DATA SIGNATURE OF SURFACE AND UNDERGROUND EVENTS—CONTINUOUS ENVIRONMENTAL MONITORING IN A FORMER UNDERGROUND GOLD MINE

Stephen Gabriel[1*], Purushotham Tukkaraja[2], Srivatsan Jayaraman Sridharan[2], and Akash Adhikari[2]
[1]Spearfish School District 40-2
525 East Illinois, Spearfish, SD 57783
[2]Department of Mining Engineering and Management
South Dakota School of Mines and Technology
Rapid City, SD 57701
[*]Corresponding author e-mail* sgabriel@spearfish.k12.sd.us

ABSTRACT

A network of real-time environmental monitoring stations plays an important role in identifying events in an underground environment that could pose hazards to that facility personnel and equipment. The purpose of this study is to identify surface and underground events with a dedicated network of monitoring stations. The data signature of an identified event, events in other parts of the facility can be identified or predicted. For this study, two surface and two subsurface events were identified and analyzed. The surface events include power outages and surface weather conditions. The subsurface events are related to blasting and water inflow. Surface and underground events do create data signatures that are unique. With limited monitoring stations in a mine environment, comparable data signatures could be used to predict similar occurrences in different locations in the facility.

Keywords

Environmental Monitoring, Mine Ventilation Network, Underground Climate, Data Signature

INTRODUCTION

The Sanford Underground Research Facility (SURF) is housed in the former Homestake Gold Mine, Lead, South Dakota. The mine was closed in 2002, ending its 126-year history. The mine was converted to an underground research facility managed by the South Dakota Science and Technology Authority (SDSTA). The Yates Shaft, is one of two ventilation intakes to the mine. The other intake, the Ross Shaft, is located approximately one km from the Yates Shaft. There are two exhaust shafts, the Oro Hondo and the #5 Shaft. During the period of study, the Oro Hondo fan typically exhausts approximately 220,000 cfm (104 m^3/s) and the #5 Shaft fan is responsible for ~70,000 cfm (30 m^3/s) for a total underground ventilation rate of 290,000 cfm (137 m^3/s). Two (350 HP & 150 HP) vane-axial fans are installed at the #5 Shaft. The 150 HP fan is running with the 350 HP as backup. The Oro Hondo uses a centrifugal (3000 HP) fan and a vane-axial (350 HP) fan for backup. The flow rate of the Oro Hondo was increased to around 418,000 cfm and the 150 HP fan at the #5 shaft was adjusted 45,000 cfm on August 16th 2022. Fan locations in the ventilation network are shown in (Figure 1).

When Barrick Gold Company decided to close Homestake Gold Mine, the scientific community pursued the site for the Deep Underground Science and Engineering Laboratory (DUSEL). In 2007, the Homestake Gold Mine was chosen for a national deep underground laboratory. There are several on-going experiments situated in the facility.

A network of real-time environmental monitoring stations is crucial in maintaining a safe working environment. Building a well-calibrated mine ventilation network is very time-consuming and requires great effort in airflow and pressure surveys, fan performance measurement, and comprehensive data analysis. Frequent network recalibration is also necessary since changes can always occur during the lifetime of a mine. The fluctuation in the readings frequently impacts the interpretation of the survey results. Many factors can contribute to the fluctuation of the airflow within a mine, such as mining activities, mine fan operation, atmospheric conditions (barometric pressure, temperature, and humidity), sensor performance, etc. (Zhou et al. 2022). Recent developments in the Internet of Things (IoT) have made real-time atmospheric monitoring more accessible, and studies have shown that the data can help improve miners' safety (Choiri et

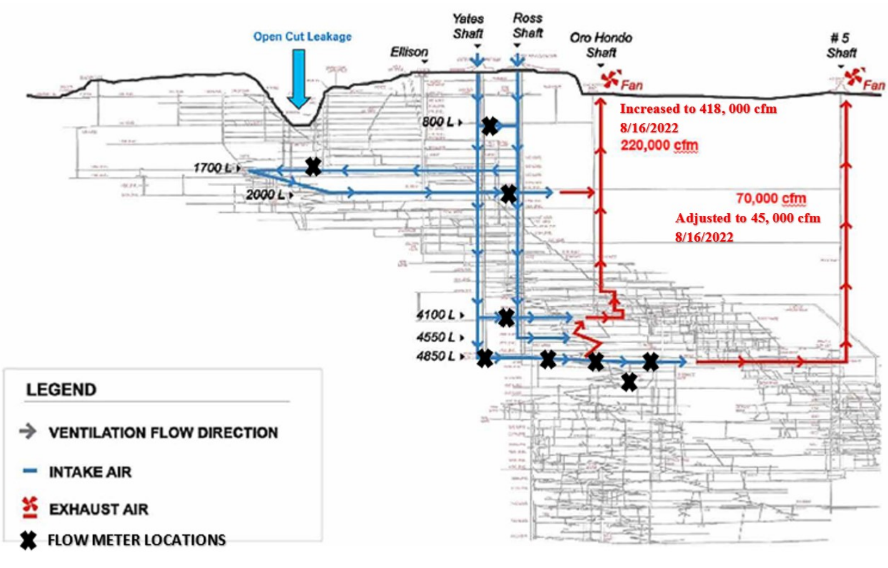

Figure 1. SURF ventilation model with flow meter locations (Artz et al. 2015).

al. 2021; Jha and Tukkaraja 2020; Jha et al. 2022; Khan, et al. 2021; Li, et al. 2020; Moridi et al. 2015).

In 2012, two flow meters were installed at the 4850L (1478-m) at SURF. These flow meters gather data including enclosure temperature, drift temperature, relative humidity, pressure, airflow direction, air velocity, and airflow rate. The airflow rate is calculated by using air velocities and cross-sectional areas from 3D LiDAR scans that are accurate up to 3 millimeters. During the last ten years, the flow meter network has grown to nine units throughout the underground. These flow meters are used to monitor intake and exhaust flow from the 4850L and key locations underground where power and internet are available. Flow meters are located on the following levels at SURF: 800L (244-m), 1700L (518-m), 2000L (610-m), 4100L (1250-m), four at 4850L (1478-m), and 5000L (1524-m) (Figure 1). During the summer of 2020, much of the network was overhauled, renamed, reconfigured, and reinstalled in critical underground areas. Many improvements have been implemented over the years, making the data more reliable and useful. Data from each of the nine flow meters are recorded every five seconds, averaged over a five-minute period and sent to the surface, where plots are displayed on an internal website at SURF. The underground flow meter network is controlled through a remote desktop interface using a secure socket layer connection.

A previous study (Li et al. 2008) has shown that events such as gas leakage, oxygen-enriched spots, and water seepage can be detected using monitoring data. A similar study was conducted at the Safety Research Coal Mine (SRCM). Their goal was to use continuously monitored airflow to improve a mine ventilation network model and mine fire simulation models.

This paper aims to identify the causal effect of different surface and sub-surface events on the continuous air monitoring data (data signature). This knowledge will ultimately help in developing a detection/prediction model for surface/sub-surface events based on underground air monitoring data.

METHODS

Major Surface Events: Power Outages: Fan Shutdown (August 5, 2013)—In 2013, there were two flow meters located at the 4850L, the Seventeen ledge, and the Four-Winze Wye (Figure 2). Data from both instruments on August 5, 2013, are shown in (Figure 3). The airflow data confirm the Oro Hondo fan was shut down from 7:05 to 14:07 (separate monitoring of 4850L radon concentrations showed a coincident increase in the same time period) (C. Lichenwalner, personal communication, August 6th, 2013).

Major Surface Events: Power Outages*:*Ventilation Survey (October 11, 2018)—On October 11, 2018, a ventilation survey took place at SURF. During this survey, three surface fans were turned off and on in different stages, as shown in (Table 1). These fan stages cause different flow rates at different levels in the mine as seen in (Figure 4).

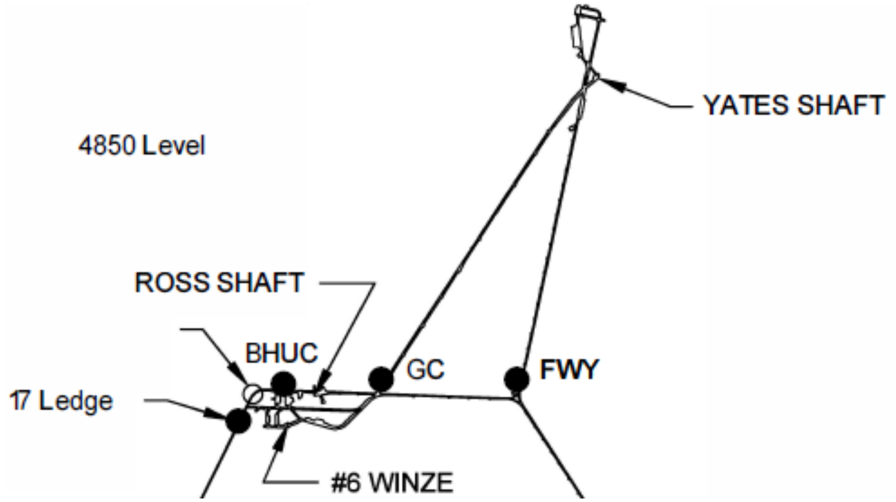

Figure 2. Location of flow meters in the 4850L.

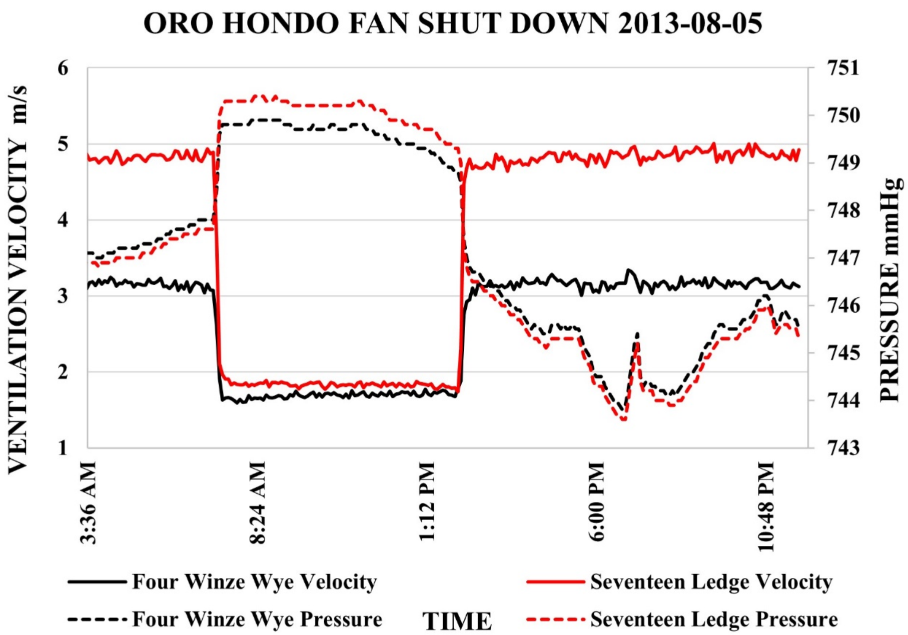

Figure 3. During a ventilation fan outage event, air velocity decreases and air pressure increases at two locations on the 4850L. Air velocities are plotted on the left axis with solid lines and the air pressure is plotted on the right axis with dotted lines.

Table 1. Fan configuration during the ventilation survey on October 11, 2018.

Stage	#5 Shaft Fan	Oro Hondo American-Davidson	Oro Hondo Spendrup
1. 7:35-8:00	off	off	off
2. 8:00-8:40	on	off	off
3. 8:40-9:40	on	off	on
4. 9:40-10:15	off	off	on
5. 10:15-11:00	off	on	off
6. After 11:00	on	on	off

Different fan configurations need to be understood because scientists at SURF need to understand the environmental impacts. Both the power outage and the fan shutdowns cause a pressure increase and a decrease in airflow. These differences influence radon and other gases that need to be mitigated for the safety of personnel and to minimize the background noise that would interfere with sensitive experiments.

Major Surface Events: Power Outages: Weather caused power outage—On March 29, 2021, a wind storm caused a power outage at SURF that affected facility ventilation. The result of this power outage was captured by the networked flow meters at multiple SURF levels. The pressure increased at each level as shown in (Figure 5), and a decreased airflow is seen in (Figure 6). Twenty-six raise flow

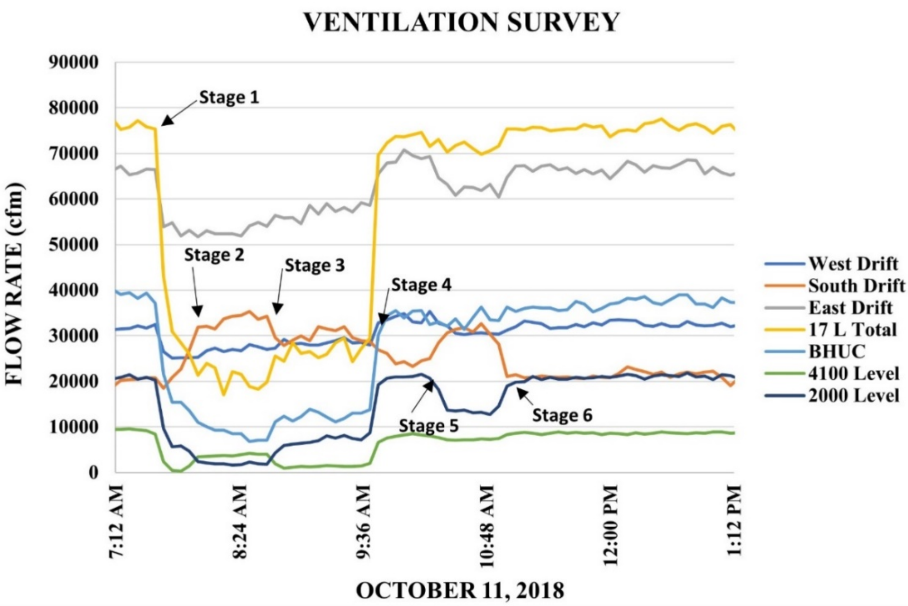

Figure 4. Ventilation survey showing the response of the flow meter network during the six stages of fan configuration testing.

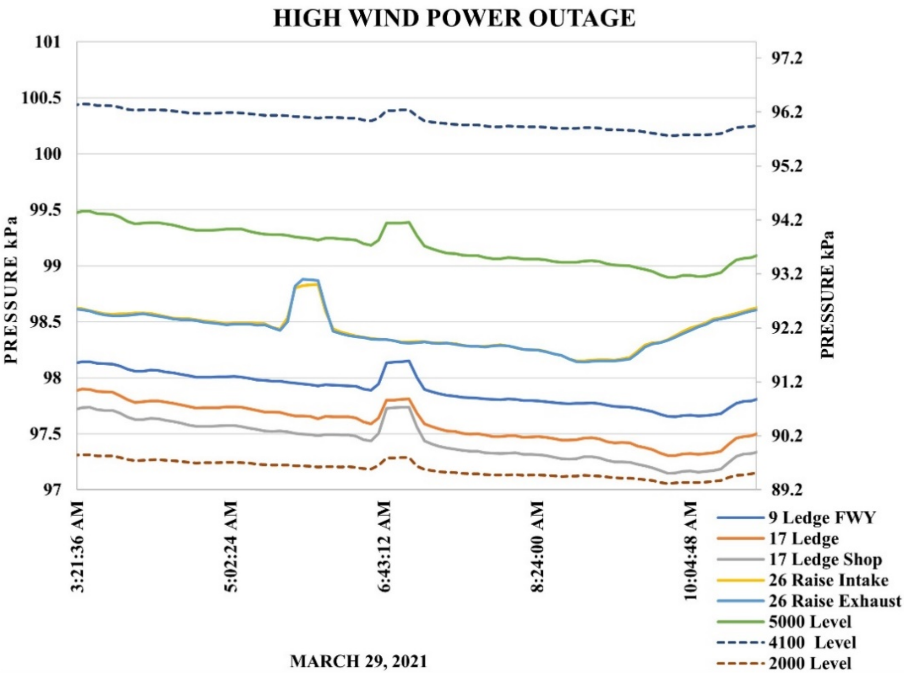

Figure 5. Underground air pressure changes measured during a power outage at SURF. The 2000L and 4100L flow meters with the dotted lines are plotted to the right axis. The nine ledge, 17 ledge, 26 Raise and the 5000L flow meters have solid lines and are plotted on the left axis.

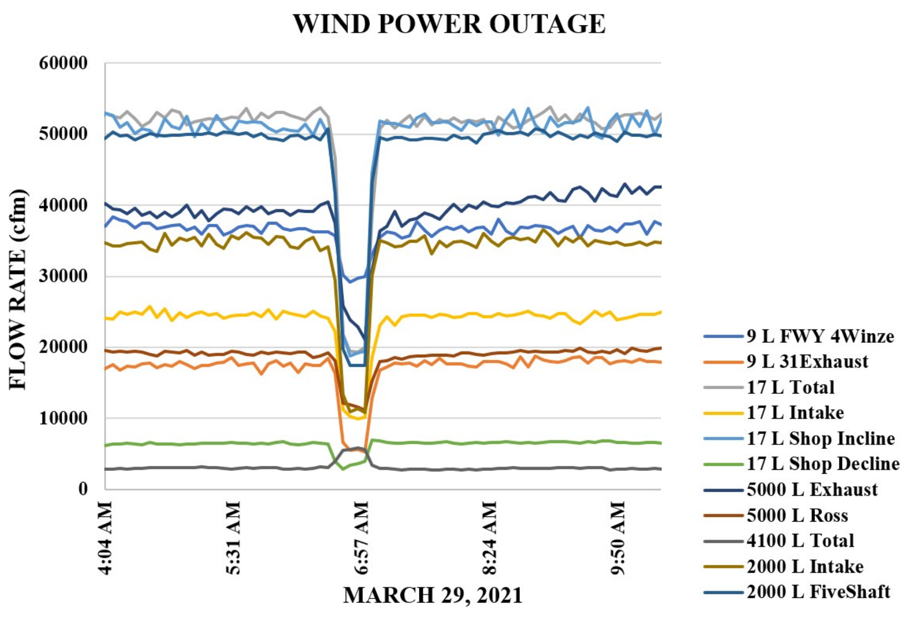

Figure 6. A power outage on March 29, 2021, affected every level with a flow meter station.

meter data are offset by an hour because the station was in a remote location and daylight savings could not be implemented. The flow at the 4100L was the only level that increased.

Major Surface Events: Surface Weather Conditions: Clyde Ice Field Weather Station Spearfish—Seven days of surface weather data from Clyde Ice Field Airport in Spearfish (WeatherForYou.com 2014-2015) were compared on a seasonal basis to one underground SURF flow meter during dates in 2014 and 2015. Spearfish is located about 10 miles (16 km) north of Lead, SD at an elevation of 1,111-m (3,645 ft). It is clear that the barometric pressure is directly correlated between the surface and the underground. Weather-caused power outages in the Lead area and underground can be seen with a network of environmental sensors. The week of seasonal data was combined to see if there was a yearly pattern. A seasonal pattern could not be established, and additional data need to be compared to see if an annual pattern exists (Figure 7).

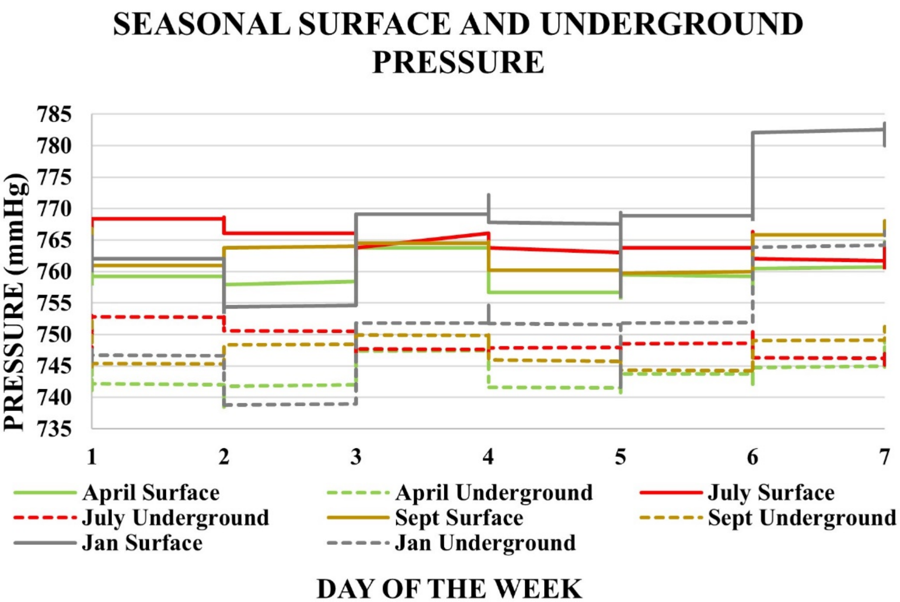

Figure 7. Seasonal plot for a week of surface and underground pressure during the same period.

Major Subsurface Events: Blasting: Prior to LBNF construction—Test blasting in the south drift on the 4850L took place on December 9 and 10, 2015, and then again on March 8, 2016. The airflow distribution during the test blasts and the location of the flow meters are shown in (Figure 8). These tests were conducted because SURF is home to very sensitive scientific experiments and will be housing the large neutrino detectors of the Deep Underground Neutrino Experiment (DUNE). Pressure and flow rates for the trim and test blast conducted

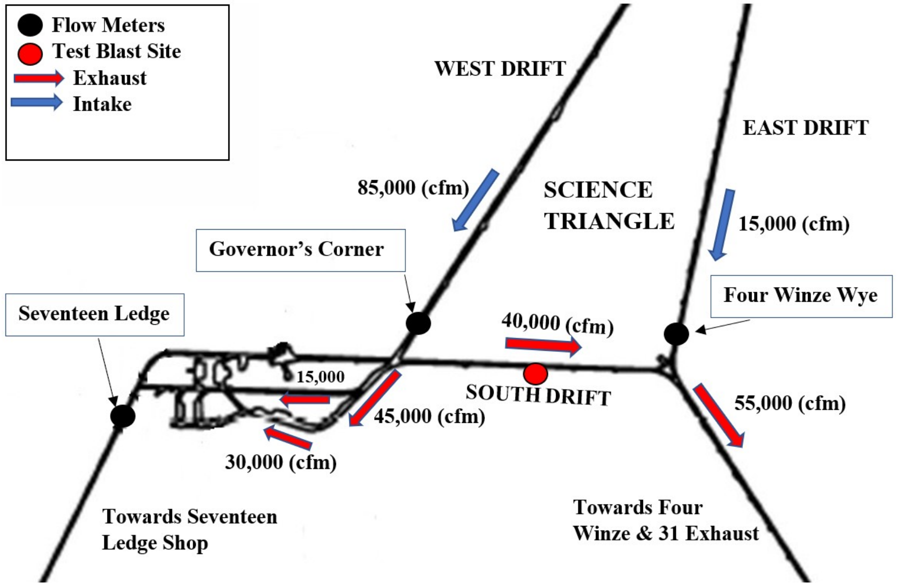

Figure 8. LBNF Blast Vibration Study-SDSTA Blast Plan, December 4, 2015 (Vardiman 2015). This design is to exhaust blast gasses out towards Four Winze and 31 Exhaust. The black dots show the flow meter locations, and the red dot shows the test blast location.

in December 2016 can be seen in Figures 9 and 10. Pressures and flow rates for the test blast of March 8, 2016, can be seen in Figures 11 and 12. Following these tests, six blast doors were installed to control the blast-induced gases in the underground environment, especially near

the construction site, and to protect the experiments underground during the blast.

Major Subsurface Events: Blasting: Blast Door Closure Study in preparation for LBNF Construction (5/21/2021)—Thyssen Mining conducted a ventilation blast door test on May 21, 2021. Ventilation surveys were taken in locations labeled 1-10 on the 4850L map (Figure 13). This map also shows locations for four flow meters, the six blast doors and the times that the doors were closed. There were minor changes in pressures and flow rates during the first three stages of the test. When doors at stage four (blast doors five and six) were closed there were large scale changes in pressures and flow rates throughout the lower levels of the mine. The pressures decreased and flow rates dropped. Pressures and flow rates recovered during stages five and six. The 5000L flow meter capture the most interesting data (Figure 14). The flow rates at the 5000L captured all six stages of the door closures.

This test suggests a vacuum is created in the lower levels of the mine and the upper levels compensate for the ventilation changes at the 4850L. Even though stage four is relatively short it strains the ventilation system. The effects of closing

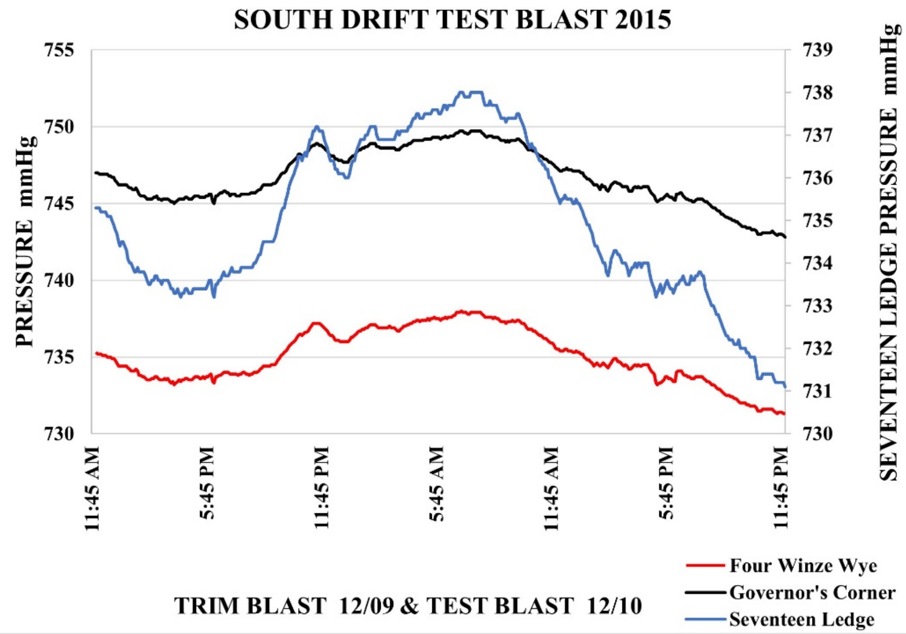

Figure 9. Pressure wave of trim blast detected by the three flow meters on the 4850L Seventeen Ledge flow meter is plotted to the right because it was not calibrated with the other two flow meters.

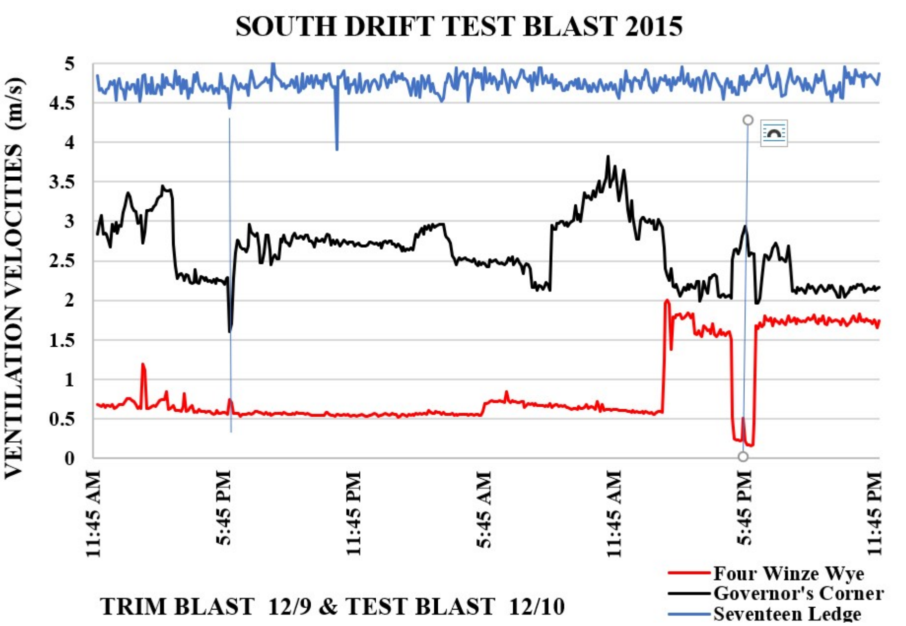

Figure 10. The ventilation changes for the trim and test blasts. The trim blast occurred at 6:00 p.m. on the 9th and the test blast occurred at 6:00 p.m. on the 10th.

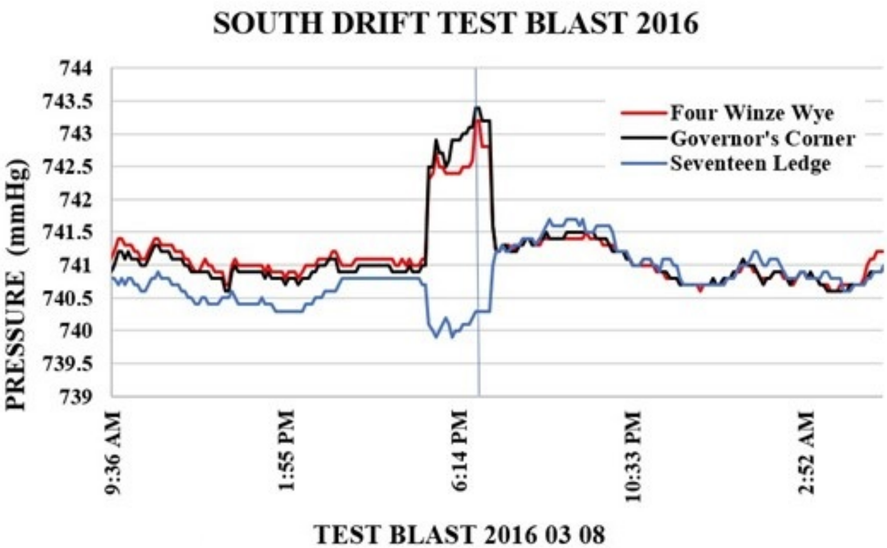

Figure 11. The pressures increased at the Four Winze Wye and Governor's Corner and decreased at Seventeen Ledge because the ventilation changes were made to exhaust the gases out of Four Winze Wye.

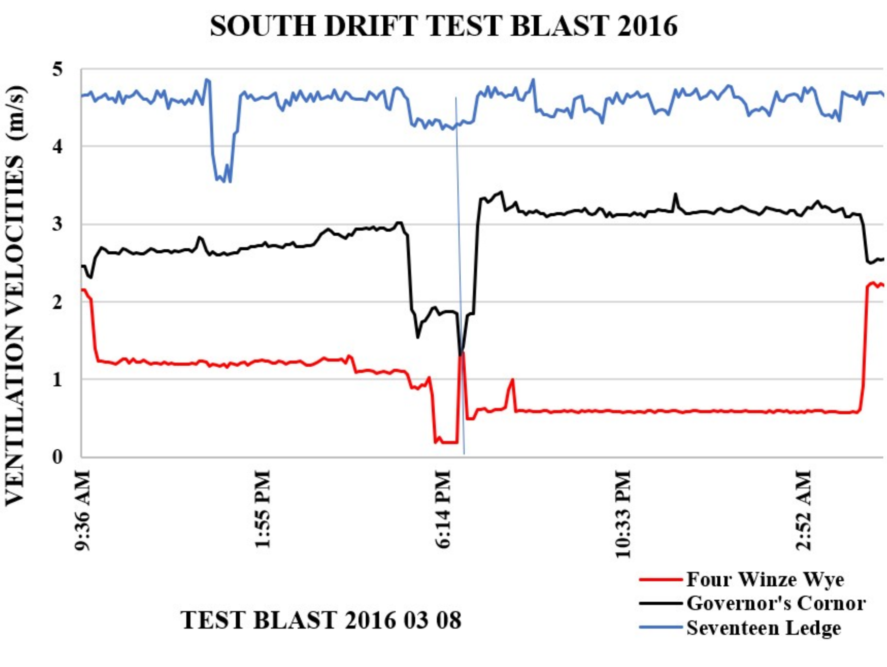

Figure 12. Air velocity recorded at Governor's Corner (West Drift) and Four Winze Wye (East Drift) decreased prior to blast. After the blast Governor's Corner (West Drift) increased to expel exhaust gases down Four Winze Wye drift.

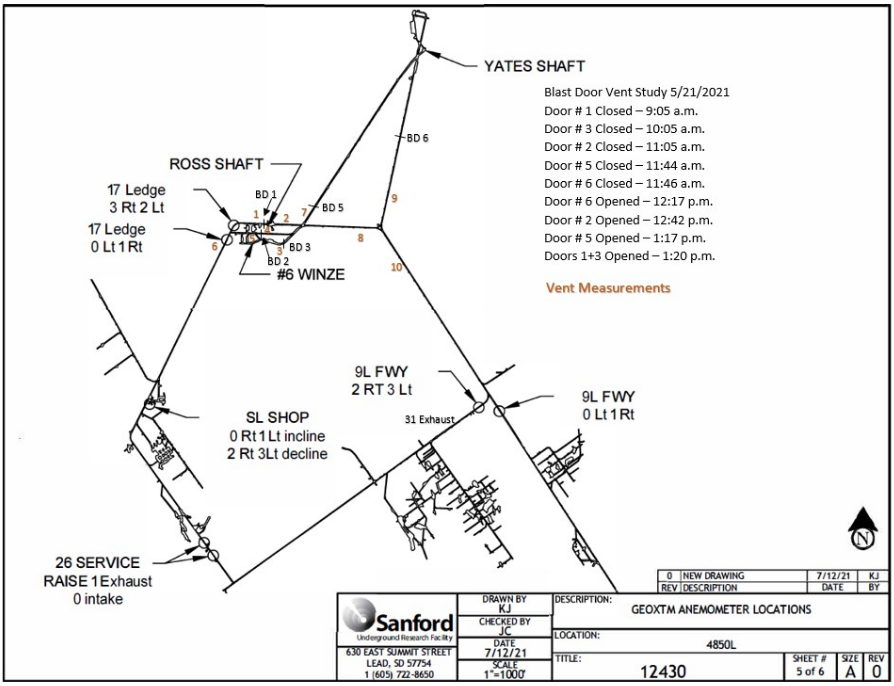

Figure 13. The full 4850L SURF showing locations of the flow meters on that level.

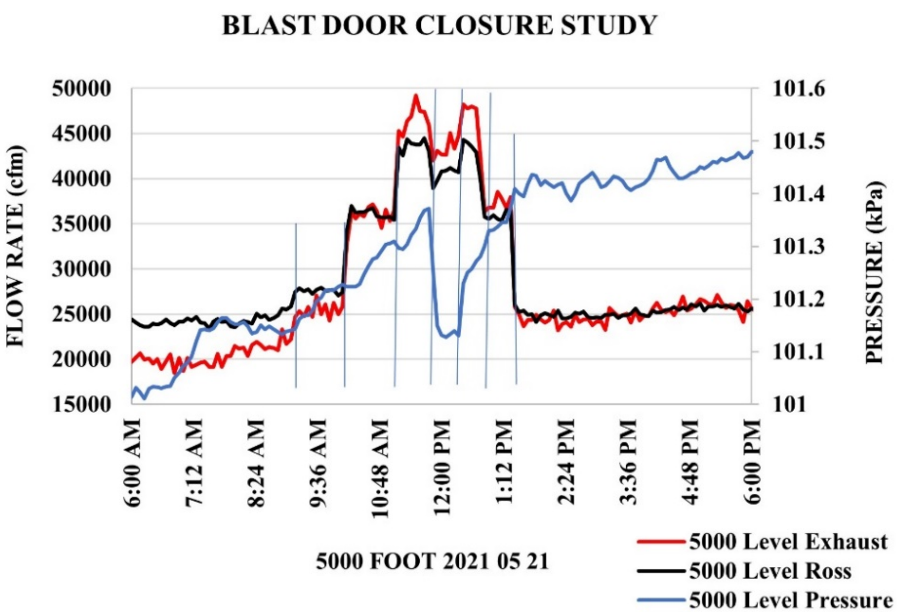

Figure 14. All phases of the blast door closure shown at the 5000L. Air flow with the red and black lines are plotted to the left axis and pressure in blue is plotted to the right axis.

these doors need to be understood because the effects are felt at multiple levels at SURF, especially the 5000L.

Major Subsurface Events: Blasting: Blasting for LBNF Construction—Data were collected from the Nine Ledge Four Winze Wye Flow Meter (9L/FWY) in October and in June 2021 to show how construction changes underground environmental conditions. These data were selected because they were taken by the only flow meter that is located on the same level and downstream of the LBNF/DUNE project and that is not behind a blast door. Similar data can be seen by the other flow meters on that and other levels. Flow meter data from 9L/FWY show direct detection of the blast door closure on a regular interval with a decrease in pressure during October and June as shown in Figures 15 and 16. It is easier to see flow rate, temperature, and humidity changes corresponding to the pressure spikes in October than in June. This is caused by an increase in flow, drift enlargement and the use of a new vent raise that was installed downstream of the construction, as shown in Figures 17 and 18.

Major Subsurface Events: Water Events--Two different water events that occurred in the SURF underground were chosen to study. The first water event occurred on March 4, 2018. The sump at the 1250L (381-m) level overflowed into the Ross Shaft (Minutes of the Science Integration Meeting, 2018). 5678 liters per minute of water flowed down the Ross shaft for several hours. This event caused an increase in particle count at the Black Hills Underground Campus and the Davis Campus including the Majorana Detector Room. These particle counts correlated with significant changes in the flow meter monitors. The water event caused Ross Campus trouble alarm, to sound due to high humidity.

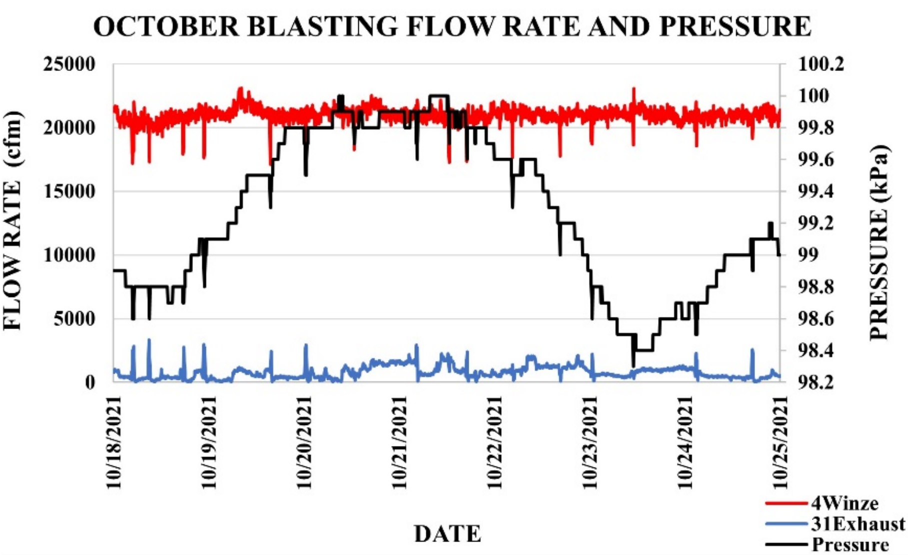

Figure 15. Nine Ledge Four Winze Wye Pressure and flow rates for 7 days in October 2021. Pressure and flow rate spike signature of blast door closure. The red and blue lines are flow rates plotted to the left axis and the black line is pressure plotted to the right axis.

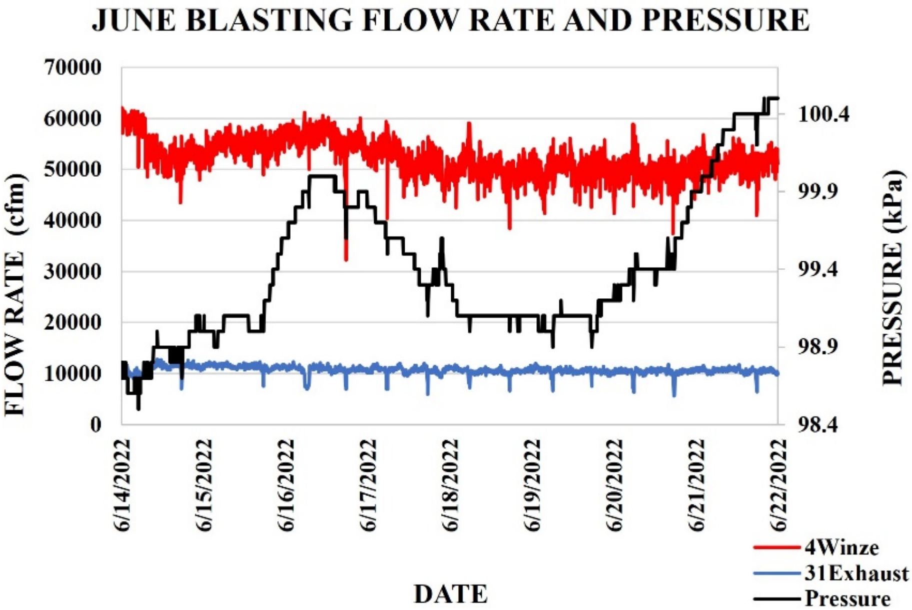

Figure 16. Nine Ledge Four Winze Wye Pressure and flow rates 7 days in June 2022. Pressure and flow rate spike signature of blast door closure. The flow rate in June is higher than in October. The red and blue lines are flow rates plotted to the left axis and the black line is pressure plotted to the right axis.

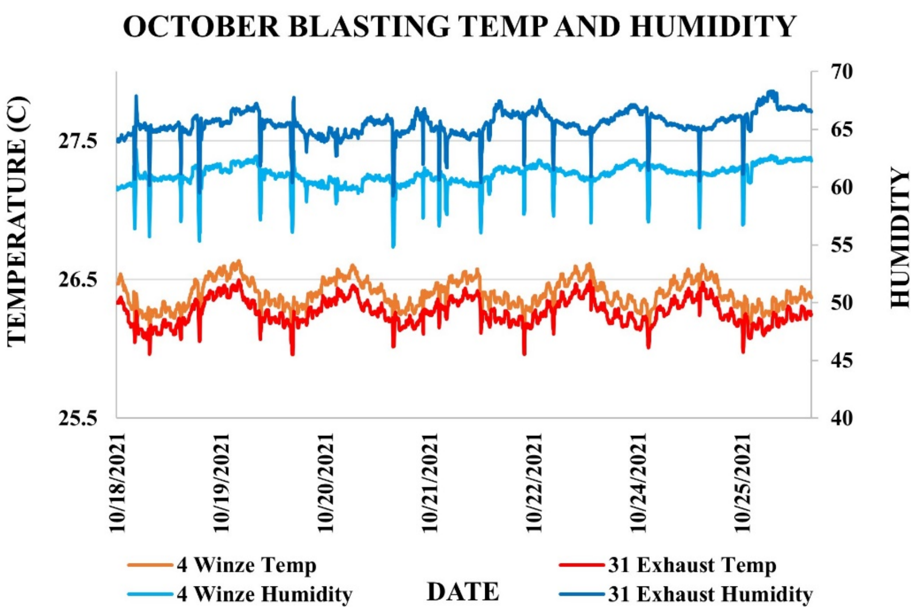

Figure 17. Nine Ledge Four Winze Wye Temperature and Humidity for 7 days in October 2021. Temperature and Humidity changes though small are detectable. The temperatures in orange and red are plotted to the left axis and the blue humidity lines are plotted to the right axis.

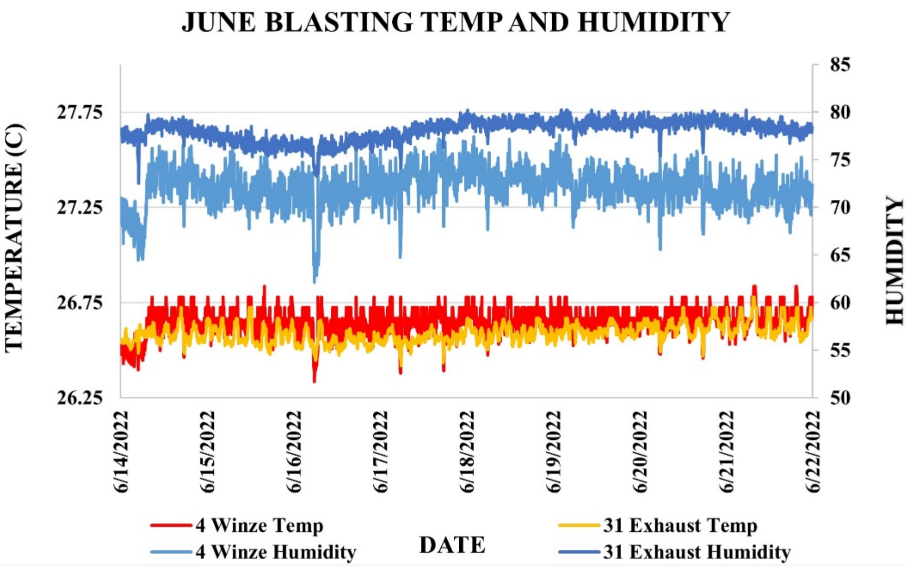

Figure 18. Nine Ledge Four Winze Wye Temperature and Humidity for 7 days in June 2022. Temperature and Humidity changes are harder to distinguish. The temperatures in orange and red are plotted to the left axis and the blue humidity lines are plotted to the right axis.

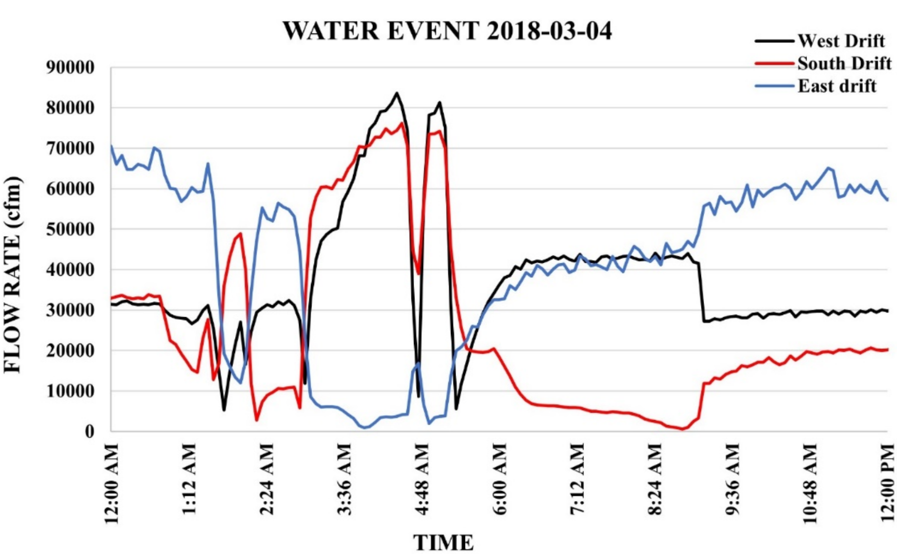

Figure 19. Water event in March of 2018 showing flow rate changes in the science triangle at the 4850L. The West drift is plotted in black, the South drift in red and the East drift in blue.

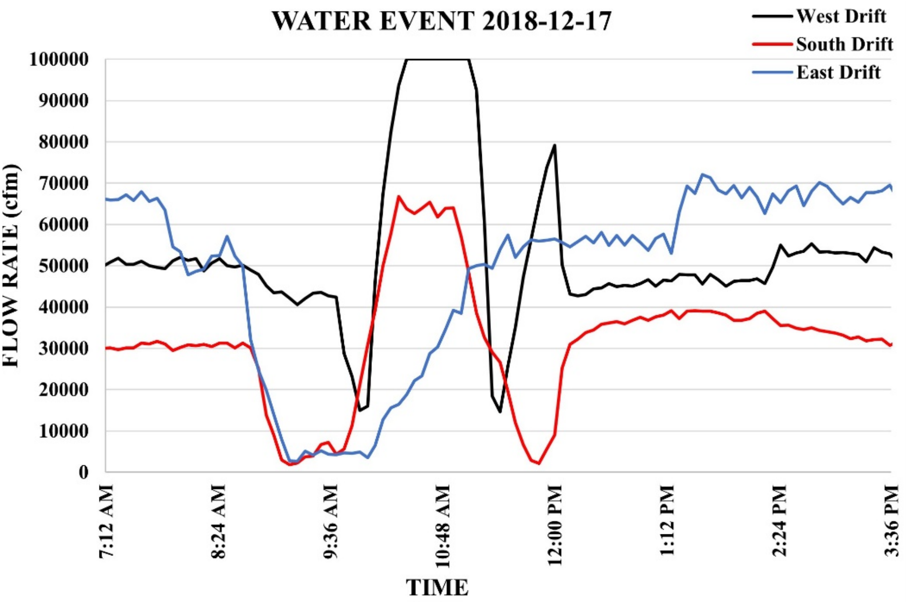

Figure 20. Water event in December of 2018 showing flow rate changes in the science triangle at the 4850L. The West drift is plotted in black, the South drift in red and the East drift in blue.

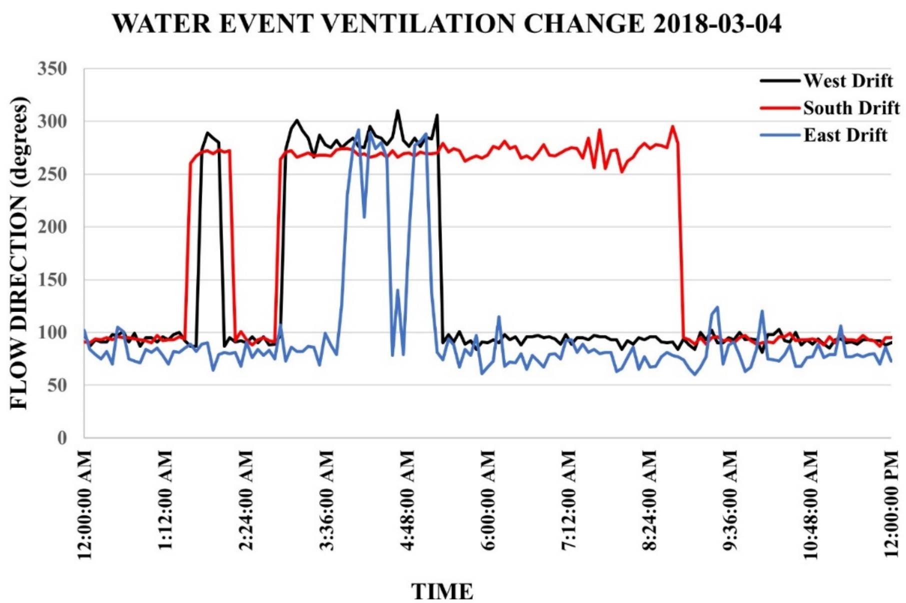

Figure 21. Two different ventilation direction changes for each of the three drifts in the science triangle at the 4850L. The West drift is plotted in black, the South drift in red and the East drift in blue.

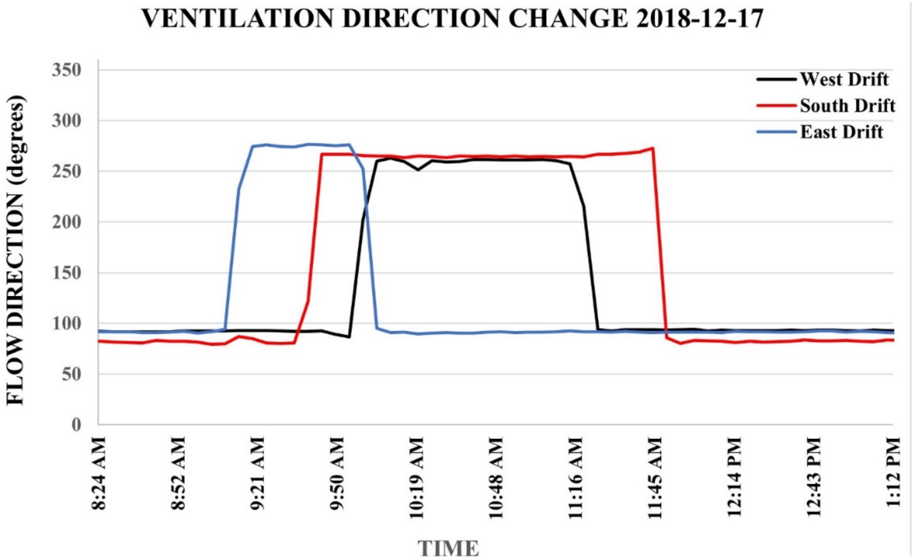

Figure 22. Data from one ventilation direction change in each of the three drifts in the science triangle. The West drift is plotted in black, the South drift in red and the East drift in blue.

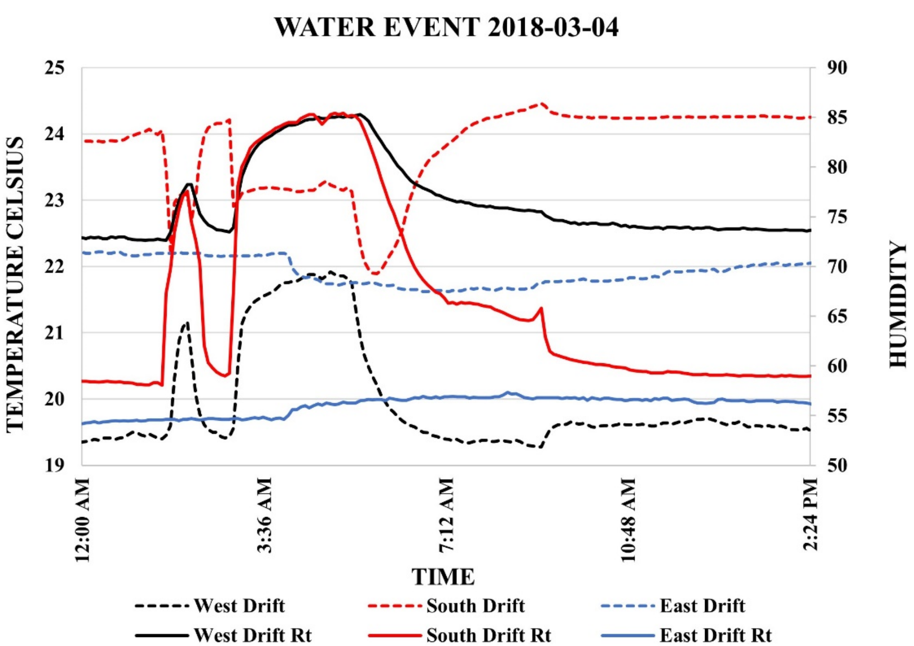

Figure 23. Water events showing data signatures that have larger effects in temperature and humidity. The dotted lined temperatures are plotted to the left axis with the West drift in black the South drift in red and the East drift in blue. The humidity levels are the solid lines plotted to the right axis with the West drift in black the South drift in red and the East drift in blue.

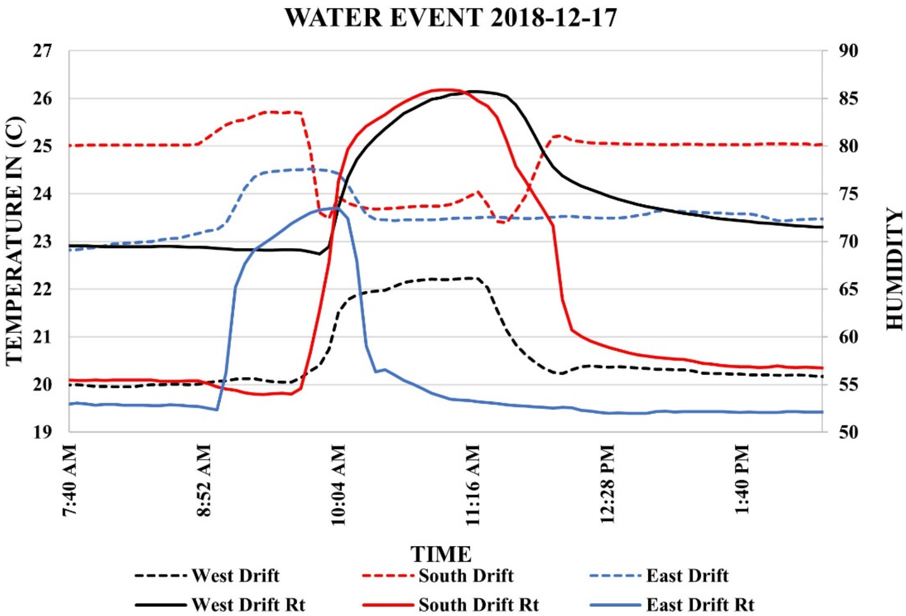

Figure 24. The December water event showing a data signature that having larger effects in temperature and humidity. The dotted lined temperatures are plotted to the left axis with the West drift in black the South drift in red and the East drift in blue. The humidity levels are the solid lines plotted to the right axis with the West drift in black the South drift in red and the East drift in blue.

Another water event occurred on December 17, 2018, including a power failure in the Oro Hondo ventilation fan. The two flow meters, Governor's Corner and the Four Winze Wye flow meters (Figure 2), were used for the analysis. The acoustical anemometers are installed with normal air flow at ninety degrees so if both anemometers show an increase of 180 degrees, then the airflow has changed direction. For simplicity only one anemometer in each drift was used. The air flow for the March 4, 2018, water event is shown in (Figure 19). The air flow for the December 17, 2018, water event is shown in (Figure 20). The ventilation direction change for the March 4, 2018, water event is shown in (Figure 21). The ventilation direction change for the December 17, 2018, water event is shown in (Figure 22). The temperature humidity changes for the March 4, 2018, water event is shown in (Figure 23). The temperature humidity changes for the December 17, 2018, water event is shown in (Figure 24).

DISCUSSION

Underground environmental monitoring at SURF is in its tenth year. The unique nature of the facility, and the extensive footprint makes it challenging to study. Different events can take place, potentially altering the environmental conditions. However, common data signatures can be captured by a network of environmental sensors during these events.

Data sample rate is an important factor in the study of the underground environmental conditions. Many underground environmental events can be missed if appropriate data sampling frequency is inadequate. A sample rate of five seconds with data averaged over a five-minute period produces a manageable amount of data with the ability to capture important events underground. Monitoring the underground environment is becoming more important because SURF is a multi-use facility that occupies multiple levels.

When a fan outage occurs, pressure increases throughout the mine causing a decrease in flow rates and changes in temperature and humidity. Ventilation regresses to its natural state, which can change ventilation directions. In most events, variations in temperature and humidity are minor compared to pressure and flow rates. It is clear, pressure trends felt on the surface of a mine are transferred to the underground regardless of season. Ventilation surveys done with a combination of main and back-up fans can be detected with an underground network of sensors. It would be interesting if the data signature captured on October 11, 2018, could be repeated. If water is extracted to expose deeper levels of the mine, the ventilation pattern could change.

Test blasting that was done in 2015 and 2016 shows that changing ventilation patterns using a combination of opening and closing ventilation doors can be detected by underground sensors. Pressure and flow rate changes on both test blasting dates are detected. Six blast doors were installed to protect scientific experiments at the 4850L. When these doors are closed to conduct a blast, ventilation changes are easily detected. Flow rates and pressures changes at this level and other levels were detected. The effect of closing blast doors is felt at other levels of the mine. The most drastic effect of the blast door closure test was detected at the 5000L. The effect of blasting door closure is different in June than it was in October. This could be due to the enlargement of, and the addition of drifts and a major change in flow rate due to the vent raise that was installed on the exhaust side of the expansion. Data produced by the flow meter network make it clear that the lower levels of the mine experience a vacuum effect and the upper levels seem to mitigate the effect.

The largest effect to the underground conditions in the study was associated with water events. An underground water event can change ventilation directions, pressures, temperatures, and humidity at all levels. These changes could also happen multiple times during a water event. Therefore, environmental monitoring is of prime importance to understand the impact of different events on the environmental conditions and for the safety of a multiuse, multilevel facility like SURF.

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