate underground coal mine conditions in laboratory environments. High humidity values can provide a closer approximation to realistic scenarios [125], [126]. However, if dust analysis equipment is tested, there must be a baseline to compare what high humidity can create in airborne particle concentration; and then determine whether or not this can affect instruments concentration readings.

CHAPTER 3

METHODS

The development of this project focused initially on the construction of infrastructure and conditions for the testing platform and further experiments to verify underground coal mine conditions inside the testing body. This chapter includes the construction of two chambers and a humidity control station for respirable dust testing; an explanation of the equipment used for testing; and the step-by-step followed for concentration, airflow, humidity, and monitoring systems experiments.

3.1 Dust Chambers

Two dust chambers were built for respirable dust lab testing during this research. Chambers had different sizes, and properties are explained in Table 2.

Table 2. Dust chambers comparison

Chamber	Material	Dimensions	Doors/Access	Accessories
Chamber A	Polycarbonate	36” L x 24” W x 36" H	Removable front sheet	None
Chamber B	Static dissipative PVC	35” L x 24” W x 25" H	Air lock Side door Removable sheet	Work surface Airlock Automatic RB valve Humidity module Pressure gauge Recirculating system Gloves

For the development of this project, testing was going to be initially conducted in Chamber B. However, delivery times (due to Covid-19 outbreak) highly affected the initiation of experiments, and for this, a provisional dust chamber (Chamber A) was built in the lab.

Dust chamber A was initially built to test the system's humidity and dust quantities estimations. This chamber was perfect for initial testing considerations and provided estimated values for future testing; however, access and cleaning were not the easiest, and the material could have been better. It is not possible to move things inside without opening the chamber. This was considered a provisional chamber and a point of comparison for future body testing constructions.

Dust chamber B was designed as the final monitoring systems testing chamber. This chamber has three ways to access it to change things on the inside during and after the experiments. Also, cleaning is easier because it has a recirculating system; and multiple accessories allow more flexibility during testing.

3.1.1 Chamber A

The first step in building chamber A was researching different dust chamber options in the market to know about possible materials, sizes, adaptations, and options for design based on a proposed design shown in Figure 5. The aim was to create an affordable product capable of adapting to the conditions needed for experiments. Some considerations involved making a product easy to modify and drill if necessary, affordable and easy-to-work materials, and access to the chamber to place equipment. Once a north was defined, the design was the next step. The goal was to make the chamber as simple as possible; the design shown in Figure 6 was followed. After this, all products were ordered to start construction.

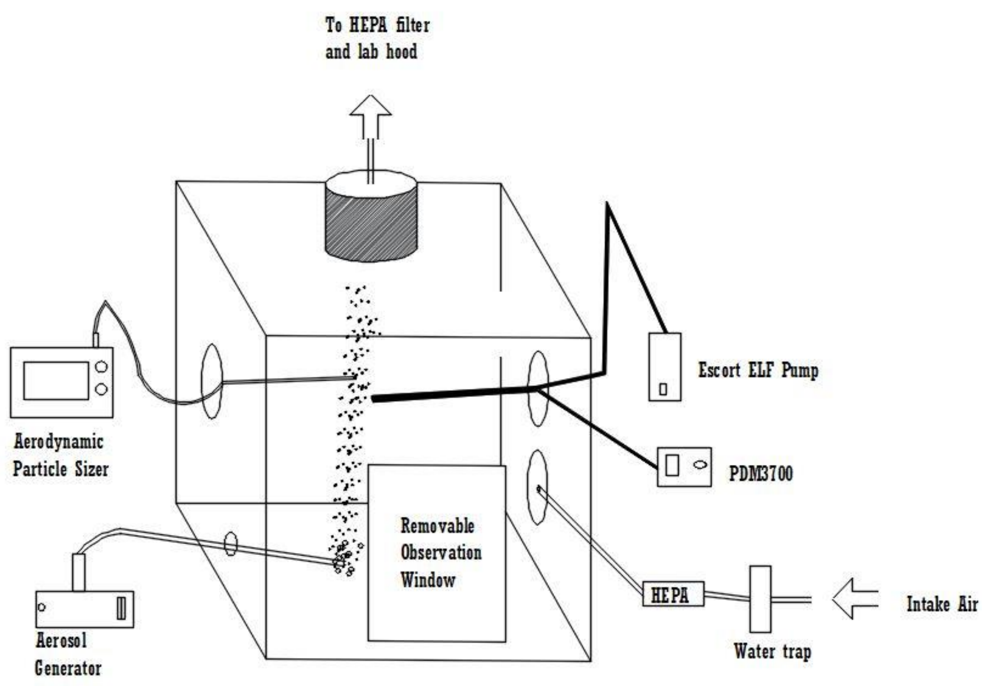

Figure 5. Initial proposed design

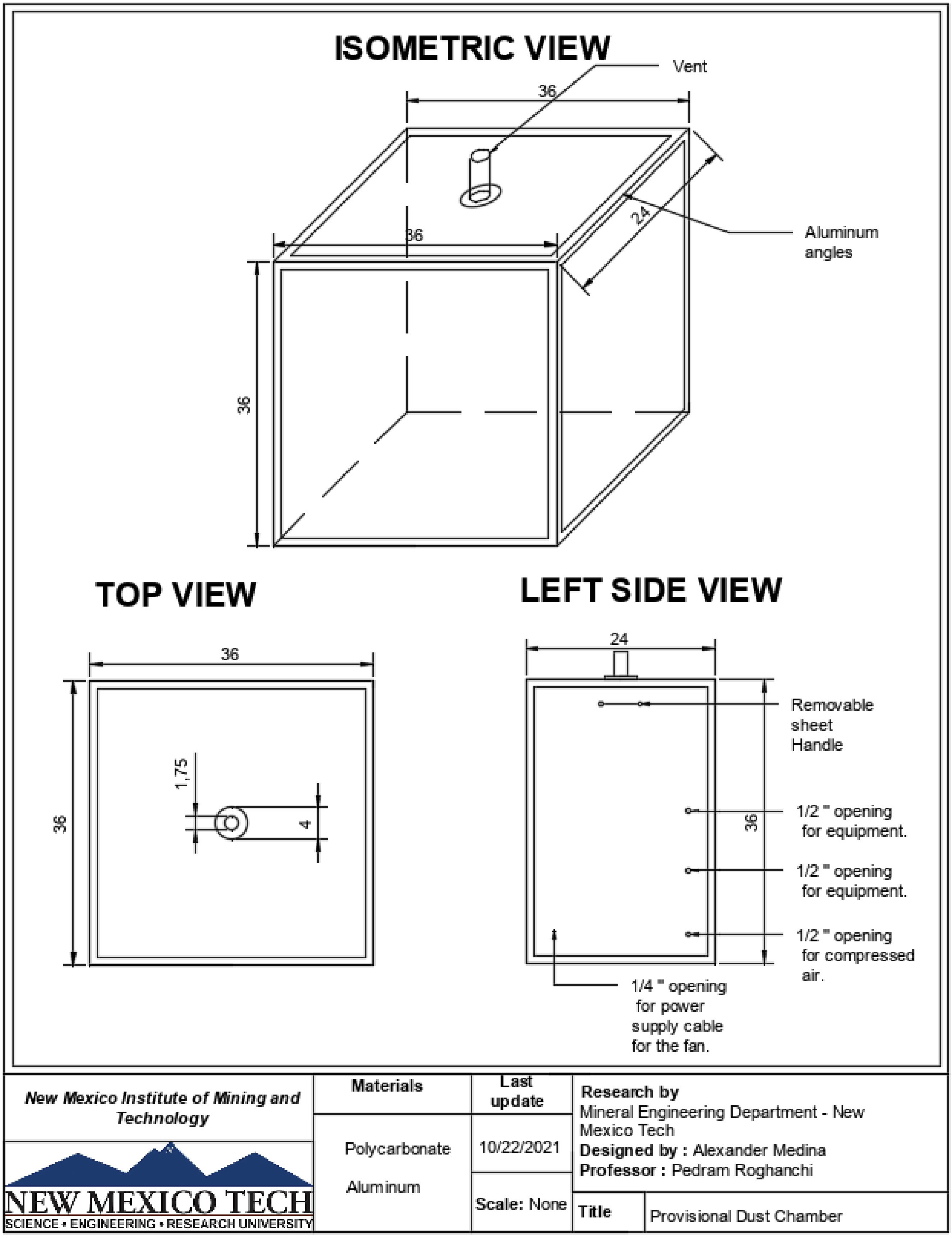

Figure 6. First dust chamber design.

The chamber was designed to be a sealed structure made of polycarbonate sheets and reinforced with aluminum angles to provide more rigidity to the system. Dimensions were 36 L x 24 W x 36 H inches, with a total volume of 18ft^3. Some adaptations were made to allow access to the equipment; compressed air entry was included for cleaning purposes after each experiment. A small fan was placed inside to keep particles in the air. Finally, a vent was installed at the top of the chamber to let particles go out with the help of compressed air and using a flexible pipe to guide them to a fume hood.

The following materials were used for the construction.

- Polycarbonate sheets (2 of 36”x36”x1/4" and 4 of 24x36” x1/4")
- Silicone Sealant.
- Foam Rubber Seal.
- Steel handle.
- Cement for Plastic.
- Aluminum angles.
- Screws and nuts for the structure.
- Silicone rubber sealing washers.
- Different bits for screws and openings.
- Saw-hole drill bit to make an opening at the top of the chamber.
- Pipes.
- Sealing tape.

Having all the materials, the construction step-by-step was as follows.

1. Once all the materials were in the lab, it was ensured that the polycarbonate sheets had the exact dimensions.

2. The next step was drilling holes for the angles and polycarbonate sheets, as shown in
3. Figure 7, to install angles in the corners and reinforce the dust chamber structure from the inside. For this project, angles with round leg edges were used. However, for reinforcing outside the chamber, it is recommended to use angles with square leg edges.

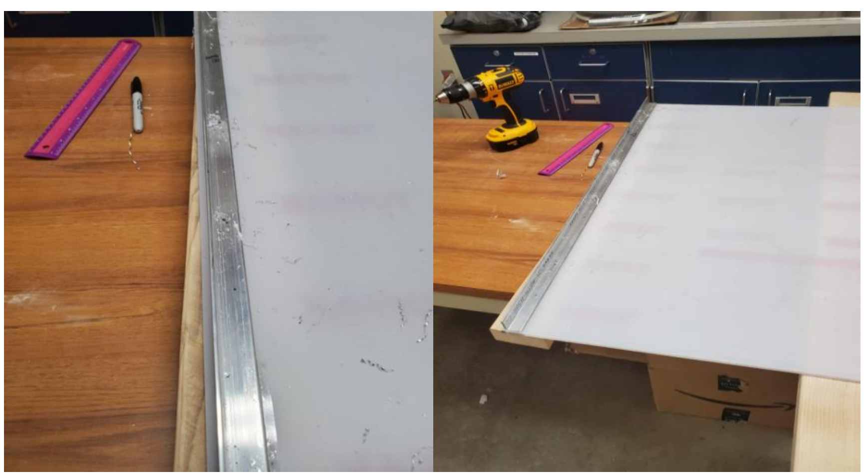

Figure 7. Initial drilling in polycarbonate sheets.

4. Initial aluminum angles were pre-installed inside the chamber to connect the polycarbonate sheets interceptions and have a stable box, as shown in Figure 8.

Figure 8. Aluminum angles installation.

5. Then, the polycarbonate sheets were glued with transparent cement for acrylic; this guaranteed a first sealant stage in the chamber, as shown in Figure 9.

Figure 9. First sealing stage, gluing Polycarbonate sheets.

6. After that, more angles were attached to the polycarbonate sheets with screws and nuts to reinforce the structure and get one solid cube, as shown in Figure 10.

Figure 10. Preliminary chamber structure.

7. Once everything was together, as shown in Figure 11, super silicon sealant was added to the corners to have a second sealing stage.

Figure 11. Second sealing in the chamber.

8. After that, additional angles were installed to permit the opening and closing of a removable polycarbonate sheet. It was ensured that contact areas with no glue in

the chamber were sealed with a foam seal around the perimeter for the removable sheet. The red lines are contact areas between the chamber’s body and the removable sheet. Also, an extra opening was made at the chamber's top, using a saw hole drill to create a vent to take the particles out and conduct them to the fume hood with a pipe. A better illustration is shown below in Figure 12.

Figure 12. Removable sheet and the top opening of the chamber.

9. Openings were drilled in the removable sheet to provide access to the cables for equipment, compressed air, and power for the small fan inside the chamber Figure 13.

Figure 13. Adaptations for the first chamber.

10. The top's opening was closed, and a lid was added to close the hole when the chamber was used, as shown in Figure 14.

Figure 14. Dust chamber opening lid.

11. In addition to the lid, a flexible pipe was included in the chamber and should be connected to the chamber's top to expel the particles in the air once the experiments are done. The pipe conducts to a fume hood-Figure 15.

12. Figure 15. Pipe to take out the particles

13. Figure 16 shows yellow sealing tape added to the chamber to protect corners and add an extra level of sealing to the system.

Figure 16. Yellow tape to protect edges.

14. The next step was to build a wood base for a fan that would be on all the time during experiments inside the chamber to help have uniform concentration, as shown in Figure 17.

Figure 17. The base for the fan.

15. Finally, as shown in Figure 18, the removable sheet was drilled and attached to an aluminum angle with screws and wing nuts for closing and opening the chamber. From inside the chamber, screws pass through the aluminum angle, and the removable sheet and wing nuts close and tighten the chamber outside. These nuts and screws help to have a system that guarantees strong attachment and reliable sealing with the foam sealing across the perimeter of the contact area when closing the chamber.

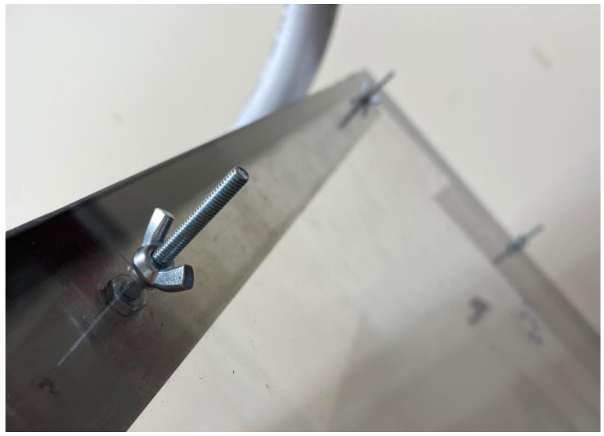

Figure 18. Wing nuts to open the chamber.

3.1.2 Chamber B

Chamber B was a collaborative work with a company called Terra Universal to build a platform with adaptable features to test RCMD and RCS. A design was created in collaboration with the company considering materials, accessories, size of the chamber, and functionality. The design is shown in detail in Figure 19.

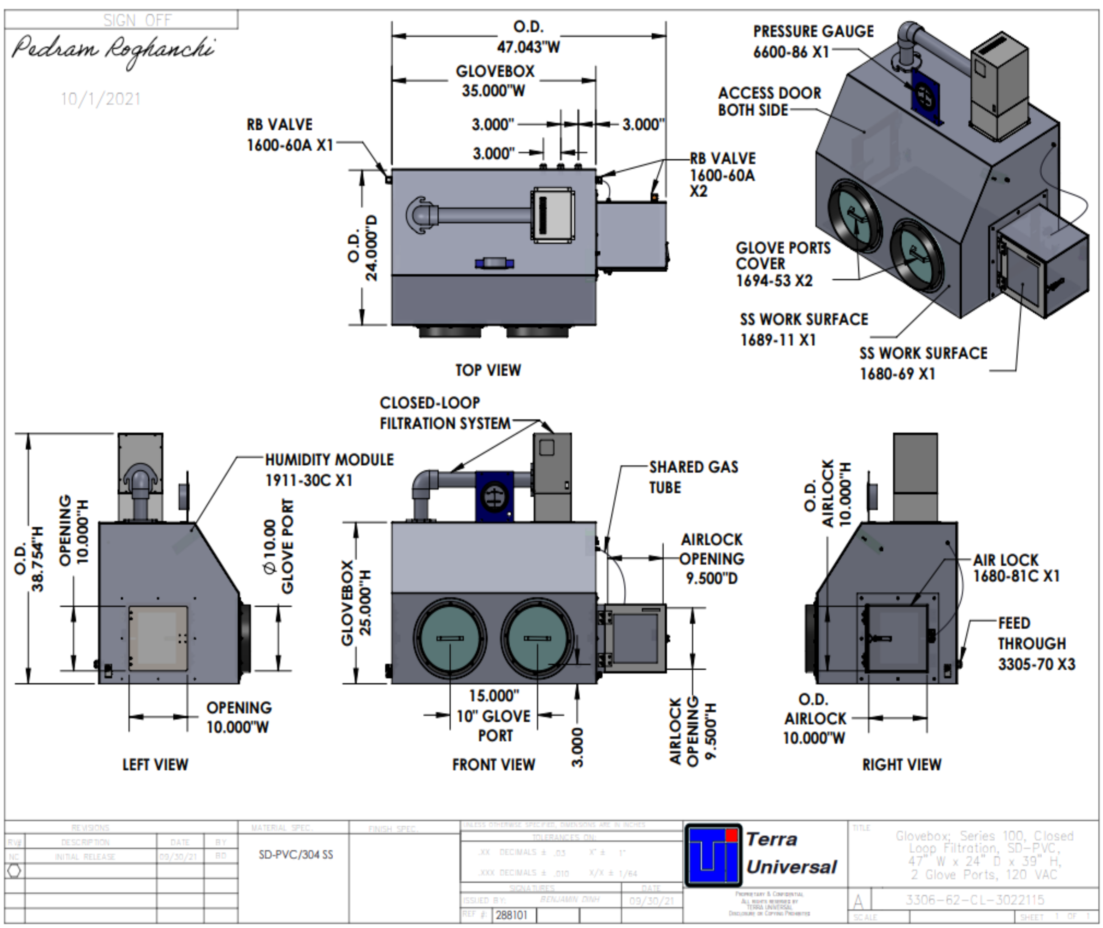

Figure 19. Chamber B design.

The decided material for the material was static dissipative PVC to avoid particles getting attached to the chamber walls during experiments. Also, it included the following accessories. Some product explanations were taken from a quote from Terra Universal[127].

- **Stainless steel work surface:** It is a stainless-steel sheet installed on the bottom of the chamber to prevent damaging the plastic surface. This is removed from the chamber in some experiments to avoid static attraction to the bottom of the chamber.
- **Airlock**: It is a small chamber attached to the right side of the main chamber. It comes with a draw latch to open and close the door, allowing easy pass-through of parts into and out of the chamber while testing.
- **Automatic RB valve**: it keeps a stable pressure inside the chamber to avoid overprescribing the system.
- **The humidity module:** This instrument controls a range of humidity inside the chamber. The Terra Universal instrument description document explains that the device includes a humidity sensor, LED display, solenoid valve, and circulation fan. Although the RH level can be specified anywhere between 0 and 99.5% RH, the practical setpoint range is from room ambient (highest setting) down to the RH of the supply gas (lowest setting). So then, the driest value depends on the system or equipment supplying air [128].
- **Differential pressure gauge**: It shows the internal pressure during testing expressed in inches of water.
- **Glove ports and gloves:** This chamber allows gloves to move equipment and instrument without opening the chamber or stopping the experiment. The system also has glove port covers to remove gloves and close the holes whenever they are not wanted inside.

3.1.3 How to Use the Dust Chambers

Before performing any experiments, these are some general considerations for using and cleaning the chambers:

Chamber A

- Make sure the fume hood is on and working correctly.
- Before starting any new experiments, ensure everything is clean inside and no dust remains from previous experiments. For this, connect the compressed air from one of the openings and replace the lid with the flexible pipe. Place the pipe inside the fume hood and add air for 10 minutes to clean any contaminations from previous experiments.
- Disconnect the pipe and put the lid again at the top of the chamber.
- To open the door, unscrew all wind nuts and pull out the door using the handle.
- Once the door is open, spray DI water inside and wipe until it is clean.

- To close the door, align screws from the chamber structure with the holes in the removable sheets and tighten them up with the wing nuts.
- Make sure to add sealing tape to the openings to reduce the chances of leaks.

Chamber B

- Make sure the fume hood is on and working correctly.
- Ensure everything is clean inside and no dust remains from previous experiments. For this, connect the recirculating system and keep it running for 10 to 20 minutes to clean dust particles inside the chamber.
- Make sure to replace the recirculating system's filter after continuous use. There is no defined time to replace it. However, it is recommended to open the recirculating system box monthly to check the filter's condition and change it if necessary.
- Access to the chamber could be through three ways—first, the door on the left side. Second, through the airlock. Third, opening the back sheet of the chamber, to remove this sheet, it is necessary to unscrew all the screws in the back side of the chamber and carefully remove the sheet.
- Once the door is open, spray DI water inside and wipe until it is clean.
- To close the chamber after removing the sheet and cleaning, align the sheet with the chamber and screw back everything.
- Gloves can be removed and changed for glove ports' lids. If gloves are installed, ensure they are tight enough to avoid opening during the experiment. The lids can also be left inside to remove gloves from the chamber during experiments.
- Make sure pressure is always between allowable limits.

3.2 Humidity Control Station

3.2.1 Construction

Humidity is a critical aspect of simulated underground coal mine conditions. Most of the time, underground coal mine conditions are very humid environments. Thus, an instrument capable of humidifying the air without contamination is needed. From the literature review, one of the assumptions for testing in simulated conditions is that particles can agglomerate when moisture is high in the air, which can lead to inaccurate readings in monitoring equipment. Hence, to test instrument accuracy in humid environments, some dry RH ranges should also be generated as a baseline for comparison with readings in high-humidity environments.

A humidity control station was built based on one a design found in the New Mexico Tech Chemistry Department to provide dry and humid air inside the chamber. Initial designs are shown in Figure 20; this is an easy-to-modify system that can add or remove lines of dry or humid air if needed; thus, the final product may differ from the initial proposed design.

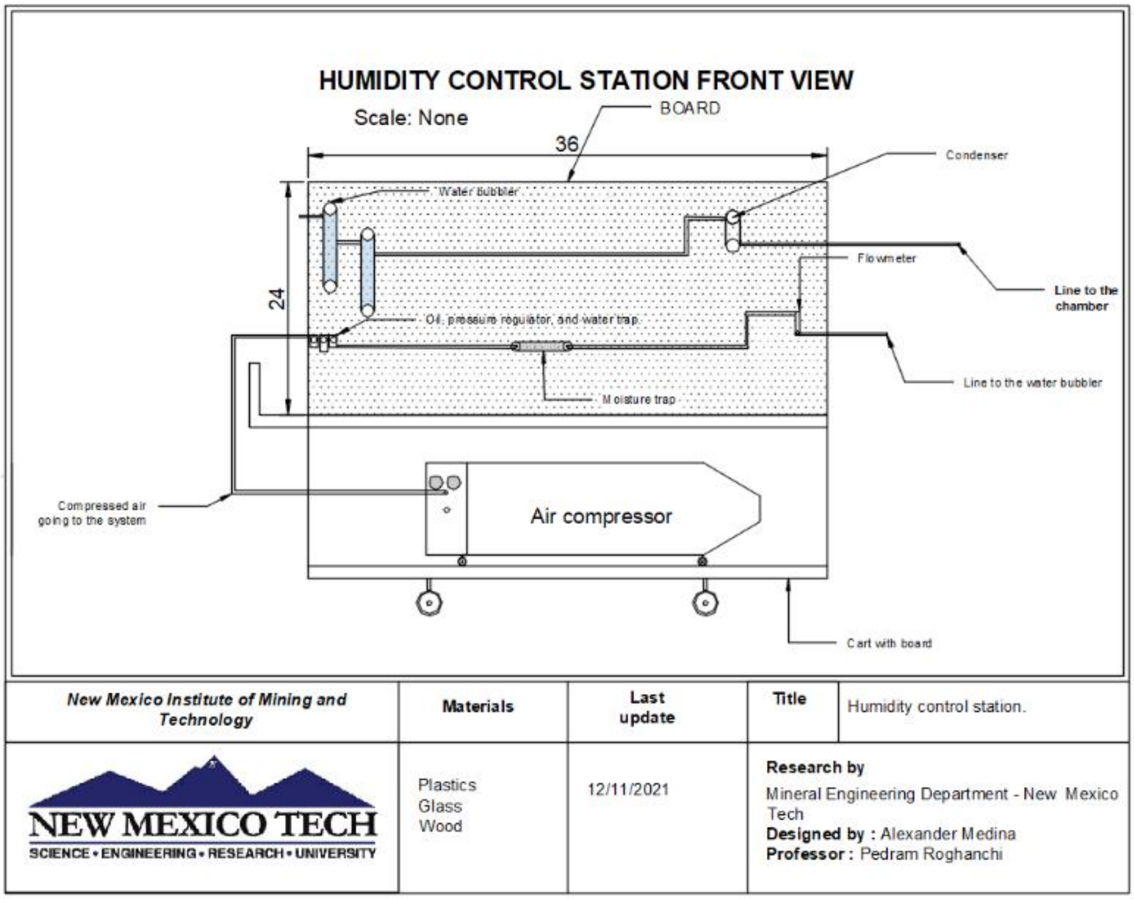

Figure 20. Humidity control station (HCS) design

Once the design was defined, the next step was to order the items to build the HCS. Table 3 shows the needed parts for construction.

Table 3. HCS parts

Equipment	Quantity
Steel cart with perforated board	1
Moisture trap with compression fitting	1
Water bubbler	2
Water filter	1
Humidity sensor	1
Oil and water trap unit with pressure gauge.	1
Tubing	50 ft
Flowmeters	1
Air compressor and fittings for connections	1
Water bubbler - Female Connector: Compression x FNPT	2

Water bubbler - Male Connector: Compression x MNPT	2
Water bubbler - Ultra-Torr Vacuum Fitting, Union.	1
Water trap - Male Connector: Compression x MNPT	2
Oil and water trap - Male Connector: Compression x MNPT	2
Flowmeters - Ultra-Torr Fitting x Male NPT	2
Zip ties	1
Plastic hanger Strap	1

The instruments were attached to the perforated board of the steel cart after having everything needed to construct the HCS. After that, following the order proposed in the design, tubing was used to connect the system. The final products are shown in chapter 4 of this document.

3.2.2 How to Produce High Humidity Values?

1. Turn on the air compressor and fill up the tank to have enough air to supply the system for the necessary experiment time. If the compressor has a small tank, a constant air supply should be guaranteed, filling up the tank every time the air ends.
2. Direct the air to the oil, water, and pressure regulator in the bottom left part of the humidity control station. This is needed as an additional precaution since compressed air often contains oil and water.
3. After that, pass the air through the moisture trap. The moisture trap could reduce the moisture levels to as low as 5% RH. Also, it will reduce contamination in the air.
4. The next step in the process is to pass the air through the flowmeter; this controls the flow rate that will go to the water bubblers.
5. Once dry, clean, pressure controlled, and flow-regulated, the air goes through the water bubblers to increase humidity values. Depending on the flow rate and pressure of the air, water bubblers are usually filled up at ¼ of their capacity. distilled water (DI) should be used.
6. When higher humidity values are needed, a heating band should be used to wrap around the bottom of the water bubbler to increase the water temperature and, therefore, increase RH values.
7. After reaching high humidity in the air, the air goes through a condenser or water filter to eliminate any water drops in the system.
8. Finally, the air is conducted into the dust chamber.
9. The process can be seen better in Figure 21.

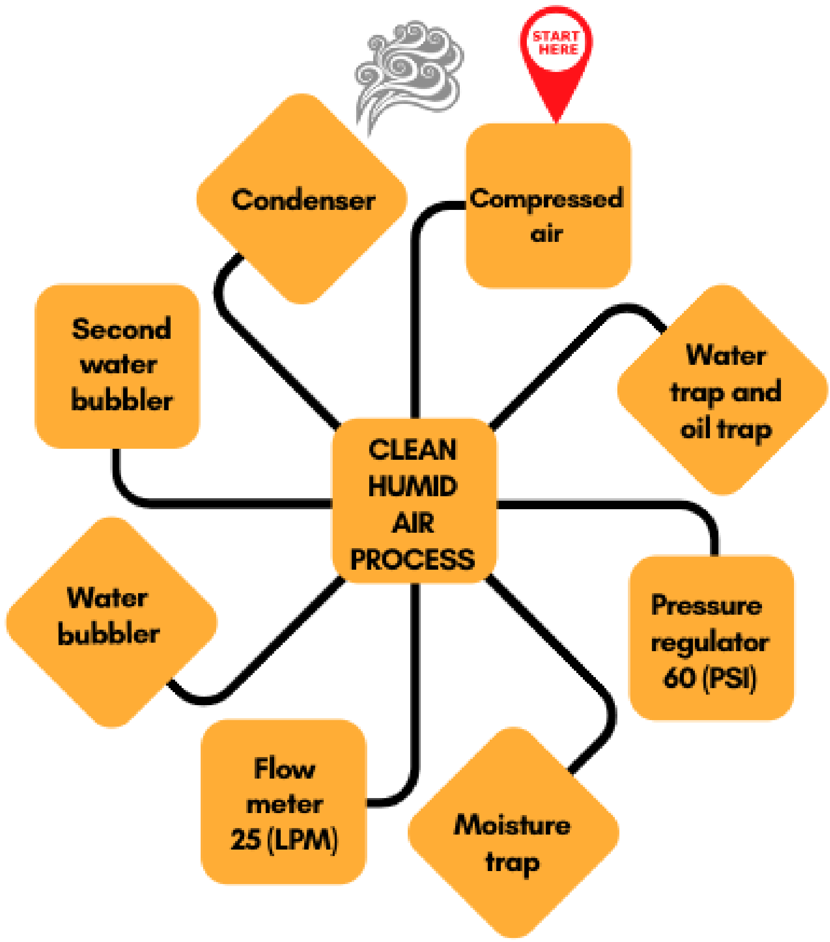

Figure 21. HCS humid air process

3.2.3 How to Produce Dry Air?

1. Turn on the air compressor and fill up the tank to have enough air to supply the system for the necessary experiment time. If the compressor has a small tank, a constant air supply should be guaranteed, filling up the tank every time the air ends.

2. Direct the air to the oil, water, and pressure regulator in the bottom left part of the humidity control station. This is needed as an additional precaution since compressed air often contains oil and water.
3. After that, pass the air through the moisture trap. The moisture trap could reduce the moisture levels to as low as 5% RH. Also, it will reduce contamination in the air.
4. The next step in the process is to pass the air through the flowmeter; this controls the flow rate that will go to the chamber.
5. Connect the tubing to the chamber.
6. The process can be seen better in Figure 22.

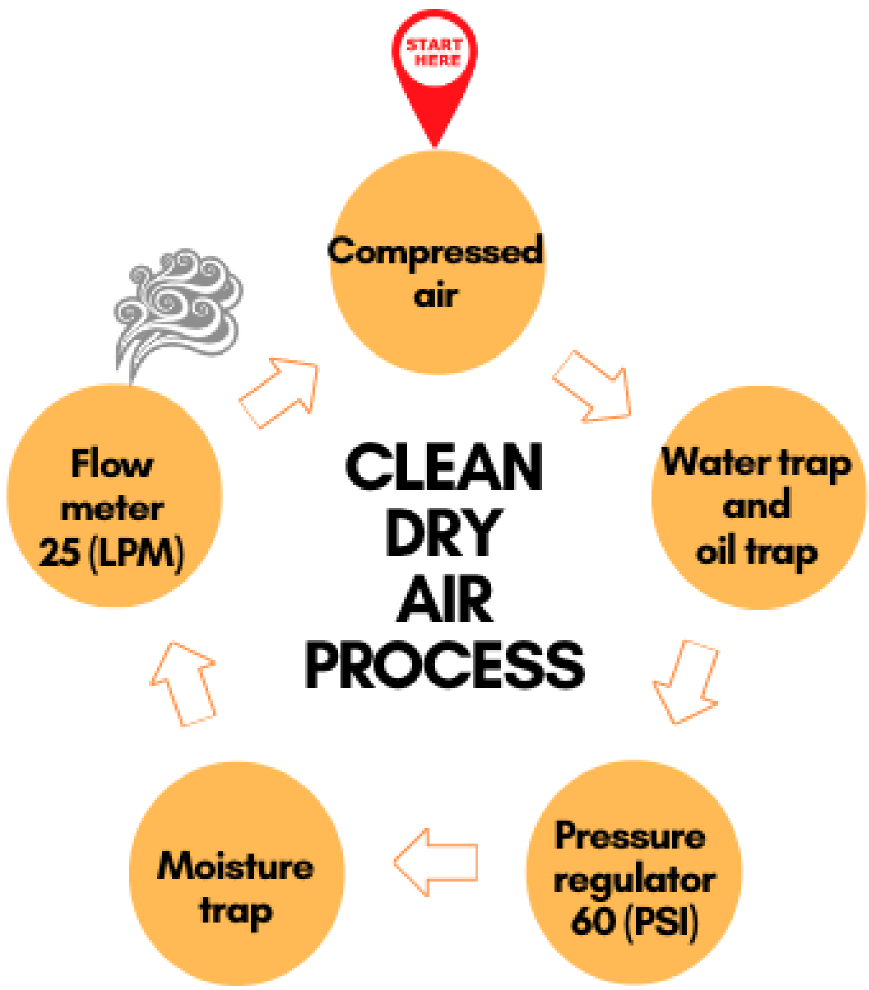

Figure 22. HCS dry air process

3.3 Sample Preparation

Coal samples from three mine sites were collected on site and grind to produce particles for use with the Topas solid aerosol generator SAG 410 U (AG), which only can use particles less than 100 µm. Once particles were taken to the lab, grinding and sieving was the next step. The ball mill used was the 755RMV jar mill, which has 9.5 D and 8.5 H inches, using zirconia balls radius end cylinder of 1/2 × ½ inch, magnesia stabilized.

The procedure for this sample preparation was an adaptation of the sample preparation made by Salinas et al. 2022 [29].

1. Before having contact with the materials, make sure to have the required PPEs for the sample preparation: a mask/respirator, safety glasses, lab coat, and gloves.

2. Reduce the sample with a hammer, mortar, and pestle. The material must pass a U.S.A. standard sieve No. 6—a minimum of two hundred grams of each sample is needed.
3. Weight the sample.
4. Pour the sample into a pan and keep it in the oven at 60-75 degrees Celsius for at least 12 hours. After drying, weigh the sample again and take the weight.
5. The next step is grinding the sample for 6 hours, but before, ensure the balls inside the jar are clean and without any other material to avoid contamination. Pour the dry sample and the balls into the jar, tighten the lid, put the jar in the equipment, and turn it at maximum speed. Turn it off after 6 hours.
6. Sieve the sample with U.S.A. standard sieve No. 120 (opening: 125 µm).
7. To obtain a higher portion of particles less than 10 µm, grind the sample again for 6 hours without cleaning the ball mill. Make sure again that the speed is at the maximum.
8. Collect the sample after the 2nd grinding and separate the sample from the balls using a sieve, a brush, and a pan. Recover as much material as possible. If the samples are needed for the aerosol generator, samples should be less than 100 µm for the Topas SAG 410 U model, so depending on what is needed sample should be sieved again to meet equipment requirements. U.S.A. standard sieve No. 230 (opening: 63 µm) was used for this research to get the desired particle size in samples.
9. After getting the desired particle size, the sample should be weighted, labeled, and stored in the freezer.
10. Clean the ball mill by pouring around 800g to 1 kg of sand into the jar. Add the balls and grind for around 2 hours. Then, remove the ground sand, wash the balls with water and soap, and rinse with DI water. Balls can be oven-dried, but not the jar.
11. Clean all the sieves and elements used during the grinding and preparation, wash them with water and soap, and rinse with DI water.

3.4 Equipment

3.4.1 PDM3700

The PDM3700 is one approved NIOSH sampler for RCMD; as mentioned before, this device can give RCMD values but not RCS content. Therefore, in lab testing, this device could be compared to the ones that can give mass concentration in the chamber, like the SPS30 sensor, the mass concentration from the APS 3321, and some readings from the Ring-IR device. The minimum sample time should be 30 minutes to get concentrations, and the device must warm up for 35 minutes before any lab testing.

3.4.2 SPS30 Particulate Matter Sensor

The sensor is a low-cost PM monitor with multiple uses in some industries. For research purposes, this low cost can be used to monitor a small, controlled environment inside the dust chamber and get values of different ranges of PM. The device can measure particles in the air as soon as it starts working; it is very small and provides continuous readings for the needed experiment time. Multiple sensors can be used simultaneously from all corners of the chamber to get an average reading of particle concentration in the air. Since this device can measure particles in the air without distinction, it will be used to compare the RCMD reading with the PDM through different humidity values inside the chamber.

3.4.3 TSI Aerodynamic Particle Sizer (APS) 3321

The APS 3321 could be used to measure aerodynamic particle size and particle concentration inside the chamber. Also, this device is used to confirm that the prepared samples are between the allowable limits for the experiments. The APS with the SPS30 sensor can help to determine the needed dust concentration for experiments inside the chamber while testing. The APS is also used to determine particle size distributions of the samples in different positions inside the chamber.

3.4.4 Topas Solid Aerosol Generator SAG 410 U

This device can work with different materials, but particle sizes must be 0 to 100 µm. It will produce the needed airborne particles inside the chamber so that the other devices can read more accurate values. Usually, for experiments inside dust chambers, the feed rate is used in very low percentages since the instrument can produce high concentrations in short periods.

3.4.5 ELF Pump with Aluminum Cyclone and Cassettes with Filters For FTIR

For comparison purposes, samples are taken through this sampler unit during the experiment inside the chamber. Once the sample is taken, cassettes are analyzed using the FAST method to find silica content with the portable FTIR. Usually, concentrations in the chamber with the aerosol generator supplying dust are assumed to be higher than in the mine since it will be an environment above the PEL for RCMD and RCS most of the time, and cassettes will have more dust content. Thus, the testing time is shorter than a shift with minimum speed rates from the aerosol generator.

3.4.6 Self-Made Humidity Control Station (HCS)

The HCS is a set of instruments that provide humidity values from 10% to 80% depending on the size of the testing body or, in this case, the chamber. The instrument could take up to 1 hour to reach the conditions when humidity values are very high or very low, so this time should be considered for the total testing time.

3.4.7 Ring-IR Instrument (Prototype)

This device is still under testing for development by Ring-IR to measure silica values in almost real-time in RCMD samples. A student in this same NMT research team is conducting testing in chamber B in a similar research project. Results are compared to values obtained from NIOSH-approved methods and FTIR using the NIOSH FAST method. So far, the prototype allows taking a sample every couple of minutes, taking a background check, and comparing values with dust concentration in the taken samples.

3.5 Experiments

3.5.1 Humidity Comparison

Humidity experiments were performed, to reach humidity values under 10% and above 70% inside the testing body. Experiments were initially performed for a model and chamber A. The model used for the experiment was a zip-closed bag with a side opening to connect tubing and supply air. The chamber and the model had different sizes; in this case, the volume that had to be replaced with dry and humid air was smaller in the model, and the assumption was that values would be reached faster.

Equipment involved dust chambers, a humidity control station, a humidity sensor, and an air compressor. The procedure is shown in Figure 23.

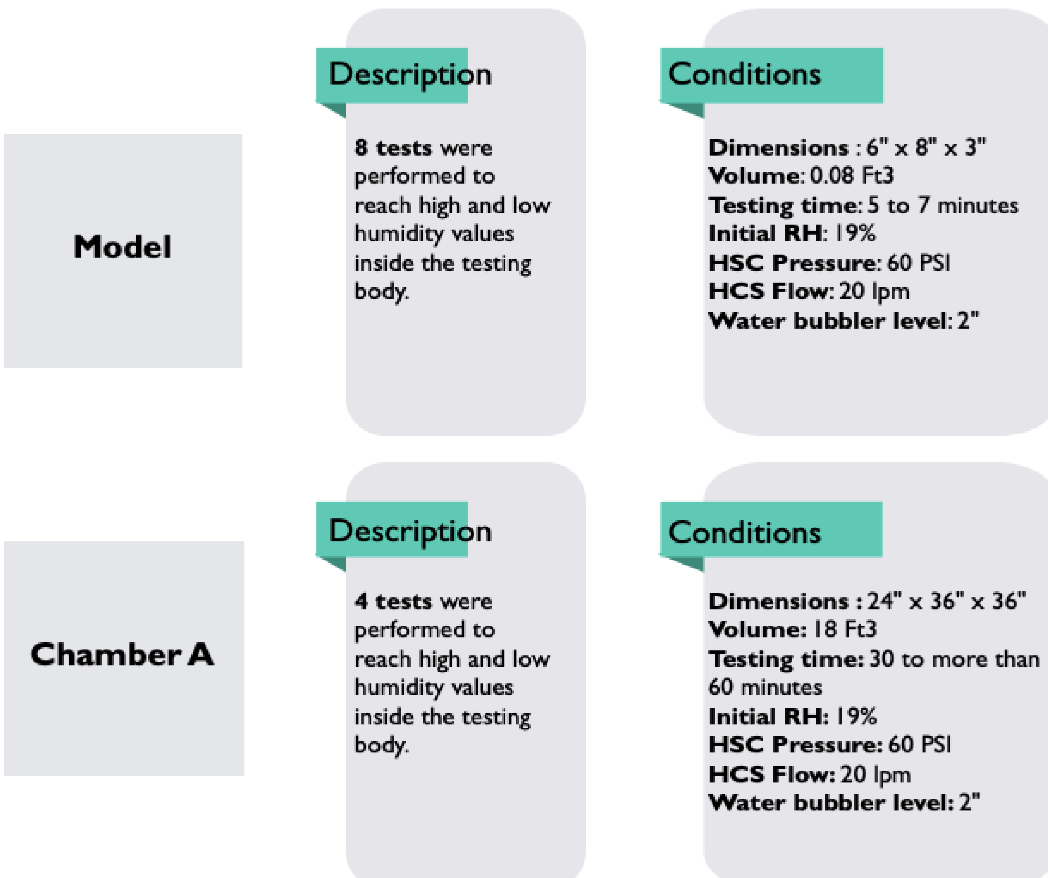

Figure 23. HCS model vs. chamber experiments

Further experimentation was performed to reach higher humidity values. As mentioned before, a heating band was added to the process, and this one was wrapped around the bottom of the water bubbler to increase the water temperature and, increase RH values.

3.5.2 Concentration Experiments

The concentration experiments aimed to determine the best internal area inside the chamber to place sampling heads, sensors, and tubing feeding equipment. Six internal areas were evaluated and continuously tested to determine whether the areas were reliable and had constant readings. Dust chamber B was used for concentration testing, divided into six quadrants, as seen in Figure 24.

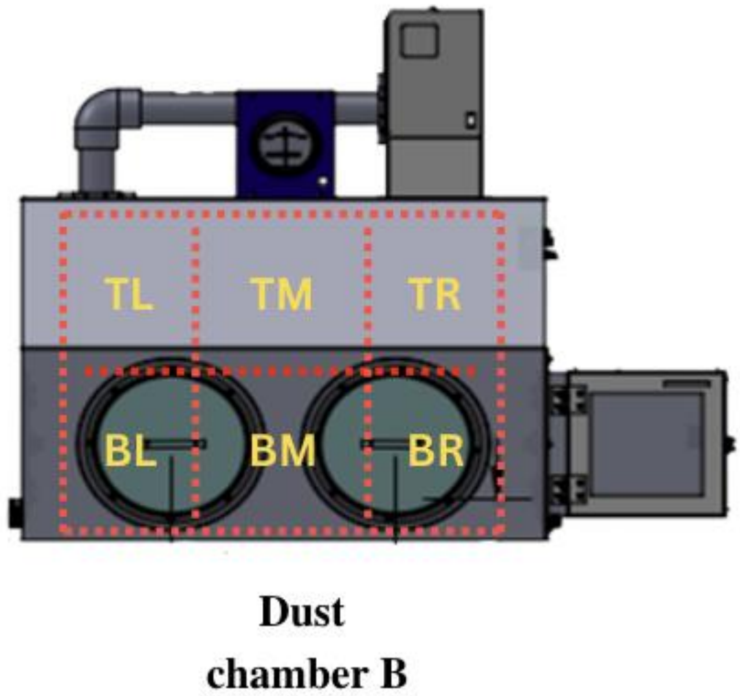

Figure 24. Concentration experiments – chamber internal areas for testing

The quadrants (internal areas) names are defined as follows.

- BR: Bottom right of the chamber
- TR: Top right of the chamber
- BM: Bottom middle of the chamber.
- TM: Top middle of the chamber.
- BL: Bottom left of the chamber.
- TL: Top left of the chamber.

Equipment used for the experiment included SPS30 sensors, APS3321, a small fan, and a Topas solid aerosol generator SAG 410 U. Equipment distribution was shown in Figure 25.

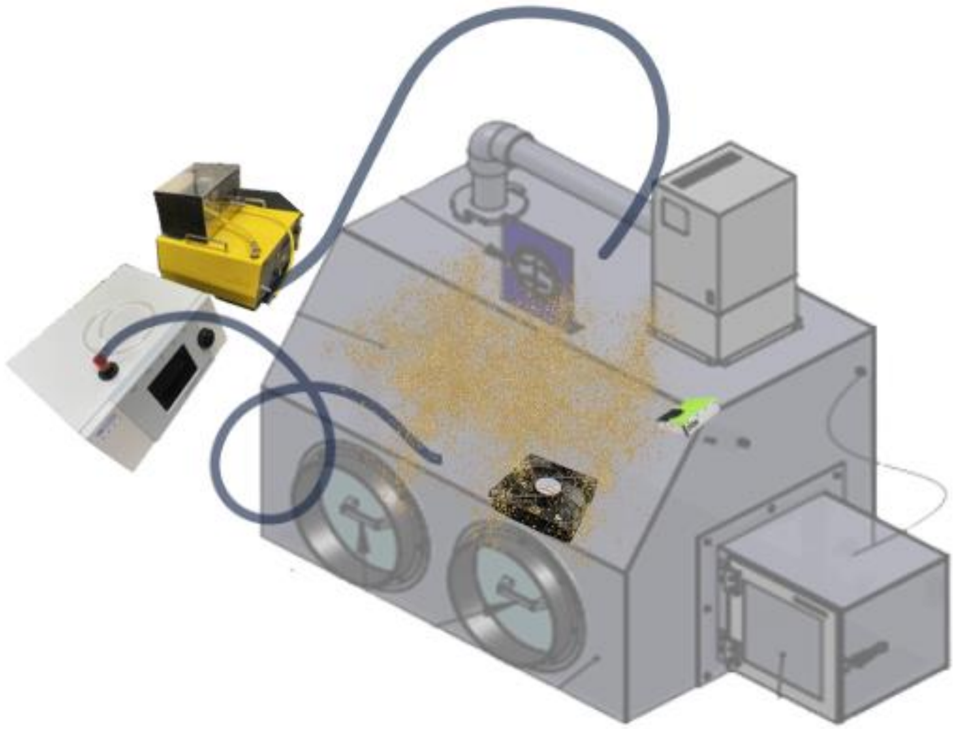

Figure 25. Concentration experiments

Initially, nine short tests were performed to determine the best way to approach the experiments. Arizona dust (0 to 5 µm) and coal dust (0 to 63 µm) were used. The aerosol generator (AG) was used at different feed rates to find a reasonable and constant range of particle concentration inside the chamber for testing; for these experiments, desired values were between 0 to 4 mg/m3.

After having an idea of how to do testing, experiments 10, 11, and 12 were performed with Arizona dust, and experiments 13 and 14 were performed with coal dust. Once knowing better what could change during the experiment, a short final test was done to compare with a longer test.

Cleaning conditions were changed to verify how this could change concentrations. The final tests were defined as follows.

- **Concentration experiment 1 (Long test): 6** internal areas, **3** tests in each area, **10** minutes for each test, readings every minute. With cleaning between readings.
- **Concentration experiment 2 (Short tests): 6** internal areas, **3** tests in each area, **3** minutes for each test, readings every minute. Without cleaning between readings.

The general process for testing was as follows.

- Check that all the equipment is ready for use.
- First, clean the chamber inside with the recirculating system for at least 10 minutes. It is recommended to check concentration values with the SPS30 sensor and the APS.
- When the sensor and the APS show a concentration value close to 0, open the chamber, spray DI water, and clean with delicate wipers.
- Turn on the fan inside the chamber at medium speed.
- Start the aerosol generator at a value that can generate particle concentrations between 2000 to 4000 pt/m3. A good value for this test was a feed rate of 0.7%, which can vary depending on material and equipment. Leave it running for 10 minutes before doing experiments to stabilize concentration inside the chamber. This research considered the standard-size ring of the AG equipment for testing. However, more consistent concentration results could be achieved with a small dosing ring in the equipment. Future research will be performed with a smaller ring in parallel research in the same NMT research team
- Keep the air compressor supplying air during the experiments to the aerosol generator. The air should be dry and clean, so a water and oil filter are needed.

For the long experiment, the tubing for the APS is in the first internal area, and the experiment is run three times for 10 minutes each. Later, everything is cleaned for 3 minutes with the recirculating system, and after 7 minutes of waiting to stabilize concentration, the tubing for the APS is moved to the second area. The same procedure is followed for the six internal areas.

For the short experiment, the tubing for the APS is in the first internal area, and the experiment is run three times for 3 minutes each. Next, the APS tubing was moved to the second area and continued with all the experiments without any cleaning. The same procedure is followed for the six internal areas.

3.5.3 Airflow Experiments

The air velocity distribution was the main factor in determining the fan's position inside the chamber. Two anemometers were placed in different quadrants inside the chamber to measure the air velocity in multiple positions, while a fan was placed in other quadrants. This was done to determine which quadrant of the fan could produce the most uniform air distribution. Quadrants are shown in Figure 26. The test was done as follows.

- Chamber is opened and cleaned, spraying DI water and wiping walls.
- The fan was placed in the first position.
- Three anemometers were rotated in all possible quadrants during each fan position except for the quadrant with the fan.
- The process was repeated, rotating the fan for all twelve quadrants.
- Speed was done first at low fan speed, then medium speed, and lastly, at high speed in all the quadrants.

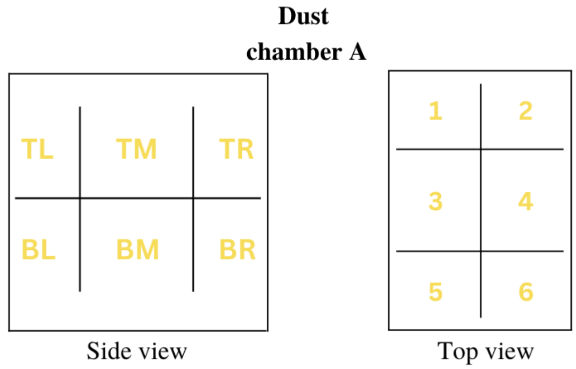

Figure 26. quadrants for the dust chamber.

3.5.4 Monitoring Systems Proposed Experiments

A proposed design of the experiment was created to test monitoring systems inside the chamber. The goal was to compare equipment readings for RCMD and RCS under different humidity conditions. The equipment needed for the experiments involved a PDM3700, four SPS30 particulate matter sensors, a data logger for humidity and temperature, a TSI aerodynamic particle sizer (APS) 3321, a Topas solid aerosol generator SAG 410 U, an ELF pump with aluminum cyclone and cassettes with filters for FTIR, a Self-made Humidity control station (HCS), a Ring-IR instrument, a computer with multiple USB ports, and chamber B as shown in Figure 27.

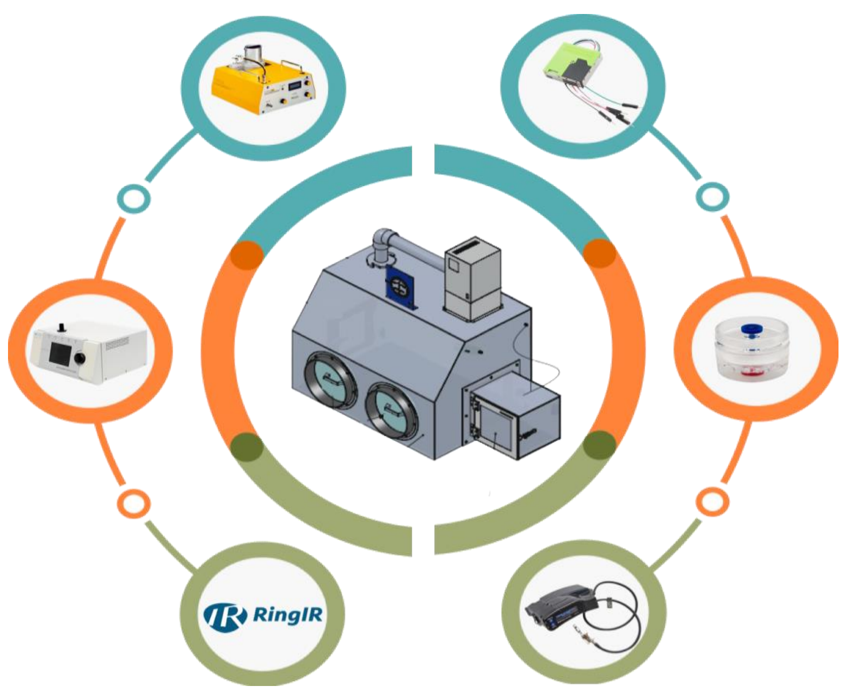

Figure 27. Chamber B and equipment

The design of the experiment is explained in Table 5, and a timeline of experiments is shown in Table 5.

Table 4. DOE for monitoring systems

<table>
<tr><th colspan="2">DOE sheet</th></tr>
<tr><td colspan="2">Process

1. Check that all the equipment is ready for use.
2. Start introducing the air inside the chamber to get the desired humidity; for humidity values above 50%, the heating band must be used.
3. Warm-up equipment. PDM3700 (35 min before experiments), Ring-IR (10 minutes before experiments). Ring IR will take lectures every 5 minutes. 7 lectures in total. PDM3700 will do a continuous reading.
4. Start with the aerosol generator 10 minutes before experiments once the desired humidity is reached. The feed rate will be 0.7 for coal dust and 0.5 for silica dust for all the experiments without any changes.
5. After 10 minutes of pumping dust inside the chamber, the experiment will start.
6. Write starting time.
7. The cassette for silica must be new.
8. APS must be set up for 7 samples each 5 minutes.
9. All 4 SPS30 sensors have to be on and reading.
10. Data logger for humidity and temperature inside the chamber.
11. Ring - IR must be set up for 7 samples each 5 minutes as follows.
First sample: 0 minutes.
Second sample: 5 minutes.
Third sample: 10 minutes.
Fourth sample: 20 minutes.
Fifth sample: 25 Minutes.
Sixth sample 30 Minutes.
12. ELF pump must start at minute 0.
13. Once the first experiment is done, all equipment must be set up again to take the next readings.
14. Write the final time.
15. The cassette must be changed for the next experiments.
16. Once five experiments are done with the first humidity, the same procedure must be repeated for the second humidity experiment until reaching 80% RH.
17. Once experiments are done for the first material, cleaning must be done before moving to the second material.</td></tr>
<tr><td colspan="2">Problem Statement: Testing is needed to compare monitoring systems for RCMD and RCS and test the accuracy of new and adaptable technology.</td></tr>
<tr><td colspan="2">Objective: The experiment's main objective is to initially test the RING-IR device under variable humidity conditions to evaluate performance and accuracy, then compare results with approved monitoring equipment.</td></tr>
<tr><td>Start date: Minute 0</td><td>End date: Minute 35</td></tr>
</table>

Factor	Type:	C or N	Range of interest	Anticipated interactions	How measured
Time	Attribute	Controlled	2 hours		Timer
Concentration	Variable	Controlled	0.2 to 4 mg/m^3	Feed rate and material	APS, PDM3700, and sensors
Feed rate	Variable	Controlled	0.7%		Aerosol Generator
Temperature	Attribute	Noise	19 C		Sensor
Humidity	Variable	Controlled	10-80%		Sensor
Wind speed	Attribute	Controlled	N/A		Fan
Material	Attribute	Controlled	Coal and silica		N/A

Table 5. Experiment timeline

<table>
<tr><td colspan="35">Test preparation - minutes</td></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td><td>31</td><td>32</td><td>33</td><td>34</td><td>35</td></tr>
<tr><td colspan="35">PDM3700 warm-up time</td></tr>
<tr><td colspan="12">Install new cassette</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="11">Turn on the pump (min 36)</td></tr>
<tr><td colspan="12">Start the data logger and put it in the chamber – any time before the test.</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="12">Set up APS</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="11">Start APS (Min 36)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="11">Check sensors and start them (Min 36)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="11">Ring -IR warm-up time 10 minutes before. First testing minute 36.</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="11">A. Generator on for 10 min before @ feed rate 0.7 or 0.5</td></tr>
<tr><td colspan="35">Set up chamber humidity</td></tr>
</table>

CHAPTER 4

RESULTS AND DISCUSSIONS

This chapter summarizes the finalized constructions, obtained samples, and experiment results following methods explained in Chapter 3. Also, it will provide discussions about different potential solutions for the experiments and some common causes of error with the current layout. Finally, it will discuss what has been beneficial for experiments and what could be improved to maintain a reliable testing platform.

4.1 Dust Chambers Results

Table 6 briefly describes each chamber, its construction phase, and experiments performed or potential use.

Table 6. Dust chambers state

Chamber	Material	Dimensions	Construction phase	Experiments
Chamber A	Polycarbonate	36” L x 24” W x 36" H	Completed	• Humidity • Dust consumptions • Airflow
Chamber B	Static dissipative PVC	35” L x 24” W x 25" H	Completed and delivered	• Concentrations • Monitoring systems (DOE)

4.1.1 Chamber A – Provisional Chamber for Testing

Figure 28 shows the completed construction of chamber A as a provisional chamber for this research while waiting for chamber B. This chamber was easy to modify and had good sealing for initial dust experiments. However, the way to access it was complex, and the structure was not so rigid since it was made of ¼" thickness polycarbonate sheets, which was not strong enough to support all the weight of the 18ft^3 body—Among other limitations of the chamber.

Also, cleaning was complicated since it did not have a recirculating system. All particles had to be collected via a flexible pipe connected to a fume hood. The chamber was successfully used for preliminary testing of the HCS and aerosol generator and has worked as a reference for learning about future dust chamber constructions.

Figure 28. Completed chamber A

4.1.2 Chamber B – Final Dust Chamber for Testing

Chamber B is shown in Figure 29. The chamber permits easy access to the system and has static dissipative materials that have worked well with fine coal particles without creating any attraction to the walls.

Figure 29. Completed chamber B

Multiple instrument sampling probes and sensors were successfully connected, passing tubing through feed through adaptations and quickly moving the inside with the gloves or just accessing from the side door.

Modifications to the chamber included removing the stainless-steel surface because it could attract particles to the bottom. In addition, the chamber's humidity module was turned off for some experiments since it limited the air coming inside, and external factors like room ventilation and humidity changed internal humidity ranges.

The RV valves have proven to be effective in the control of the internal pressure of the chamber. Even though some particles may come out from these RV valves, the constant dust supply from the aerosol generator is enough that dust concentration changes are negligible. Nonetheless, actions should be taken to not contaminate the testing room with dust particles expelled from the valves.

The chamber always maintained an internal pressure of 0.05 inches of water measured with the chamber's pressure gauge during experiments. However, this value may fluctuate when moving things around, using the recirculating system, or opening doors. Most of these fluctuations do not impact the chamber's integrity and may be neglected for testing purposes.

The internal recirculating system has effectively reduced particle concentration every time it is needed, which has been confirmed by concentration readings measured with the APS3321, the PDM3700, and the SPS30 sensors. Four SPS sensors have been added to the top corners of the chamber to read PM behavior in real-time before, during, and after experiments.

4.2 Humidity Control Station Results

4.2.1 Construction

The completed construction of the unit is shown in Figure 30.

Figure 30. Humidity control station

4.3 Sample Preparation

Four samples were prepared following the grinding and sieving procedure explained in chapter 3. Three of them with particles less than 63 µm and one with particles less than 20 µm. Also, Arizona dust with a particle size from 0 to 5 µm was purchased and used for preliminary concentration experiments in the dust chamber. Samples are shown in Figure 31.

Sample 1: The Sample was taken from a New Mexico surface coal mine and sieved to less than 63µm. Also, another sample was prepared and sieved to less than 20µm

Sample 2: The Sample was taken from a West Virginia underground coal mine and sieved to less than 63µm.

Sample 3: The Sample was taken from a Colorado underground coal mine and sieved to less than 63µm.

Sample 4: Arizona dust with a particle size from 0- 5 µm.

Figure 31. Final sample preparation for experiments

4.4 Experiments Results

4.4.1 Humidity Comparison

The results of the testing explained in Figure 23 in chapter 3 are shown in Figure 32. Humidity values were taken with the INKBIRD IBS-TH2 sensor, and captures were taken from the humidity sensor app called Engbird [129].

Model

- 84.4% average humidity for the most humid condition with a standard deviation of 2.2%.
- 4.4% average humidity for the dryer condition with a standard deviation of 0.66%

Chamber A

- 56% average humidity for the most humid environment.
- 8.45% average humidity for the dryer condition.

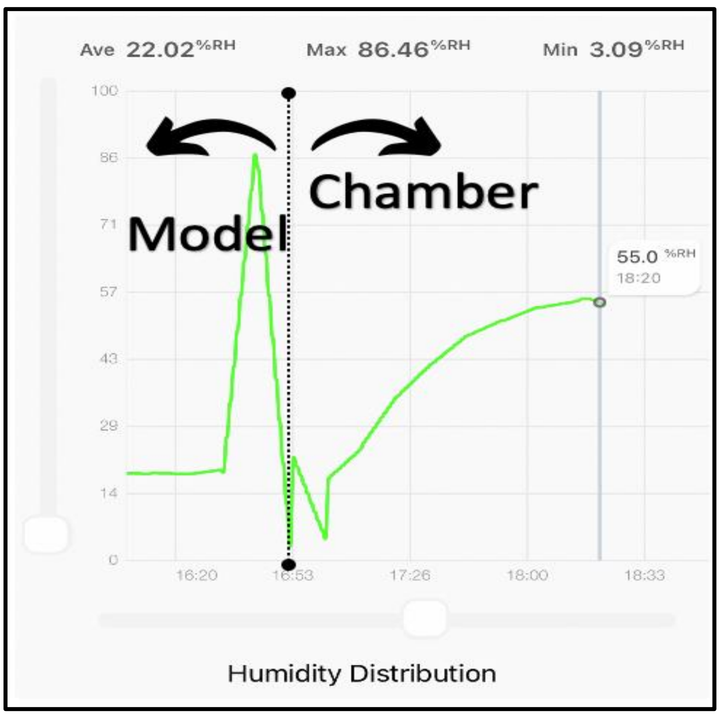

Figure 32. Humidity comparison results

Testing was done to compare changes in humidity in a model and chamber A. The experiment was mainly a time problem because each testing body had a different internal air volume that had to be replaced with dry and humid air. For instance, the volume of the model was smaller, leading to a faster result regarding reaching high or low RH values. On the other hand, the process was always slower in the chamber and had to be more controlled in terms of checking equipment during experiments.

Furthermore, another aspect to consider for the test was that the flow rate and pressure of the air coming into the chamber accelerated the process—the more air coming inside, the faster the results. However, instruments had limitations, which defined the maximum air flow and pressure that could pass through the system. For humid air, the air was limited by the maximum capacity of the water bubbler before getting water into the system or exploiting it because of over-pressurizing. In the dry air line, the moisture trap defined the maximum capacity of air coming into the system since, after certain pressure, it was not working correctly.

Figure 32 shows a graph with the humidity values for the model on the left side and the chamber on the right side of the figure. As can be seen, during the experiment, there were quick changes in humidity for the model section and slower increases and decreases for the chamber section due to the size of the testing body. Humidity in the model varied from a range of values from close to 3% to near 86% in minutes since the air produced by the HCS could quickly replace the internal air in the model. On the other hand, changes in the chamber were slower, and the range of RH values was reduced to 8% for dry air and 56% for humid air. Experiments inside the chamber sometimes took more than an hour to get very high or low RH values.

After this first set of experiments, there was a base for the desired conditions; However, high humidity values still wanted to be reached. Therefore, improvements were made to get values higher than 80% RH for future testing to simulate underground coal mine conditions. For this, the best approach was to gently heat the water in the bubblers with a heating band to get higher humidity values. Testing was done in chambers A and B. As mentioned before, the heating band wrapped the bottom part of the water bubbler, as shown in Figure 33, and as a result, humidity increased to values above 70% due to increasing water temperature, as shown in Figure 5, where the test was completed in chamber B.

Finally, as seen in Figure 34, The changes in humidity over time are low. However, this stable condition may change due to external conditions like moisture in the air, ventilation, and temperature in the room. For this test, after almost 1 hour and a half of stopping supplying humid air to the chamber, the reduction in RH was just 1%, showing constant and reliable values for future testing.

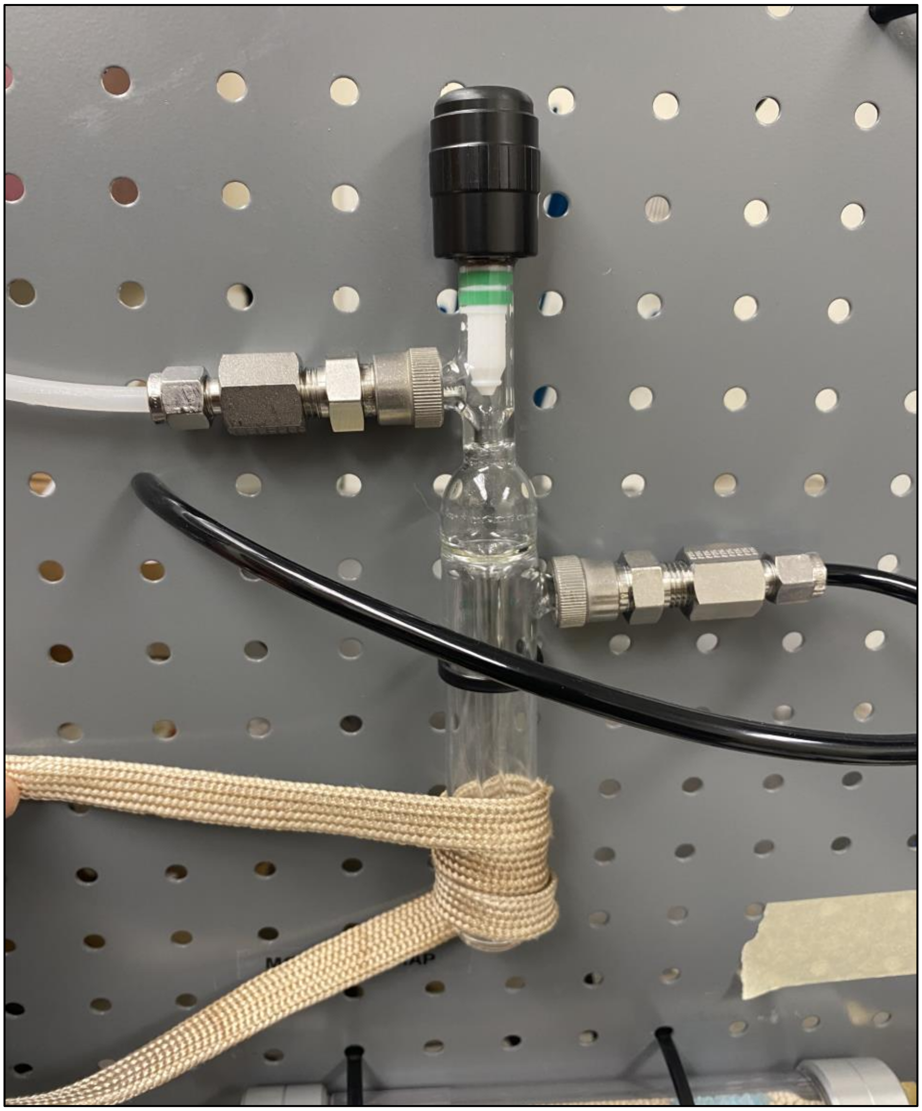

Figure 33. Heating band wrapping water bubbler

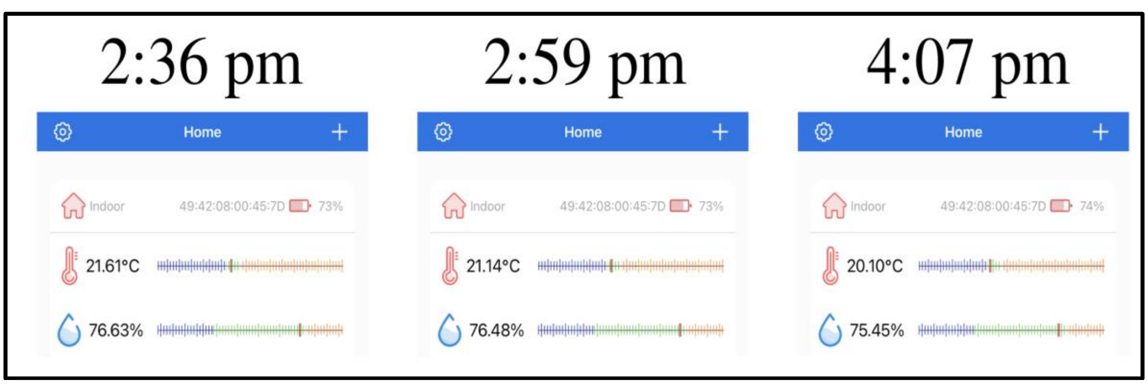

Figure 34. Changes in humidity inside chamber B.

4.4.2 Concentration Experiments

As mentioned in chapter 3, after initial testing to identify the optimum set-up for the experiments, two concentration experiments were performed to define the best possible area inside the chamber for the instruments. The goal was to find a reliable and constant area inside the chamber for concentration levels considering initial variables such as feed rate, dust-supplying tubing positions, equipment position, and test duration. Readings and data analysis for the long and short tests are shown below in the following tables and graphs. Values were obtained by supplying the air with the aerosol generator and reading particle concentration with the APS 3321 and SPS30 sensor.

Concentration experiment 1 (Long test)

The error and average values were calculated by taking the data obtained at each internal area of the chamber (BR, TR, BM, TM, BL, TL). The goal was to have 10% agreement between values. Figure 35 shows the internal areas of the chamber in red and the experiment order distribution in yellow.

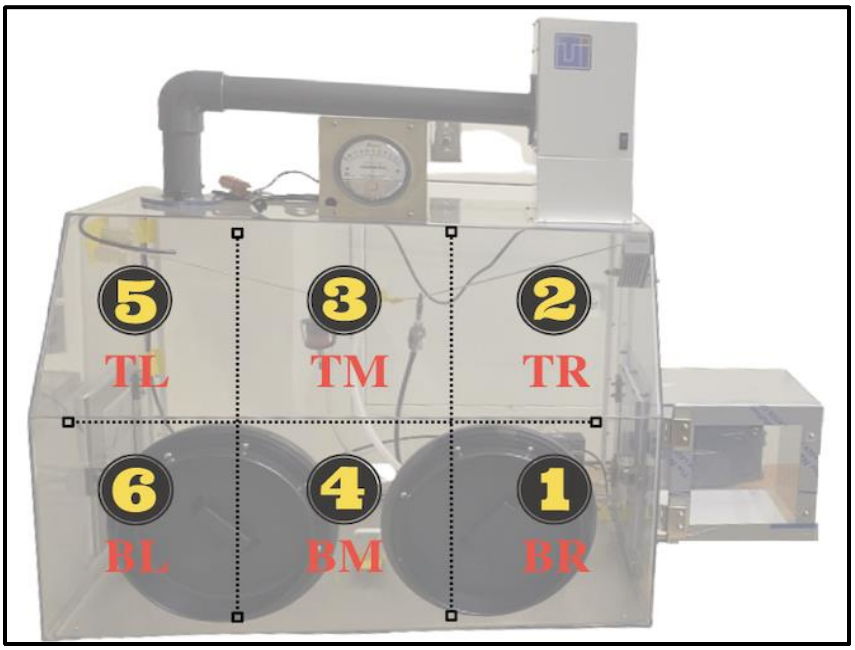

Figure 35. Internal areas of the chamber and experiment order

Figure 36, Figure 37, and Figure 38 show graphs of time vs. concentration for each internal area for 10 minutes concentration tests. Also, average (all areas) and median (all areas) curves were included in the graph and calculated by taking the average of the average values and median of the average values of each internal area between the three tests for every minute, as explained in chapter 3 and shown in Table 7.

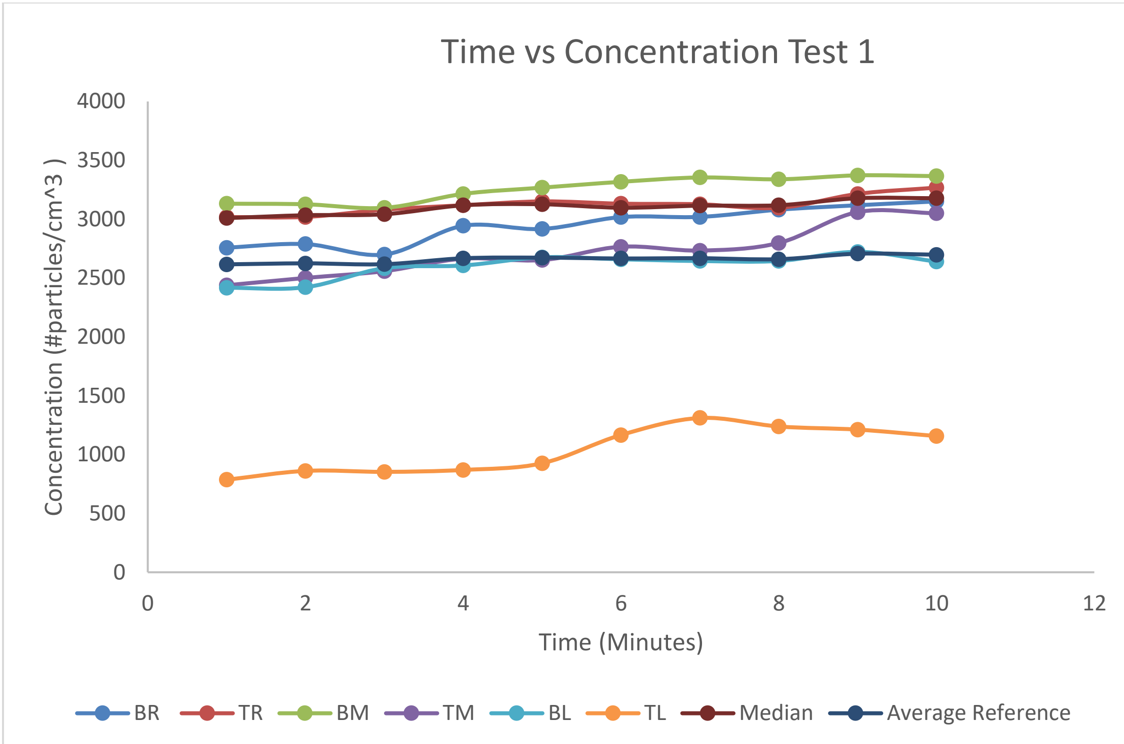

Figure 36. Test 1 (First 10 minutes)

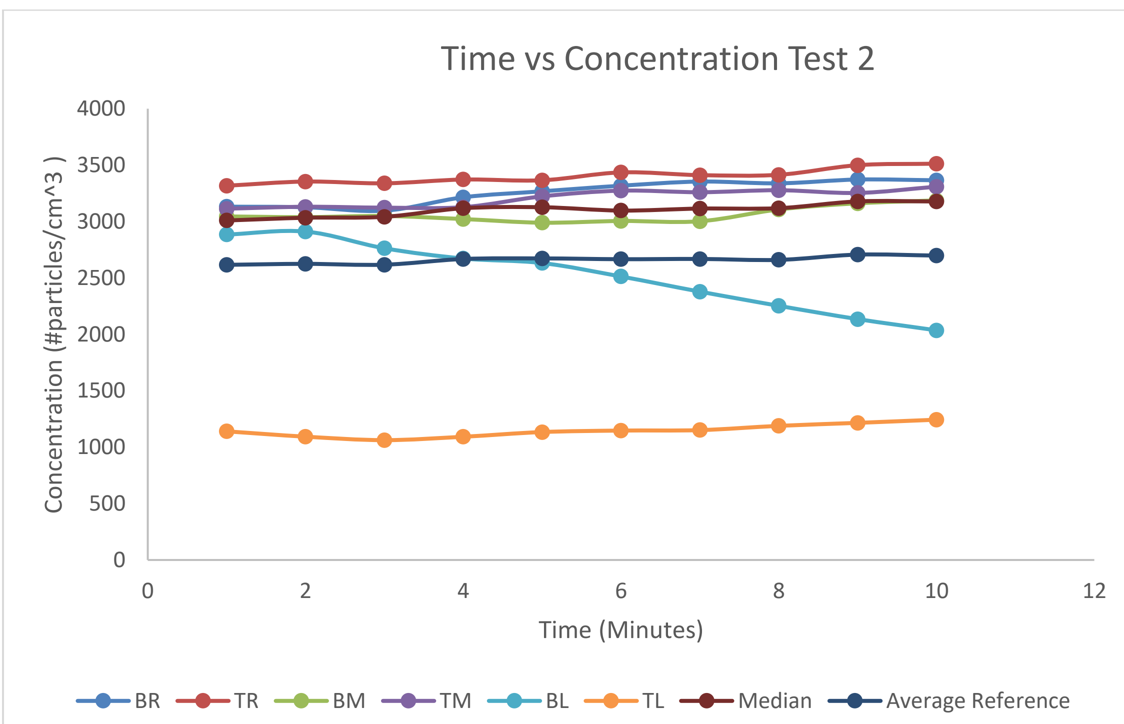

Figure 37. Test 1 (Second 10 minutes)

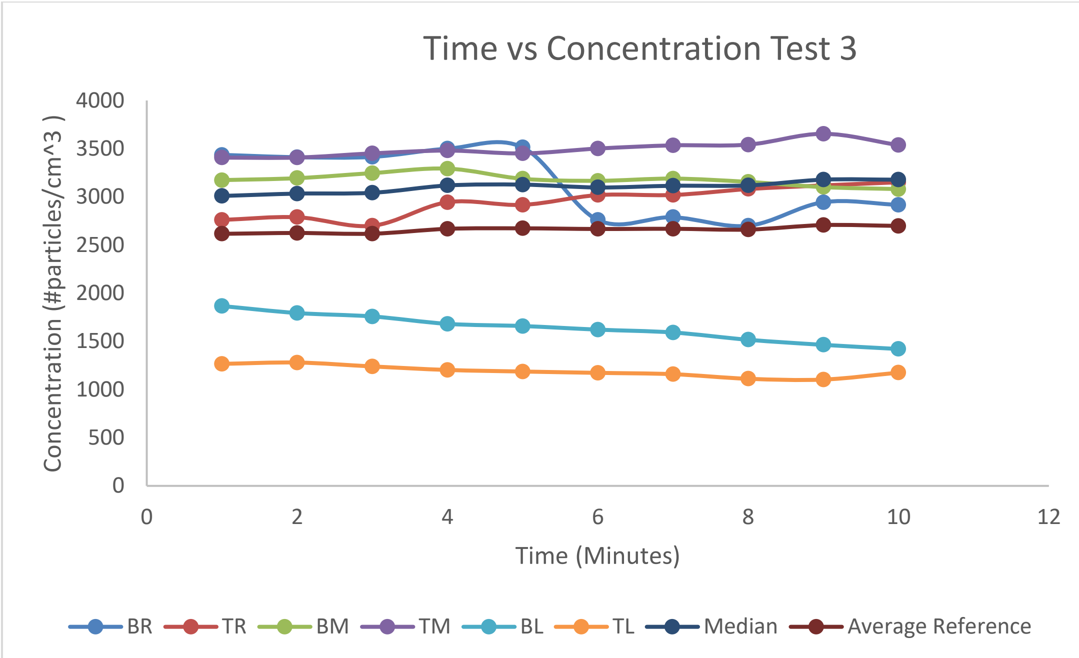

Figure 38. Test 1 (Third 10 minutes)

Table 7 shows the average total concentrations (TC) in the number of particles per cubic centimeter (#pt /cm³) in each area between all three tests at each minute (t). The last two columns are the average of all average areas and the median of the average. These two values were used as references for the variability of readings in each curve.

Table 7. Average particles concentration at each internal area – long test

Average values for the 3 tests at each internal area								
(t)	**TC BR (#pt /cm³)**	**TC TR (#pt /cm³)**	**TC BM (#pt /cm³)**	**TC TM (#pt /cm³)**	**TC BL (#pt /cm³)**	**TC TL (#pt /cm³)**	**Average (All areas) (#pt /cm³)**	**Median (All areas) (#pt /cm³)**
1	3108	3032	3117	2986	2389	1064	2616	3009
2	3109	3054	3120	3013	2376	1078	2625	3033
3	3070	3040	3131	3044	2368	1052	2617	3042
4	3219	3145	3176	3091	2320	1055	2668	3118
5	3232	3144	3148	3109	2322	1082	2673	3127
6	3031	3195	3163	3180	2265	1162	2666	3097
7	3054	3186	3182	3176	2205	1207	2668	3115
8	3040	3197	3200	3206	2138	1180	2660	3118
9	3145	3277	3211	3322	2107	1177	2707	3178
10	3144	3310	3211	3298	2032	1192	2698	3178

From values obtained in Table 7, the following table graph was created to analyze better the proximity between values and determine which internal area had more variance across the experiments.

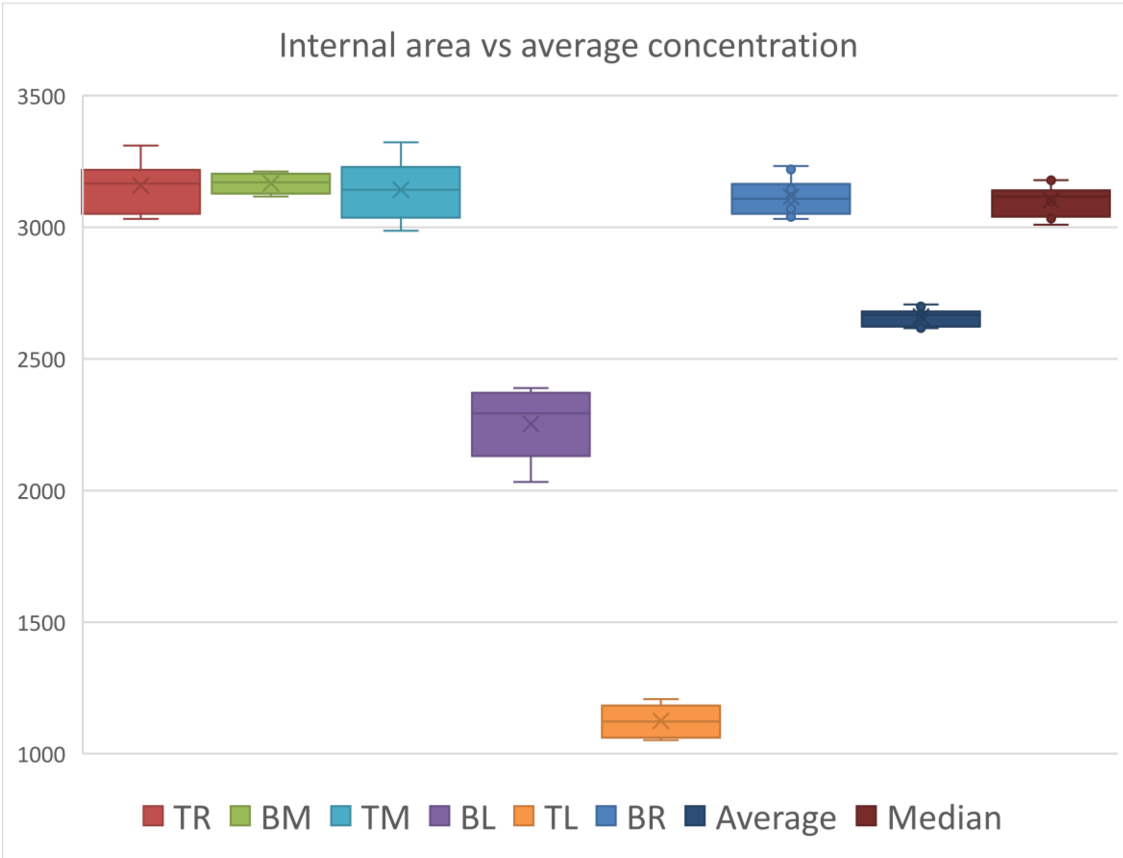

Figure 39. Box and whisker graph with the average values of the 3 tests

As seen in Figure 39 the internal areas with less variability across the 30-minute (10 minutes each test) testing were bottom middle (BM), top left (TL), and bottom right (BR). Table 8 shows the summary of the average concentration for the 10-minute test in each area.

Table 8. Summary of results - long test

Internal area_ Test	**Total average test concentration (#Pt/cm3)**	**Avg. value (#Pt/cm3)**	**% Compared to the Avg.**	**Error Absolute value %**	**% Avg. error**	**%Avg. Error of errors**
Ave. BR_T1	2949	3115	94.67	5.33	3.55	7.20
Ave. BR_T2	3258		104.60	4.60		
Ave. BR_T3	3138		100.73	0.73		
Ave. TR_T1	3122	3158	98.87	1.13	5.15	

Ave. TR_T2	3402		107.73	7.73		
Ave. TR_T3	2950		93.40	6.60		
Ave. BM_T1	3259		102.93	2.93		
Ave. BM_T2	3061	3166	96.68	3.32	2.21	
Ave. BM_T3	3178		100.40	0.40		
Ave. TM_T1	2722		86.62	13.38		
Ave. TM_T2	3209	3143	102.12	2.12	8.92	
Ave. TM_T3	3496		111.26	11.26		
Ave. BL_T1	2602		115.51	15.51		
Ave. BL_T2	2518	2252	111.79	11.79	18.20	
Ave. BL_T3	1637		72.70	27.30		
Ave. TL_T1	1038		92.28	7.72		
Ave. TL_T2	1147	1125	101.94	1.94	5.14	
Ave. TL_T3	1190		105.78	5.78		

Concentration experiment 2

As in the concentration experiment 1, the error and average values were calculated by taking the data obtained at each internal area of the chamber (BR, TR, BM, TM, BL, TL); area distribution and experiment order are shown in Figure 35. The goal was to have 10% agreement between values.

Figure 40, Figure 41, and Figure 42 show graphs of time vs. concentration for each internal area for 3 minutes concentration tests. Also, average (all areas) and median (all areas) curves were included in the graph and calculated by taking the average of the average values and median of the average values of each internal area between the three tests for every minute, as explained in chapter 3 and shown in Table 7.

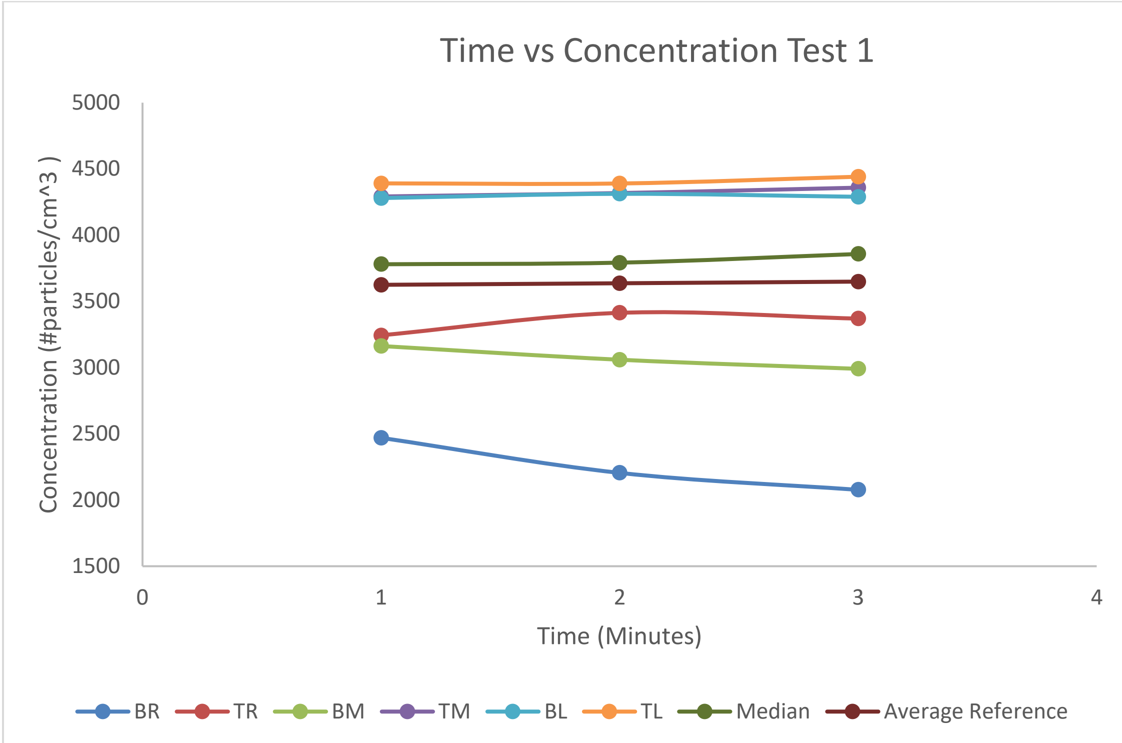

Figure 40. Test 1 (First 3 minutes)

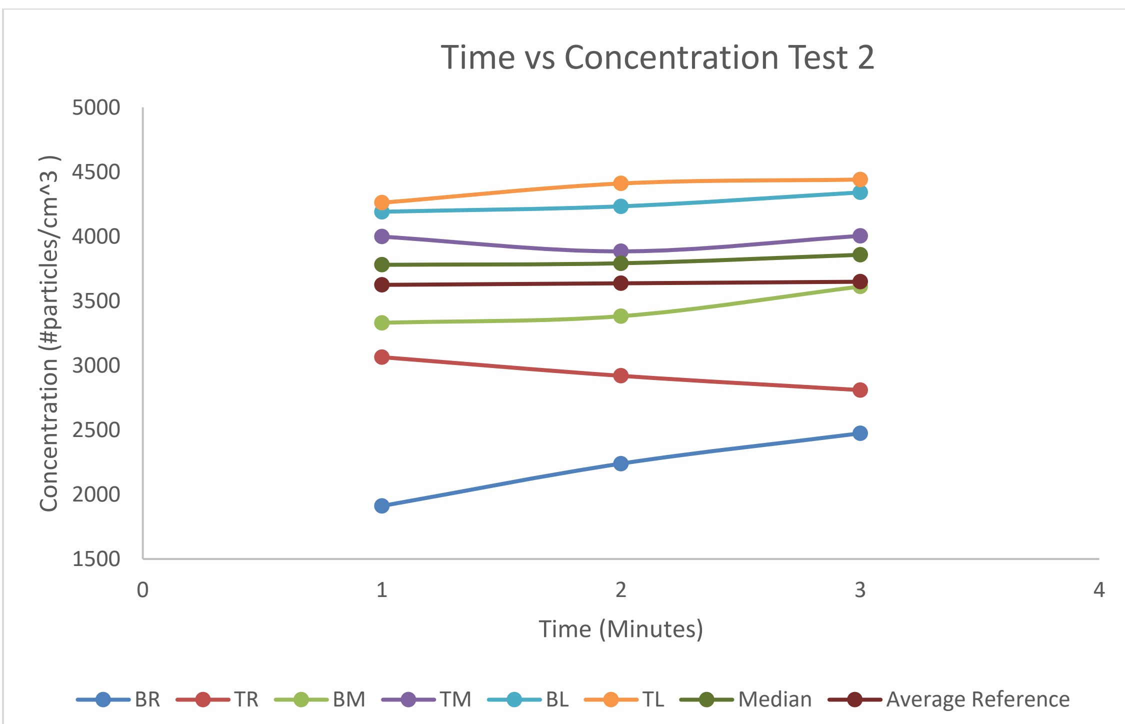

Figure 41. Test 2 (Second 3 minutes)

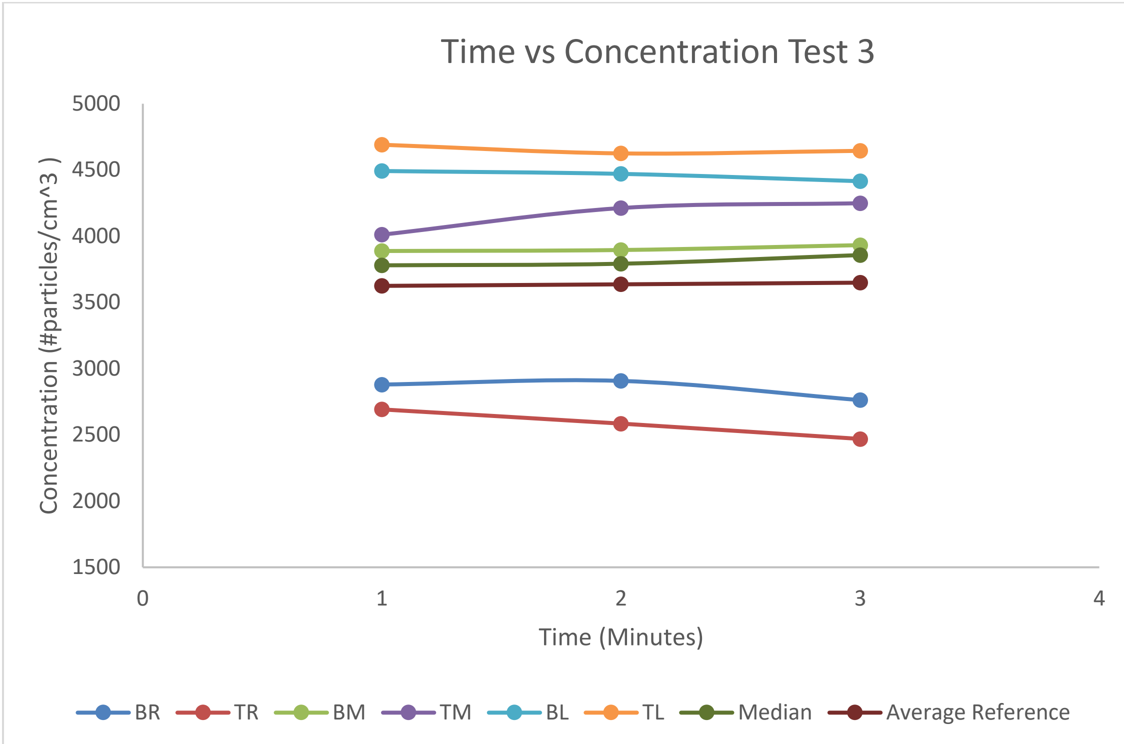

Figure 42. Test 3 (Third 3 minutes)

Table 9 shows the average total concentration (TC) in the number of particles per cubic centimeter (#pt /cm³) in each area between all three tests at each minute (t). The last two columns are the average of all average areas and the median of the averages. These two values were used as references for comparison purposes for the variability of readings in each curve.

Table 9. Average particles concentration at each internal area - short test

Average values for the 3 tests in each area								
(t)	**TC BR (#pt /cm³)**	**TC TR (#pt /cm³)**	**TC BM (#pt /cm³)**	**TC TM (#pt /cm³)**	**TC BL (#pt /cm³)**	**TC TL (#pt /cm³)**	**Average (All areas) (#pt /cm³)**	**Median (All areas) (#pt /cm³)**
1	2420	3000	3460	4100	4321	4447	3625	3780
2	2450	2972	3446	4138	4338	4475	3637	3792
3	2438	2883	3511	4204	4348	4509	3649	3857

From values obtained in Table 9, the following table graph was created to analyze better the proximity between values and determine which internal area had more variance across the experiments.

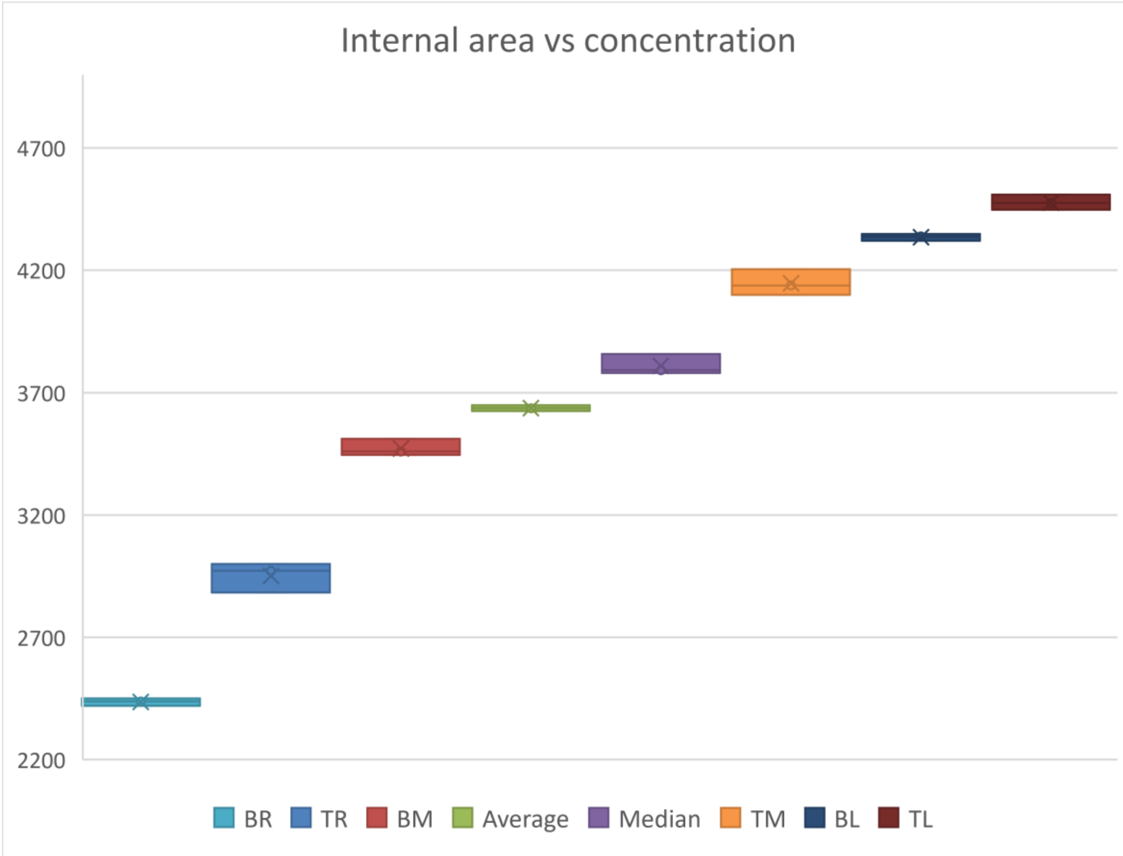

Figure 43. Box and whisker graph with average values of the 3 tests

In Figure 43, the top right (TR) and top middle (TM) were the internal areas with more variability for the total 9 minutes test duration (3 minutes for each test). In addition to the bottom left that showed good similarity, as in the long test, bottom middle (BM), top left (TL), and bottom right (BR) were the areas with more proximity between values. In this case, the internal area closer to the average and median was bottom right (BM), which shows consistency with what was observed in the 30 minutes test, even though it had more variability during readings during this test.

Table 10 summarizes the average concentration for each 3-minute test in each internal area.

Table 10. Summary of results - short test

Internal area_ Test	**Total Average test concentration (#Pt/cm3)**	**Avg. value (#Pt/cm3)**	**% Compared to the Avg.**	**Error Absolute value %**	**% Avg. error**	**%Avg. Error of errors**
BR_T1	2250	2436	92.38	7.62	11.32	5.99
BR_T2	2208		90.64	9.36		

BR_T3	2850		116.98	16.98		
TR_T1	3342	2952	113.23	13.23	8.82	
TR_T2	2931		99.30	0.70		
TR_T3	2582		87.47	12.53		
BM_T1	3071	3472	88.43	11.57	8.31	
BM_T2	3441		99.10	0.90		
BM_T3	3905		112.47	12.47		
TM_T1	4322	4147	104.22	4.22	2.98	
TM_T2	3962		95.53	4.47		
TM_T3	4157		100.24	0.24		
BL_T1	4294	4336	99.02	0.98	1.89	
BL_T2	4255		98.14	1.86		
BL_T3	4459		102.84	2.84		
TL_T1	4407	4477	98.44	1.56	2.62	
TL_T2	4371		97.63	2.37		
TL_T3	4653		103.94	3.94		

Overall, readings between areas were in 10% agreement for the summary of the results tables in concentration experiments 1 and 2 (long and short test)

Concentration was more stable for the long test, due to the longer test duration and cleaning between changes in the internal area. The bottom middle (BM) area was close to the median and average values. In addition, analyzing graphs of time vs. concentration, the bottom middle (BM) area always showed consistent values and similar ranges between tests, which makes it one of the best areas to place instruments for readings with the current experiment layout.

For the shorter test, concentration values were constantly increasing across the experiments. The first value taken was bottom right (BM), and the last one was top left (TL), which gives the impression that concentration was still regulating at the time of taking the tests. In this test, even though the bottom middle (BM) area was not the one with more proximity between readings, this internal area was closer to the average and the median, which could be beneficial for experiment consistency.

Some causes of the error could have caused decreases or increases in concentration. This could have been generated for different reasons, like not correctly controlling the air coming to the AG, the filter saturating with dust after experiments, or the equipment not working 100% right after being used for more than 8 hours. Also, moving the tubing feeding the APS could have affected values because the internal movement of the gloves may affect the dust and air distribution.

Another consideration is that the mass flow rate from the aerosol generator changed from powder to powder, most likely because of properties such as flowability, density, humidity, and mean particle size of the sample. This led to faster or slower changes in concentrations inside the chamber depending on the material. Belt speed/ring must be defined depending on each material with initial testing at the desired speed rate. For concentration experiments, a visible change was observed in the initial tests when the material was changed from Arizona dust (Sample 4) to coal mine dust (Sample 3) in the aerosol generator.

Finally, something else to consider is how humid the lab environment is because this may cause particles to agglomerate in the aerosol generator's dust tank outside the chamber and may lead to wrong readings from the APS regarding particle size and concentration. Changes may be especially seen in samples with high small particle concentrations. Therefore, a clean, dry environment should be kept while testing.

At this point, this research stopped concentration experiments; However, the same research team will conduct more future experiments on chamber B and other testing bodies to continue analyzing concentration patterns for testing.

4.4.3 Airflow Experiments

Airflow experiments were performed parallel to concentration experiments in chamber B; most of the quadrants did not have any readings because the velocity of the fan was low. When the speed was increased, some quadrants had low readings but no massive changes. This may be because of the fan size. After rotating for all quadrants, similar air velocity readings were obtained with the fan in the middle bottom areas, especially when placing the fan in the BM-3 area. Also, based on concentration results, after moving the fan in initial testing, it was notable that some regions reached high concentration when the fan was on the sides of the chamber compared with middle fan positions. Therefore, considering concentration results and after analyzing anemometer readings, the BM-3 internal area of the chamber was selected as the position to place the fan with a medium speed (7.5V) for this fan model. The fan used for the experiment was a Wathai (4.72" x 4.72" x 1") 110V with Speed Controller 3V to 12V.

4.4.4 Monitoring Systems Proposed Experiments

Preliminary results showed a good correlation between readings from the PDM 3700 and the SPS30 sensor (mainly PM4 values) for RCMD concentrations. For RCS readings, values will be compared in more experiments between the dust monitor developed by Ring-IR and a gravimetric sampler (ELF pump with cyclones) using approved NIOSH analytical methods like NIOSH 7500, NIOSH 7603, and NIOSH FAST.

Initial silica readings using NIOSH FAST methods showed insufficient silica content for the test made for 30 minutes and high concentrations inside cassette filters read by a portable FTIR for the test for more than 2 hours with the current experiment layout.

Initial experiments were completed with a particle concentration ranging from 2 mg/m^3 to 4 mg/m^3. The APS 3321 showed a mean particle diameter of 0.82 for coal samples from these readings. However, a significant fraction of the readings were particles less than 0.5 µm, indicating that the mean particle size could be slightly different since the equipment detection range is from 0.5 to 20 µm. In addition, it was noticeable that most particles were in the range of particles less than 10 µm, which led to higher concentration readings inside the chamber than in the mine since the airborne particles are mainly the respirable fraction for the test. Therefore, a high fraction of the sample was taken by the cyclones.

The competition of experiments to compare monitoring systems will be additional research conducted by the same NMT research team and will focus on the accuracy and functionality of the Ring-IR dust monitor to measure RCMD and RCS concentrations.

4.4.5 Recommendations for Future Experiments in the Platform

It is always recommended to keep easy access to the chamber during testing. Therefore, for chamber constructions is always good to spend more time adding an easy-to-open side door and an easy way to remove one sheet to access the instrument.

If more airflow and pressure are needed for the chamber, just one water bubbler can be used with an inch of DI internal water level and wrapped by the heating band to produce high humidity values. Precautions must be taken to not over-pressurize the water bubbler since it could break the instrument or disconnect the fitting.

Smaller compressors could make the work slower and require more attention to supply the system constantly.

It is necessary always to find the best setup for the aerosol generator in terms of dust concentration in the testing body when using a new material; this may highly change depending on the internal properties of the material. Also, for the Topas solid aerosol generator unit, the manual instrument comments that it could be more variability and irregular dust production when not using a small dosing ring for low feed rates. Therefore, it is recommended to have an instrument and accessories that could produce dust flow rates in conformity to the size of the testing body and the testing time.

Regarding effects in testing measurements, because of the chamber shape and size, the main impact, in this case, was an accelerated dust intake in testing instruments. Concentration conditions above PEL were achieved way faster in a smaller simulated mine environment inside the chamber because the number of respirable particles was way higher in the presented experiments in this research. This may change and improved for future experiments with some correction actions:

- The experiment could have better and more distributed particle size samples; in this experiment, even though the particles were reduced to less than 63 µm, a considerable number of particles were less than 10 µm, which led to higher intakes in cyclones.
- The dust concentration for future experiments could be divided into times of high concentration and times of low concentration. Having different concentration

intervals not exceeding by much the PEL, the experiments will have a closer approximation to mine conditions, and the dust intake may be lower.

- Dust distribution patterns can be improved to have more homogenized internal conditions and better particle size distribution; this can be achieved with more accessories in the chamber to distribute the dust, as it was mentioned by Marple et al. 1983 [105], where a honeycomb structure and a tunable drive motor were added to obtain more controlled dust patterns inside a chamber.

Even though there is no specific time for changing the filters in the platform since changing depends on usage, the correct maintenance guarantees the platform's best performance. Hence the need to keep the system clean and filters not saturated.

- In the HCS, regarding oil and water filters, these are filters that can drain liquids, so the longevity of the instruments may be more extended than other accessories.
- In the HCS, the used moisture trap was depleting very fast, so a moisture trap that can manage the experiment flow rates and pressure is recommended. Also, in case the moisture trap needs to be fixed or is not the best one, it is recommended to do a modification in the system, keeping the place oil and water filters in place but then adding two moisture traps instead of one, one after the other.
- In the chamber, the filter in the recirculating system in the chamber was full after some time, so it needed to be replaced. This last one mainly depends on dust concentrations inside the dust chambers and the number of cleanings with the recirculating system per day.

Vortex is expected to happen in sharp turns like corners; improvement actions like curving these angles may be taken in future research. Vortex may lead to irregular dust concentration in internal areas, which is not desired in a small testing body like a chamber.

Finally, it is always essential to consider using a calibrated fume hood for these experiments and the correct use of PPEs because some aerosol generators could generate very high humidity concentrations in short periods. Always check for leaks and conduct the dust to a fume hood if RV valves expel air to the room or if something is open and is expelling dust next to the testing area.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The potential health risks of exposure to RCMD and RCS have led to constant and abundant investigations of the causes of pulmonary diseases among coal miners. Many critical controls have been implemented in underground coal mines to reduce dust concentrations in working areas. Furthermore, there have been tremendous efforts in developing technology to alert miners about high-concentration areas in real-time. This thesis investigated what is used and has been developed to control these toxic materials in the field and what common conditions miners can be exposed to in underground coal mines to later recreate in lab-controlled environments. Also, this project researched RCMD and RCS sampling, dust control techniques, measurement and methods techniques, mine conditions, and lab testing structure for dust studies. Simulated underground coal mine conditions inside a dust chamber were designed to test a series of dust monitoring systems. For future testing, this research created a design of experiments with monitoring devices with the created conditions and gave recommendations after preliminary testing.

The followings are the completed sections in this study.

- The design and fabrication of two dust chambers with different sizes were discussed in this document. Also, experiments were performed in these chambers to test humidity and dust concentration distributions in the recreation of underground coal mine conditions. Limitations and benefits of each chamber were stated in the document for improvements in future research. The dust chamber results can be compared to a mine environment for initial approximations when new monitoring instruments are not allowed to take to the mine because of permissibility requirements. However, some variability may be seen because of scale. Therefore, testing times should be adapted to understand this impact in real conditions. Also, parameters like obstacles in the way, different shapes in different areas, ventilation, equipment, and people are missing factors that may affect results. All these additional parameters add size to the testing body since adaptations might take more space or increase construction complexity. It is more challenging to do this with all the considerations in a small dust chamber. Hence, a recommendation for more realistic scenarios is a bigger and more complex testing body, like a dust tunnel, which may be more appropriate to replicate mine conditions. However, this may lead to considerably more expensive research. With the presented platform, conditions and equipment were adapted to specific scenarios to have more accuracy in results, but it is critical to keep in mind that patterns and readings may change in actual mine sites since more variables are involved during sampling.

- A humidity control station was built to supply relative humidity from 8% to 80% inside chambers A and B for testing. The design was a portable product, air supplied by an air compressor, with easy-to-find instruments capable of producing humidity in different testing bodies. For testing, experiments successfully compared readings between a model and the chambers. The results showed higher and smaller RH values in less time in the model compared to the chambers, which indicates the correlation with the size factor. High humidity values were maintained in the chambers for more than an hour without adding more air. The HCS was proven to be a reliable device capable of producing clean, dry, and humid air to recreate mine conditions.

- Regarding air velocity patterns and concentrations, given the shape and ventilation of the mines, there are chances that the mines may have some parts where the dust and air are blowing directly to the intake of the cyclone. This may cause increased concentration if respirable particles are abundant in the area. On the other hand, when the operator is in a low-concentration spot with poor ventilation, the concentrations may decrease at the end of the day. Hence, the recommendation of testing during high and low concentration times inside the chamber. In the experiments of this research, concentration was kept mainly constant between the defined ranges and with constant ventilation patterns from the fan, leading to higher values in readings compared to the mine sites where the operator is not always in concentration areas more elevated than the PEL. The benefit of testing in lab-controlled environments is that conditions can be easily changed to test each aspect of the monitoring instruments in the desired condition.

- The concentration experiment provided chamber B's best possible internal area for future dust testing under the created conditions. A TSI APS 3321 and an SPS30 sensor were used to measure particle concentration inside the chamber, while a Topas solid aerosol generator SAG 410 U aerosol generator supplied dust for the test. Results were complemented after analyzing internal air distribution with anemometers inside different quadrants of the chamber. After several tests, the results helped better to understand the dust distribution scenarios inside the dust chamber and define the best internal area to place sensors, tubing for dust, and intakes for equipment. The size of the area was determined by a small steel structure holding all intakes for equipment. Also, it was noted that the specified conditions might change depending on the material's properties and equipment used during testing.

In conclusion, the platform was successfully built and tested for future experimentation with monitoring systems inside the dust chamber.

Recommendations for future research in this area.

- Dust testing can be completed using this or a similar platform to test new monitoring systems and compare results with approved NIOSH analytical methods to ensure accuracy in silica concentrations.

- Additional experiments can be performed by measuring simultaneously, in a single position, with multiple approved sampler instruments taking the dust in the mine air or simulated conditions. For this, various cyclones at different flow rates can be used to verify if there is any reduction in the total particle concentration of RCMD and how this affects accurate RCS readings compared to when they take the samples individually.

- Experiments can be performed with NIOSH-approved masks and respirators inside this or a similar platform to measure dust intake reduction. Equipment can be placed inside and outside a mannequin head with nose holes and wearing masks/respirators. Artificial nose hair and mucus fluid can be added to simulate more realistic conditions. In addition, testing could be conducted when having a beard in a mannequin and without it to analyze how this may affect the inhalation of respirable particles in simulated human breathing patterns.

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PLATFORM DEVELOPMENT AND OPTIMIZATION FOR TESTING RESPIRABLE COAL AND SILICA DUST IN SIMULATED UNDERGROUND COAL MINE CONDITIONS

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