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DETERMINATION OF A MINE FIRE INTENSITY USING ATMOSPHERIC MONITORING SYSTEM IN A VENTILATION NETWORK

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ABSTRACT

Underground mine fires have long been and continue to be a serious hazard to miners' health and safety. Continuous monitoring of carbon monoxide (CO) and other fire-related parameters by means of an atmospheric monitoring system (AMS) has been widely applied by mine operators to detect fires at a very early stage. Researchers at the National Institute for Occupational Safety and Health (NIOSH) have devoted many efforts to the study of integrating real-time AMS sensor data with mine fire simulation programs to simulate and predict the spread of smoke, so as to provide assistance to mine fire emergency response personnel. The determination of fire intensity using the monitored sensor data is the most critical component of the successful application of this integration. Direct calculation of fire intensity using AMS sensor data has been achieved by NIOSH researchers, which has proven to be very promising when a fire is within a close range of sensors. This paper presents a methodology for determining fire intensity for the complicated scenarios where a fire is distant from sensors with the presence of airflow splits and merges. The method was validated using a full-scale diesel fire test conducted in the Pittsburgh Mining Research Division (PMRD) Safety Research Coal Mine (SRCM) and can help mine operators and safety personnel make informed decisions in a fire emergency.

Keywords: mine fire, fire simulation, heat release rate, atmospheric monitoring system

INTRODUCTION

Mine fire simulation programs, which are built upon mine ventilation network analysis theory, have long been used in underground mines as an essential tool for ventilation planning, fire risk assessment, fire emergency planning, etc. The fire simulation program can analyze the interaction between mine fires and mine ventilation systems. Ventilation systems transport the products of combustion and determine their flow paths and eventual concentrations, while fires can cause extensive disturbances in ventilation that can change the flow rates and even reverse their directions. The primary purpose of using a mine fire simulation program is to plan for a fire emergency by predicting the fire development and spread of products of combustion and by establishing ventilation control strategies for underground mines. Mine fire simulation programs have proven to be a very useful tool for mine fire emergency planning. However, a lack of confidence still exists in applying them practically to assist in a mine fire emergency response due to the uncertainty in the degree of accuracy for the input data and the simulation results, the difficulty in determining fire sources quickly, and the lack of experienced personnel running the programs. The National Institute for Occupational Safety and Health (NIOSH) initiated a project to utilize data from an atmospheric monitoring system (AMS) to obtain real-time fire development information by integrating atmospheric monitoring sensor data with a mine fire simulation software, MFIRE, to provide a more accurate and reliable depiction of the state of a mine ventilation system to assist in decision-making during a fire emergency (Zhou, et al., 2019). Once an underground mine fire is detected, the integration of MFIRE and AMS (referred as "the Integration" hereafter in this paper) can obtain AMS sensor data, locate the fire, and calculate the real-time heat release rate (HRR) using the sensor data, while at the same time, launch MFIRE to conduct real-time fire simulation and predict the spread of smoke and gaseous products of combustion. The framework of the Integration has been successfully demonstrated under in-mine conditions (Zhou, et al., 2019).

In a mine fire simulation, the degree of accuracy for the input fire intensity in terms of HRR largely defines the outcome quality, especially the temperatures and the products of combustion such as smoke, carbon monoxide (CO), and carbon dioxide (CO_2). The Integration relies heavily on AMS sensor data to locate a fire and calculate the real-time HRR. The determination of the fire HRR using AMS data is the most critical component in the successful implementation of the Integration of MFIRE and AMS. Yuan et al. (2017) developed a methodology to calculate the HRR using AMS sensor data for CO, CO_2, and airflow velocity based on the theory of heat and species transfer in ventilation airflow. Very good agreements have been achieved between the calculated HRRs and the measured values determined from the mass loss rates of the combustible materials in a series of full-scale mine fire experiments (Yuan et al., 2017). The calculation of the fire HRR using this methodology requires the AMS sensor data to be collected downstream and close to the fire before airflow splitting or merging. In practice, this requirement may not be met since a fire can occur anywhere in an underground mine and the number of AMS sensors installed in a mine is limited due to the installation and maintenance cost. According to a survey by Rowland et al. (2018) on the use of AMS in underground coal mines, the number of CO sensors installed in U.S. mines varies from 2 to 300 and the sensors are mainly installed in belt entries and other strategic locations such as working faces. Therefore, it is very important to develop a method to determine fire intensity using AMS sensor data where sensors are not located within close proximity of a fire. In this paper, the authors developed a method to calculate fire intensity in terms of HRR using CO and CO_2 sensor readings from sensors that are not located in the same airway with the fire.

ESTIMATION OF HRR USING CO AND CO_2 CONCENTRATIONS

Based on the study by Yuan et al. (2017), the HRR of a fire can be determined using the CO and CO_2 production rates measured at the exit of an airway using Equation (1):

$$Q_A = \left[\frac{H_C}{K_{CO_2}}\right]\dot{m}_{CO_2} + \left[\frac{H_C - k_{CO}H_{CO}}{k_{CO}}\right]\dot{m}_{CO} \quad (1)$$

where Q_A is the actual HRR in kW, H_C is the total heat of combustion of the fuel in kJ/g that can be determined from the proximate analysis of the fuel, H_{CO} is the heat of combustion of CO, 10.1 kJ/g, k_{CO2} is stoichiometric mass of CO_2 produced per unit mass of the fuel, k_{CO} is stoichiometric mass of CO produced per unit mass of the fuel, $\dot{m}_{CO_2}$ is production rate of CO_2 from the fire in g/s, $\dot{m}_{CO}$ is production rate of CO from the fire in g/s. k_{CO2} and k_{CO} are the fuel-dependent constants and can be calculated using the carbon mass fraction of the fuel:

$$k_{CO_2} = 3.67X_C$$

$$k_{CO} = 2.33X_C$$

where X_C is the carbon mass fraction of the fuel, and its value can be obtained from fuel ultimate analysis. For combustion of a fuel within a mine entry, CO and CO_2 production rates can be determined from their bulk-average concentrations downstream of the fire by the expressions:

$$\dot{m}_{CO_2} = VA\rho_{CO2}\Delta CO_2$$

$$\dot{m}_{CO} = VA\rho_{CO}\Delta CO$$

where V is the exit average air velocity in m/s, A is the entry cross-section area in m^2, ρ_{CO2} is the density of CO_2, ρ_{CO} is the density of CO, ΔCO_2 is the increase of CO_2 concentration produced in the fire in ppm, and ΔCO is the increase of CO concentration produced in the fire in ppm. Using the CO_2 density of 1.97 kg/m^3 and CO density of 1.25 kg/m^3, Equation 1 becomes:

$$Q_A = 1.97 \times 10^{-3}\left[\frac{H_C}{3.67X_c}\right]VA\Delta CO_2 + \left[\frac{H_C - 12.6X_C}{2.33X_c}\right]VA\Delta CO \qquad (2)$$

As seen from Equation (2), the airflow rate and the concentrations of the total CO and the total CO_2 produced from a fire together with the heat properties of the fuel are needed to calculate the HRR. The airflow rate can be obtained either from ventilation simulation results or from the monitored air velocity if there is an air velocity sensor installed at the monitoring location. If the fire and the sensors are in the same airway, the CO and CO_2 concentrations measured by the sensors can be treated as the total CO and total CO_2 from the fire. Therefore, the HRR of the fire can be directly calculated using the monitored CO and CO_2 concentrations downstream of the fire. In this paper, the actual CO and CO_2 will be used to refer to the total CO and total CO_2 produced from a fire. If the fire and the sensor are not in the same airway, it is very likely that the monitored CO and CO_2 are not the actual CO and CO_2 due to possible airflow merging and splitting. Therefore, when there is airflow splitting or merging between the fire source and the sensors, the sensor readings for CO and CO_2 cannot be applied directly to calculate the HRR of the fire and, instead, the actual CO and CO_2 should be obtained to calculate the HRR of the fire.

DETERMINATION OF THE ACTUAL PRODUCTION RATES OF CO AND CO_2

The Integration consists of three key components which are the installed AMS, AMS data management program, and MFIRE (Zhou et al., 2019). The AMS installed in a mine is the front-end collecting atmospheric data and sending the data to the AMS data management program. The AMS data management program processes the monitored data, calls the fire location module to locate the fire using monitored sensor data, and launches the HRR calculation module to calculate the real-time HRR once a fire is detected by the AMS sensors. With the known fire location, at each time interval the instantaneous HRR obtained from the HRR calculation module will be fed to MFIRE to run a fire simulation.

While calculating the real-time HRR using the monitored CO and CO_2 sensor data, the relative location of the fire with regard to the sensors is a key factor that needs to be considered carefully. As mentioned above, Equation (2) can only be employed to calculate the HRR if the sensors are in the same airway as the fire; as the CO and CO_2 sensors measure the concentrations of actual CO and CO_2 produced in the fire. When the sensors and the fire are not in the same airway or, in other words, when there is airflow merging and splitting between the fire location and the sensors, the CO and CO_2 concentrations measured by the sensors may only be a portion of the actual CO and CO_2 produced from the fire. Therefore, the monitored CO and CO_2 concentrations cannot be directly used in Equation (2), and the actual CO and CO_2 concentrations from the fire must be obtained using the method described below.

As the products of combustion including CO and CO_2 are transported by airflow in a mine ventilation system, the contaminant distribution in the mine ventilation network is determined by the airflow distribution. Therefore, CO and CO_2 will be distributed to each airway following the airflow distribution. For example, the total contaminant flowing to a junction will be split to the outflow airways in an amount proportional to the airflow rate of each airway. In a well-calibrated mine ventilation network, the CO and CO_2 concentration distributions downstream of the fire can be calculated if the actual CO and CO_2 production rates are known. A mine fire simulation program typically performs these tasks. However, a reversal process needs to be employed in this study, which is to back-calculate the actual CO and CO_2 production rates from the fire with known CO and CO_2 concentrations in a certain airway downstream of the fire.

An algorithm was developed and implemented with the Integration using the flowchart shown in Figure 1. Once a fire is detected in a mine, the fire location will be determined first using the AMS sensor data through the fire location module in the Integration. The program will check if there are CO and CO_2 sensors in the fire airway and, if yes, will use the monitored sensor data to calculate the HRR directly. Otherwise, the program will follow the route of smoke spread, by searching airways downstream of the fire airway to check if there are any CO and CO_2 sensors in those airways. If any sensors are found, the program will obtain the sensor readings for further use.

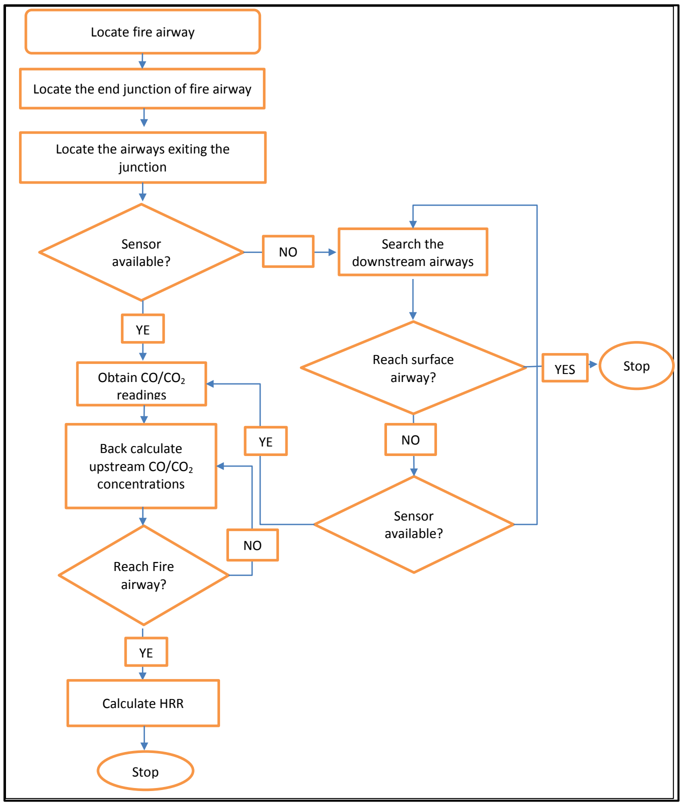

Figure 1. Program flowchart of HRR calculation module.

After the sensor readings for CO and CO_2 and the sensor location are obtained, the program will backtrack along the same smoke route. At each junction, the program will screen all inflow and outflow airways. Based on the flow mass conservation, if the amount of CO and CO_2 flowing to a junction is equal to what flows out and the amount of CO and CO_2 in each airway is proportional to the airflow rate, the CO and CO_2 concentrations in every airway upstream of the current junction can be obtained. In this way, the back calculation can proceed until it reaches the fire airway. The CO and CO_2 concentrations calculated for the fire airway using this method are considered as the actual CO and CO_2 produced from the fire. Therefore, Equation (2) can be used to calculate the HRR of the fire at each monitoring time. It is worth noting that there is always a time delay when using sensor data to calculate the HRR of a fire since it takes time for the contaminants to travel from the fire to the sensors. The farther the sensors are located from the fire, the longer the time delay, as this delay depends on the distance between the fire and the sensors and the air velocities along the traveling route. The calculated HRR of a fire needs to be offset by the time delay. More explanations about the delay time will be demonstrated in the case study section in this paper.

DIESEL FUEL TEST AT AN EXPERIMENTAL MINE

A diesel fire test conducted in the Safety Research Coal Mine (SRCM) was used to demonstrate the application of the developed testing method. The SRCM is a room-and-pillar mine with one main intake and one main return entry. A fan is installed at the surface above the main return entry to exhaust air from the mine. A plan view of the SRCM is shown in Figure 2. For this test, 11.4 liters (3 gallons) of No. 2 diesel fuel was placed in a 0.8-m by 1.1-m (32-in by 44-in) pan in the main intake entry at 10 m from the portal. Eight AMS stations installed in the mine were used to collect data during the test. Each station consists of air velocity, CO, CO_2, humidity, temperature, barometric pressure, and smoke sensors. Figure 2 also displays the locations of AMS stations (S1-S8, in blue). The collected CO and CO_2 concentration data was used to calculate the actual CO and CO_2 production from the fire using the method developed in this study. A digital load cell was placed underneath the diesel fuel pan to measure the mass loss rate of the fuel every 0.4 seconds.

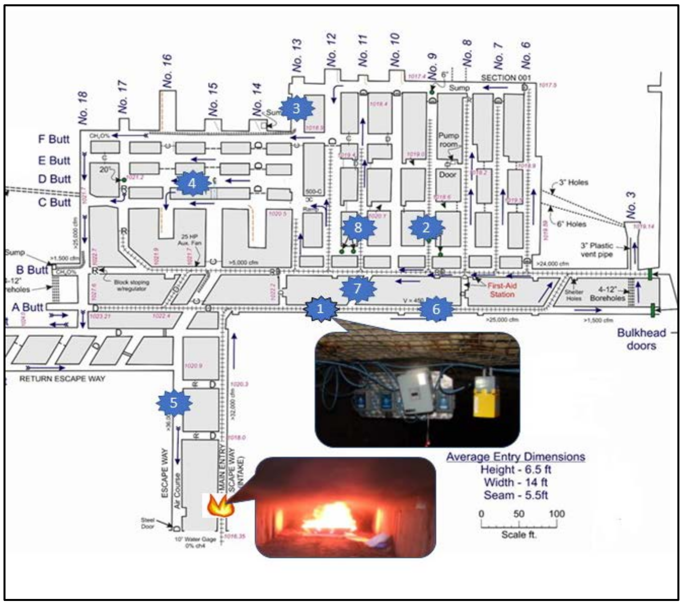

Figure 2. Layout of SRCM and AMS stations.

RESULTS AND DISCUSSION

Monitored CO and CO_2 concentrations

During the diesel fire test, the smoke produced from the fire traveled with the airflow from the main intake to AMS station S1. Most of the contaminants arrived at S1 with only a minimal amount leaking through the crosscuts that connect the main intake and the main return. After leaving S1, the airflow split into two airways where S6 and S7 are located. The two routes of smoke travel merged before the smoke arrived at S8. To the right side of the SRCM, another mine called the Bruceton Experimental Mine (BEM) is connected to the SRCM. Although bulkhead doors are installed to prevent air leakage between the two mines, 500 cfm of air still flowed to the SRCM from the BEM. The airflow leaking in from the BEM diluted the CO and CO_2 before reaching S8. The monitored CO and CO_2 concentrations at S6 and S8 are displayed in Figure 3 and Figure 4**.** It can be seen from the figures that the monitored CO_2 concentrations do not start from zero. The CO_2 reading in the atmosphere is around 400 ppm. When using the monitored CO_2 to calculate the HRR of the fire, the background CO_2 concentration needs to be deducted from the sensor readings since it is not a part of CO_2 produced from the fire.

HRR calculated from diesel mass loss rate

As previously stated, a digital cell was placed under the fuel pan to measure the total mass of the pan and the diesel fuel every 0.4 seconds. The blue dashed line in Figure 5 shows the digital cell readings during the fire test. The mass loss rate of the diesel fuel in kg/s can be calculated from the measured diesel fuel mass. Using 42,300 kJ/kg as the heat of combustion for the diesel fuel, the HRR can be calculated by multiplying the mass loss rate and the heat of combustion at each time interval. The calculated HRR curve of the diesel fire can be found in Figure 5. This HRR curve obtained from the mass loss rate is considered as the actual HRR of the fire and will be used to compare with the HRR curve calculated from the monitored AMS sensor data using the algorithm developed in this study.

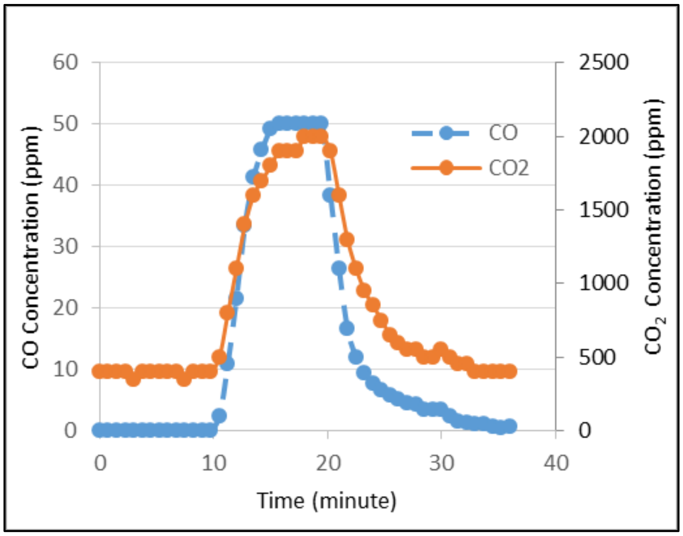

Figure 3. Monitored CO and CO_2 concentrations at S6.

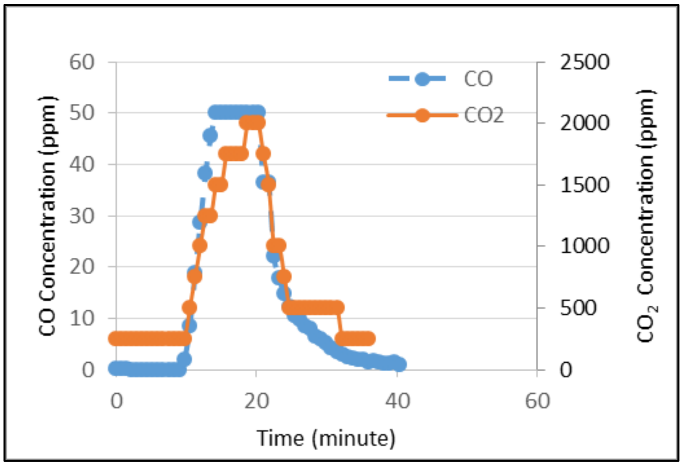

Figure 4. Monitored CO and CO_2 concentrations at S8.

Comparison of the HRRs determined from mass loss rate and AMS sensor data

Since the distributions of CO and CO_2 largely depend on the airflow distribution in a mine ventilation network, a well-calibrated ventilation network model is the key to achieving good results in the calculation of these gaseous production rates. Thorough and comprehensive ventilation surveys have been conducted at the SRCM to ensure the ventilation network model constructed in MFIRE agrees well with the mine survey data.

For the diesel fuel, the carbon mass fraction, X_c, of 0.83 and the heat of combustion of 42.3 kJ/g were obtained from a fuel ultimate analysis. With the CO and CO_2 concentrations back-calculated using the AMS sensor data downstream of the fire, Equation (2) was utilized to calculate the HRR of the diesel fuel fire. Figure 6 and 7 display the HRRs obtained from the sensor data at S6 and S8. As the main flow of the fire contaminants split into two airways after leaving S1, only part of actual CO and CO_2 reached the sensors at S6. The HRR calculated directly from the CO and CO_2 sensor readings was much lower than the HRR from the measured mass loss rate. However, the projected HRR, which was obtained using the production rates of CO and CO_2 back-calculated from the sensor readings at S6, agrees well with the actual HRR from mass loss rate after offsetting with the delay time. The projected HRR from the S8 station readings matched reasonably well with the actual HRR with slight difference. The results have demonstrated that the developed method of calculating the HRR using monitored downstream AMS sensor data in this study can be applied to the Integration to estimate the fire intensity.

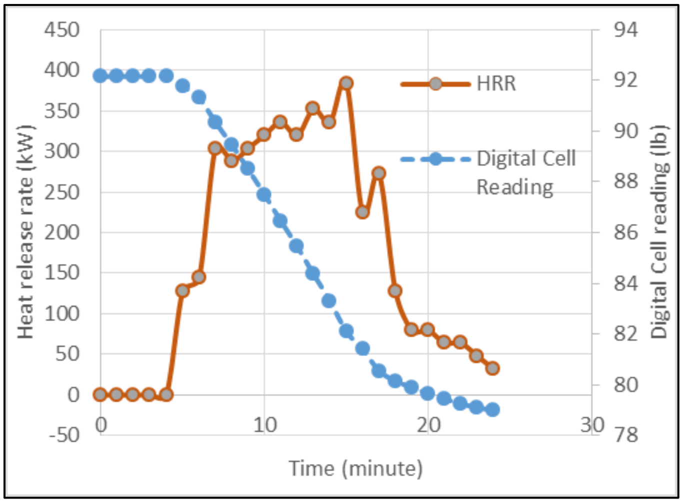

Figure 5. The HRR of the diesel fire calculated from the measured mass loss.

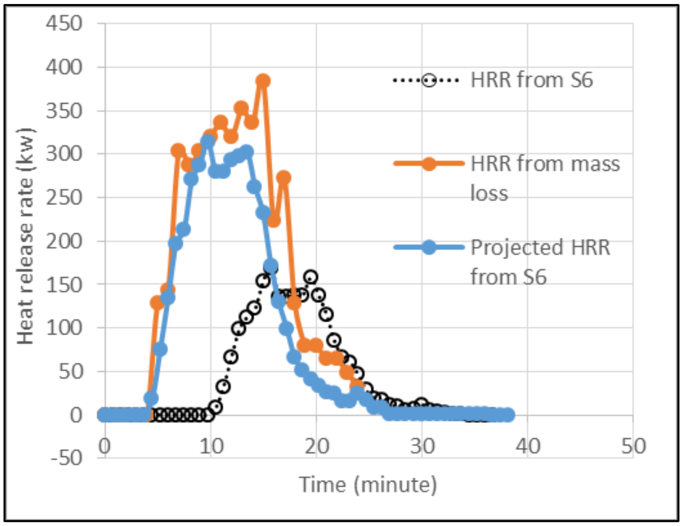

Figure 6. Comparisons of HRRs from S6.

CONCLUSIONS

This study supports NIOSH's efforts to develop workplace solutions to reduce the risk of mine disasters and improve disaster survivability of mine workers. A method was developed in this study to calculate the real-time HRR of an underground mine fire using CO and CO_2 sensor data when the fire and the sensors are not in the same airway. An algorithm to calculate the actual production rates of CO and CO_2 using the sensor readings at any location downstream of the fire was implemented into the integration of MFIRE and AMS. Results from a full-scale diesel fire test conducted in the SRCM at the NIOSH Bruceton campus in Pittsburgh, PA were used to validate this method. The diesel fire projected HRR curves calculated using the monitored CO and CO_2 concentrations at two AMS stations were compared against the actual HRR curve obtained from the measured fuel mass loss rate during the fire test, and the results agreed well. This improved fire intensity calculation method using any AMS sensor data enhances the capability and reliability of the AMS data management program for predicting the smoke and CO spread in a fire emergency.

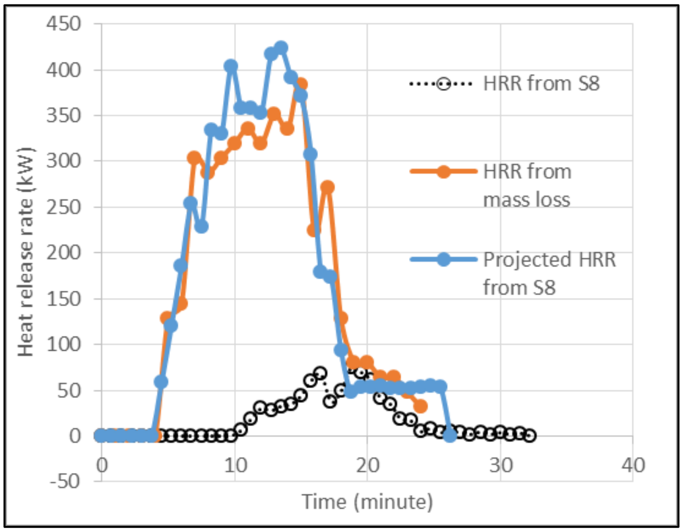

Figure 7. Comparisons of HRRs from mass loss and AMS sensors at S8.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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