SYSTEM FOR PREDICTION OF CARBOXYHEMOGLOBIN LEVELS AS AN INDICATOR FOR ON-TIME INSTALLATION OF SELF-CONTAINED SELF-RESCUERS IN CASE OF FIRE IN UNDERGROUND MINES

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ABSTRACT

Accidents associated with fires and exposure to toxic gases are one of the main causes of injury and death in underground mines. This kind of accidents requires implementation of systems and approaches to tighten and promote underground mine safety. This paper introduces a system for real-time monitoring of carbon monoxide (CO) for prediction of carboxyhemoglobin (COHb) levels in human blood for an early-warning platform and indicator for on-time installation of self-contained self-rescuer (SCSR) device in case of fire in underground mines. The proposed system seamlessly integrates monitoring and analyzing approaches using Arduino, sensor board and smartphone with a specially developed app with Coburn, Forster, Kane (CFK) model for the prediction of COHb (%). This system is designed to predict the COHb (%) formation and also alert and identify the safety limit for on-time installation of SCSR in which the user is still not affected by the clinical symptoms of CO inhalation. The idea for this paper derived from the Sago mine explosion report from which confusion and insufficient training are identified about when to install the SCSR. The main contribution of this paper is the development of a prototype system with an open source and cost-effective platform for solving the problems associated with on-time installation of SCSR, on which the process for effective evacuation in case of fire scenario in underground mines depends.

Keywords: Underground mines, safety, system, SCSR, COHb

1 INTRODUCTION

Underground mines by themselves present demanding and unforgiving environments and combined together with fire scenarios they can generate uncontrolled processes that put the lives of miners at high risk [1-2]. Underground mine safety is a complex process that focuses on improving the odds with which the emergencies and mine challenges will be met.

The purpose of this paper is directed toward the development of a better safety technology in the underground mines without further delay. In this paper a prototype system based on Arduino, sensor board and smartphone with specially developed app for prediction of COHb (%) levels in human blood is developed, which can be used as an indicator for on-time installation of SCSR in case of fire in an underground mine.

The report of investigation into the Sago Mine explosion intrigued our team to develop the system. A quotation from the Sago Mine disaster report "*…I figured as long as I could breathe, I wasn't putting mine SCSR on. And someone asked me if we should go ahead and put them on. I said, not yet, because I was trying to get the fresh air. We should have probably put them on*" [3] provides the basic idea behind the prototype model which aims to provide on-time installation of SCSR in case of emergency for every underground miner.

This paper introduces an early-warning platform based on real-time CO monitoring connected with CFK model [4] of COHb (%) formation algorithm in form of a smartphone app. Such systems that can assist personal protective equipment (PPE), and their implementation in underground mines can play a huge role in enhancing personnel safety.

The following are the prime objectives and key contributions of this study:

- In case of a fire scenario to track in real-time the concentration of CO with Arduino based, reliable and cost effective monitoring system

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- We propose stable communication and transfer of data between the Arduino based monitoring system and the smartphone
- We propose a CFK model in form of a smartphone app for the prediction of COHb (%) formation, which will use the CO monitoring information as input
- To identify the unsafe limits of COHb formation which will trigger an alarm on the smartphone for on-time installation of SCSR
- The proposed Arduino based system is small in scale and its functions can easily be integrated within the SCSR, hard hat or other PPE.

With this kind of studies and systems, we want to stimulate and contribute to the process of technological innovation that will improve the existing systems in the mines and introduce the concept of smart technologies that are already present in every segment of modern living.

2 LITERATURE REVIEW

This section reviews the currently published studies on the application of systems that can improve the safety in case of underground mine fires or other emergency situations. Now, these concepts of systems based on technology can be divided into separable categories and expert systems for safety at work in underground mines.

Adjiski et al. (2017) [5] proposed a system that can integrate information about fire risk assessment, fire detection, safety situation awareness and system for evacuation displayed on a smartphone device. The system proposed by the authors uses Internet of Things (IoT), cloud computing, sensors, detectors and smartphones for composing an effective fire safety system.

Visvam and Ambeth (2016) [6] built a system to track the presence of CO and CH_4 in real time for its use in sewers, underground coal mining or other jobs that are associated with the presence of hazardous gases. The presented system also provides alert messages broadcast using GSM technology so that the people immediately evacuate that area.

Kumar and Prasad (2017) [7] built a system for real time monitoring of underground coal mine parameters such as temperature, gases and humidity. The proposed system collects all the parameter information and sends it into the monitoring section in which threshold values for each sensor are set. If the values exceed the threshold, then a message will be sent to the high authorities.

Jo and Khan (2017) [8] presented, validated and verified a system for real-time monitoring, event-reporting and early-warning platform to improve safety and prevent accidents in underground coal mines. The presented system uses sensors for temperature, humidity, CH_4, CO_2, and CO that enable the identification of abnormal events in the harsh environment of underground mines.

Jo and Khan (2018) [9] built a system comprised of communication protocols, sensor modules and a base station with running Azure Machine Learning (AML) studio over it. Based on the real time sensed data of CH_4, CO, SO_2, and H_2S, the proposed system assesses mine air quality in terms of the mine environment index (MEI) and then the results are fed into AML studio, which enabled the prediction of MEI.

Bhattacharjee et al. (2012) [10] proposed a system to detect fire hazard in a Bord-and-Pillar coal mine panel. The proposed system uses wireless sensor networks (WSNs), and can be used to detect the exact fire location and the spreading direction of the fire. The system is also capable of early detection of fire and generating an alarm in case of emergencies.

Basu et al. (2019) [11] proposed a novel type-2 fuzzy logic system (T2FLS) for the prediction of fire intensity and its risk assessment in underground coal mines. The main functional components of their system are sensor nodes which are installed in the underground mine for real time environmental measurements, and the data are then sent to a base station through the network. The presented system is developed using the fuzzy logic approach to tighten decision making and improve safety in case of fire in underground coal mines.

Introducing and developing safety systems in underground mines based on technology is a new area of research. However, the extensive search of literature shows that there is a lack of systems that focus on user assistance for using SCSR, which in some cases is the only option for effective evacuation in case of fire in underground mines. This paper discusses the components of such a system that can be used for real-time monitoring and early-warning platform for on-time installation of a SCSR device in case of fire in an underground mine.

3 METHODS

3.1 System Overview

Arduino based CO detecting system is developed to alert mine workers of on-time installation of SCSR in case of fire in underground mines. The basic idea of this Arduino based system connected with smartphone is to monitor the mine environment and with CFK app model to predict the CO exposure in form of COHb (%) formation, and, when the system detects a value equal or greater than the safe limit, to alert the user (mineworker). The system architecture is presented in Figure 1.

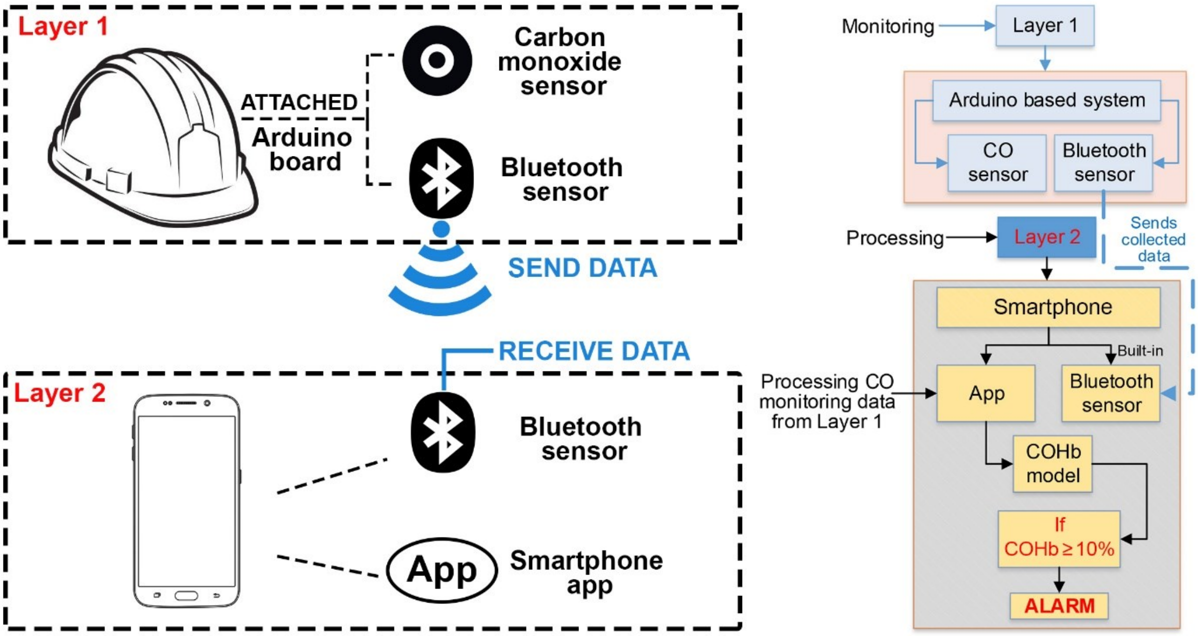


Figure 1. System architecture

The presented architecture splits the system into a monitoring and processing layer. The monitoring layer consists of an Arduino Nano 3.0 board, a MQ-7 CO sensor, a Bluetooth module and a power supply. The processing layer consists of a smartphone and a smartphone app and it uses the built-in Bluetooth sensor from the smartphone to communicate with the monitoring layer.

The system is designed to detect the presence of CO from the underground mine environment by receiving inputs in Arduino Nano board from the MQ-7 sensor. The collected environmental data are processed every 1 s, with a built-in ATmega328 microcontroller inside Arduino Nano. Algorithm is developed to average the collected CO data over the time for their use inside the smartphone app and to establish a constant stable connection and transfer of data between the Bluetooth modules. The processing inside the system and the communication between the layers is developed using the Arduino integrated development environment (C language). The smartphone app containing a CFK model is developed using the Android programing language (Java). The updating of the received data inside the smartphone app is done every 1 s (real time), and if the model calculates a concentration of COHb ≥ 10 %, then the smartphone app, via an alarm and text massage, will inform the user to install the SCSR.

3.2 System Design

3.2.1 Monitoring layer: Arduino based system

The foundations of this system are based on Arduino Nano v3, with the ATmega328 Microcontroller for digital and analog input/output (I/O) [12]. The Arduino Nano v3 with a MQ-7 sensor and a Bluetooth module board HC-05 were used for monitoring and transferring the data from the underground mine environment. Figure 2(a,b), shows the physical connection and the circuit diagram of the MQ-7 sensor and Bluetooth module attached to the Arduino Nano v3, powered by 5 V. We choose to use the Arduino system because of its open-source, low-cost and the fact that it is used by a large community for prototyping [13]. Each of the 14 digital pins on the Arduino Nano v3 can be used as an input or output, using pinMode(), digitalWrite(), and digitalRead() functions which operate at 5 V, and each of the pins can provide or receive a maximum of 40 mA. The Arduino Nano v3 has 8 analog inputs, and each can provide 10 bits of resolution (i.e. 1024 different values).

The MQ-7 sensor is suitable for sensing CO concentrations in the air anywhere from 0 to 1000 ppm. This sensor is low-cost, has high sensitivity and fast response time. The sensor's output is an analog resistance.

There are 4 leads on the MQ-7 sensor: Vcc +5V, AOUT, DOUT and GND. The Vcc +5V and GND leads establish power for the MQ-7 and the other 2 leads are AOUT (analog output) and DOUT (digital output) [14]. The terminal AOUT gives an analog voltage output in proportion to the amount of CO the sensor detects in the environment.

The Bluetooth module board HC-05 can communicate with the Arduino through serial communication. This module is designed for wireless serial communication and it is a fully qualified Bluetooth V2.0+EDR (Enhanced Data Rate) with a transmission rate of 2,1 Mbps [15]. The range for maximum wireless communication for this Bluetooth module is 10 m, and needs the power of 3,3 V, but thanks to the converters, it can be connected to the boards, power by 5 V. The Bluetooth module board HC-05 has six pins: two pins for the power supply: ground (GND) and +5 V, and two pins of serial interface: the RXD (Receive Data) and TXD (Transmits Data), one to enter the configuration mode: Key (EN must be set to HIGH (3,3 V) to enter the configuration mode and it must be disconnected to enter the communication mode), and the other to know the connection state: State (HIGH when the module is connected). Everything received via Bluetooth will be given out by the TXD pin as serial data to the microcontroller UART (Universal Asynchronous Receiver/Transmitter) receiver and every serial data given to RXD pin will be sent via Bluetooth.

The monitoring layer of the proposed system is connected to a DC-DC 3,7 V to 5 V step up voltage booster regulator to provide a power supply of 5 V.

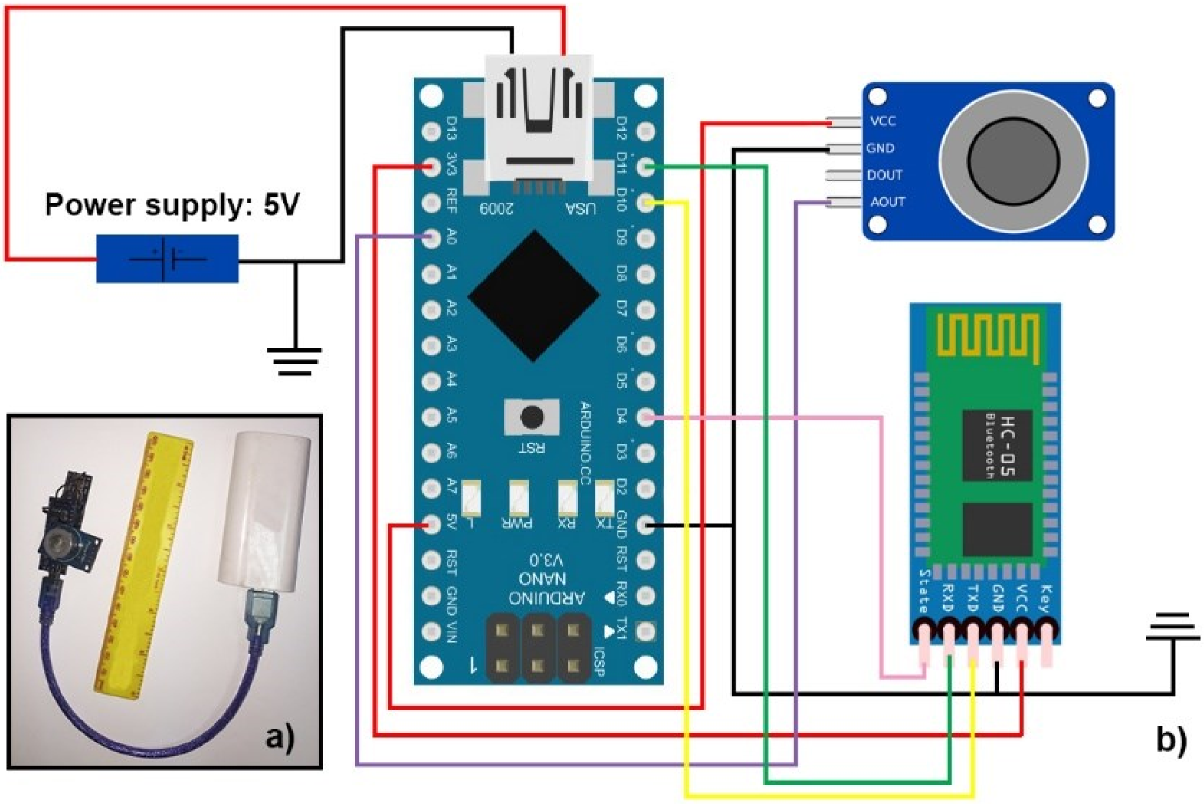


Figure 2. a) Physical connection of the monitoring layer b) Circuit diagram for the monitoring layer

3.2.2 Processing layer

The idea behind the processing layer is to use every day familiar technology because this layer will also be used for information notification to the user. The processing layer consists of a smartphone, a smartphone app and it uses the built in Bluetooth sensor from the smartphone to receive data from the monitoring layer. The smartphone app is the core of the layer and its foundations are based on CFK model [4] of COHb (%) formation as the result of exposure to CO.

The overwhelming hazard in fires is the inhaled CO that acts on human body by competing with oxygen for the hemoglobin in blood and tying it up as COHb rather than as the normal oxyhemoglobin (O_2Hb) [16-17]. The toxic effect of this process occurs when large concentrations of COHb (%) are formed in the human body and not enough O_2Hb is transported to the body tissues. Exposure to a large concentration of CO is lethal, since it has a binding affinity with hemoglobin that is more than 200 times greater than that of oxygen.

Table 1. Approximate correlation between blood COHb (%) level and clinical symptoms [16]

COHb (%)	Clinical symptoms
<1	Normal value for non-smokers
5-10 %	Shortness of breath on vigorous exertion, possible tightness across forehead, statistically significant diminution of visual perception, manual dexterity or ability to learn;
11-20 %	Mild headache and possible tightness across the forehead, dizziness, confusion and decreased exercise tolerance;
21-30 %	Throbbing headache, mild nausea, brief loss of consciousness, fainting, easy fatigability, disturbed judgment, irritability, dimness of vision;
31-40 %	Severe headache, dizziness, respiratory failure, coma, intermittent convulsions;
>40 %	Brain damage, seizures, death from severe cellular hypoxia if exposure is prolonged.

In order to estimate the exposure of miners in case of an underground mine fire scenario, mathematical models have been combined in a smartphone app for the prediction of COHb blood level, expressed as % of saturation value which is an indicator for CO uptake.

In this study, the COHb model has been selected and reliably described by the established and verified CFK model [4]. The limitations in the model are associated with the physiological variables which are needed as input to the model and are difficult to be measured (endogenous production of CO, blood volume, pulmonary diffusing capacity) [18].

The CFK model is a nonlinear differential equation, used to determine blood COHb (%) levels and is given by the following equation [4]:

$$[COHb]_t = \frac{1}{A\left(\frac{AC}{[COHb]_0}\right)} + (1-C)V_{CO}B + (1-C)P_{1,CO} \tag{1}$$

$$A = \frac{PO_2}{M[O_2Hb]} \tag{2}$$

$$B = \frac{1}{D} + \frac{P}{Va} \tag{3}$$

$$C = e^{\left(-\frac{tA}{V_bB}\right)} \tag{4}$$

where:

M - Haldane coefficient = 240

$[O_2Hb]$ - oxyhaemoglobin concentration = 0.2 ml ml^{-1} blood

$[COHb]_t$ - carboxyhaemoglobin concentration at time t in ml CO per ml blood

$[COHb]_0$ – initial carboxyhaemoglobin concentration (%COHb = 0.5% for non-smokers;

%COHb > 2% for 80% of smokers; %COHb = 10% for heavy smokers)

PO_2 - partial pressure of oxygen in lung capillaries = 13.3 kPa

V_{CO} - endogenous rate of production of CO = 0.007 ml min^{-1}

D - diffusivity of CO = 225 ml min^{-1} kPa (in reality this is not a constant but is altered by a number of factors including exercise)

P - Barometric pressure - saturated vapour pressure of water at 37 ^{0}C = 95.1 kPa

V_b - blood volume 5500 ml

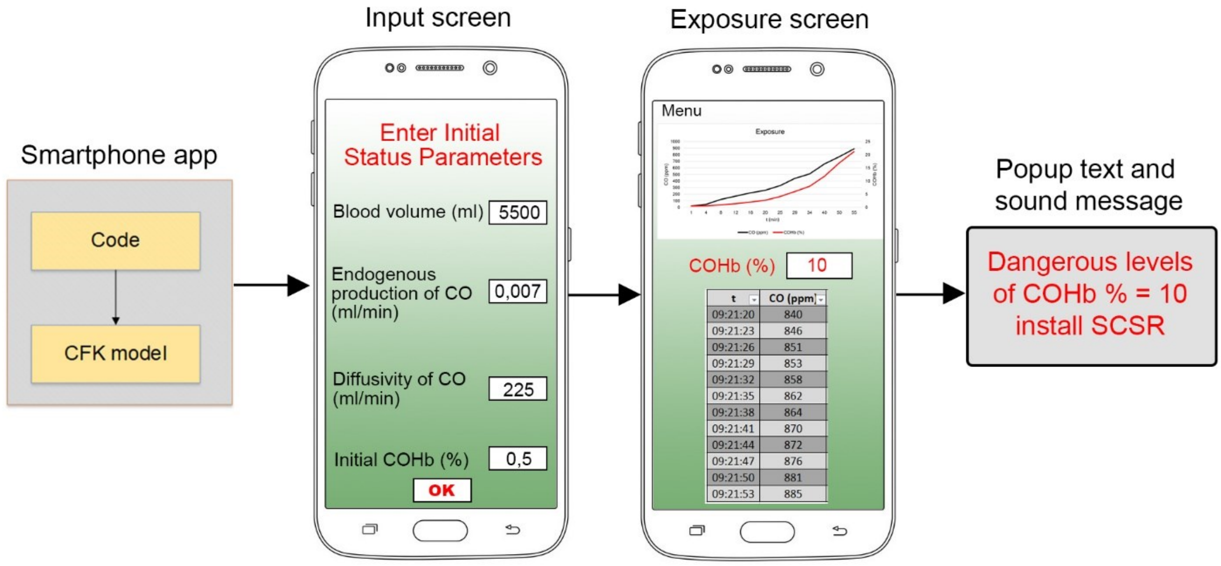
$P_{1,CO}$ - partial pressure of CO in inspired air = 0,0101 kPa (adopted for the purposes of this model)

V_a - alveolar ventilation rate = 6000 ml min^{-1}

t - exposure time in minutes

With the assumption that the O_2Hb concentration is constant and not being a function of COHb, the set of Equation (1,2,3,4) is linear, and previous studies have shown that it presents a good approximation [19].

A smartphone app is developed in this paper, based on the CFK model to predict COHb formation (Figure 3). The smartphone app function is to predict the individual's COHb formation (%), based on certain environmental and physiological inputs, which in this stage of prototype development are set as default values to assist the user. The exposure profile of the model is presented in a graphical form, and when the system detects a value equal or greater than the safe limit, it alerts the user with a text and sound message on the smartphone.



Enter Initial Status Parameters

Blood volume (ml) 5500

Endogenous production of CO (ml/min) 0,007

Diffusivity of CO (ml/min) 225

Initial COHb (%) 0,5

COHb (%) 10

t	CO (ppm)
09:21:20	840
09:21:23	846
09:21:26	851
09:21:29	853
09:21:32	858
09:21:35	862
09:21:38	864
09:21:41	870
09:21:44	872
09:21:47	876
09:21:50	881
09:21:53	885

Dangerous levels of COHb % = 10 install SCSR

Figure 3. Smartphone app interface, based on the CFK model

To avoid system confusion between two or more users, each Bluetooth connection is previously paired. Upon launching the smartphone app, the input screen is displayed requesting information on blood volume (ml), endogenous production of CO (ml/min), diffusivity of CO (ml/min) and initial COHb (%). In this stage of the app development, the default values will be used which representative normal conditions but these values can also be overwritten. After choosing or entering the data in the input screen, the system is activated and the connection between the monitoring and processing layer is established, which launches the exposure screen in the app. The graph shows the CO concentration over time with the corresponding COHb (%) formation. The COHb box shows the current COHb (%) formation and is updated every 1 s (real time). The table shows records in scrollable form, from the start to the end of CO exposure. These results can also be extracted in a file suitable for use in spreadsheet software for later analysis, which includes the user profile, the dates, CO (ppm) and COHb (%) exposure over the time period. On the menu bar in the exposure screen five items are available:

- New - Clears all inputs data and opens new empty exposure window;
- Open - Opens the previously stored and saved exposure document;
- Save As - Allows the current exposure document to be saved for later retrieval;
- Quit - Terminates the program;
- Export - Exports to a spreadsheet software with csv' extension.

4 RESULTS AND DISCUSSION

4.1 Testing the processing layer (Scenario 1)

A prototype system for real-time continuous CO monitoring based on Arduino, a sensor board and a smartphone with a specially developed app are basic features of this study. This system is developed for the prediction of COHb (%) levels in human blood which can be used as an indicator for on-time installation of SCSR in case of fire in underground mines.

Due to the complexity of the fire scenarios and the process of validating and calibrating the system, these processes will be done in another study. The current system constraints, as well its further development, calibration and validation processes are described in the next section.

At this stage of development and for the purpose of presenting the idea behind this system, we will model a hypothetical underground fire scenario from which we will extract the CO concentration over a time curve. For the purposes of modeling the underground mine fire scenario, we had used the VentFIRE™ module that is a part of the ventilation software Ventsim [20]. The process of modeling and simulation of fire scenarios are presented in different papers by the same author and can be found here [1, 21-22].

The steps behind the partial testing of the system with a modeled fire scenario are shown in Figure 4.

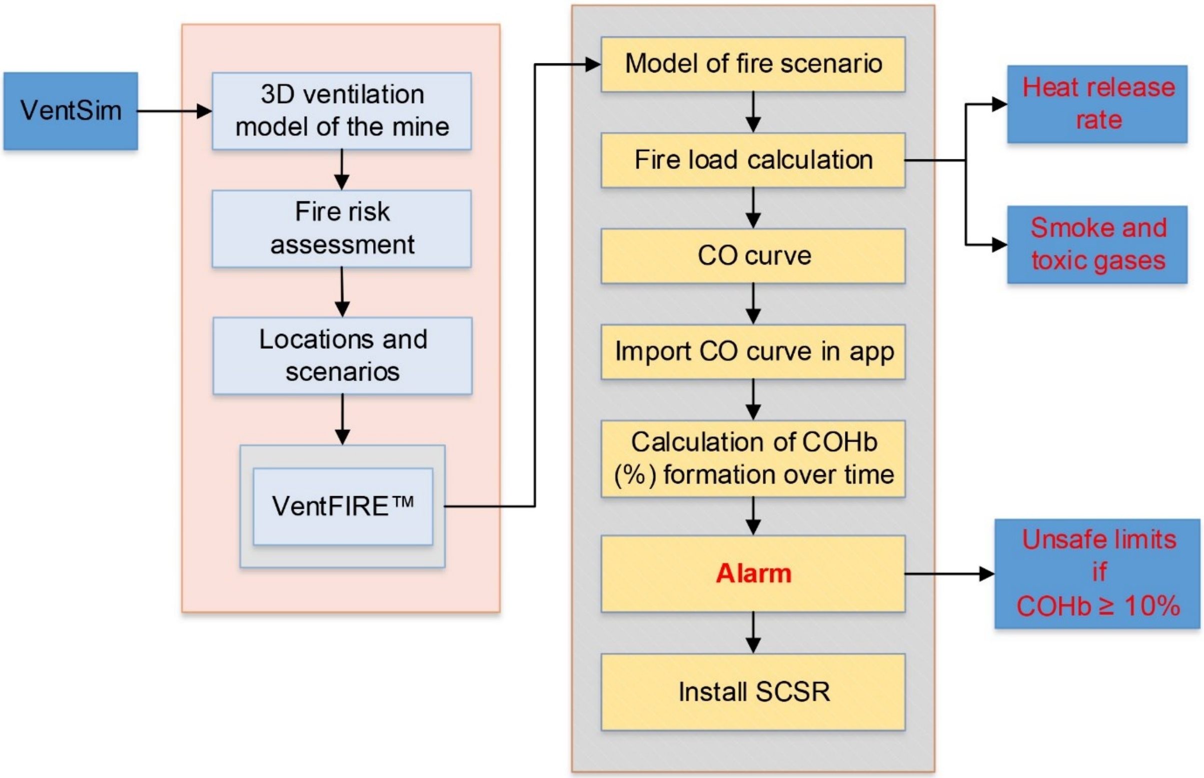


Figure 4. Steps for testing the processing layer of the system

For this stage of testing of the proposed system, a hypothetical fire scenario is modeled in which a fire is generated by the SANDVIK LH115L loader tire. To simplify the fire model, we will assume that the fire will not spread and will remain localized to only one of the loader tires. Figure 5 shows a 3D ventilation map of a hypothetical underground mine built in Ventsim software, the location of the fire scenario and the CO monitoring location.

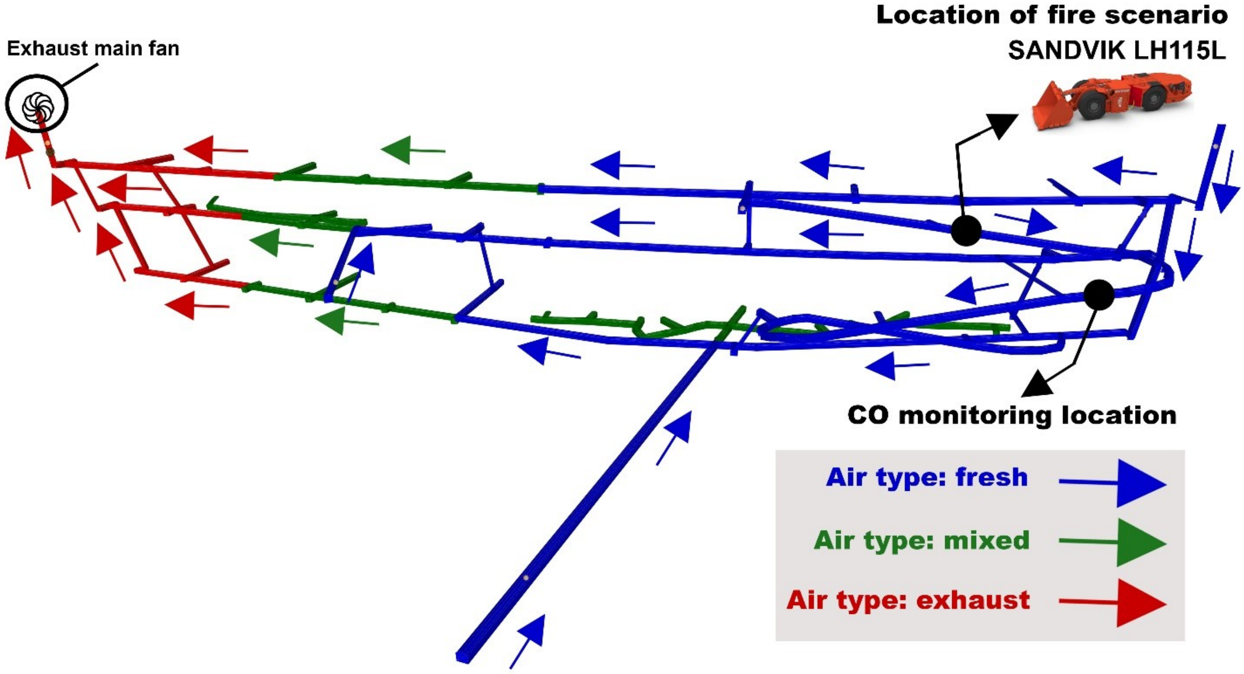


Figure 5. 3D mine ventilation map with locations for fire scenario and CO monitoring

Table 2 shows the input parameters in the VentFIRE™ module for the hypothetical fire scenario generated from SANDVIK LH115L tire.

Table 2. Input parameters for the fire scenario from SANDVIK LH115L tire

	Weight [kg]	Density [kg/m^3]	Heat of combustion [Mj/kg]	Burning rate of material [kg/m^2*s]	O$_2$ consumed [kg/kg]	Yield CO$_2$ [kg/kg]	Yield CO min [kg/kg]	Yield CO max [kg/kg]	Yield Soot [kg/kg]
Tire	248	1150	44	0.045	3.62	0.9	0.13	0.23	0.1

From the analysis and calculations of this hypothetical fire scenario in the VentFIRE™ module and the characteristics of the tire shown in Table 2, in the selected CO monitoring location we get the CO concentration over time curve shown in Figure 6. The generated Heat Release Rate (HRR) from the fire scenario is shown in Figure 7.

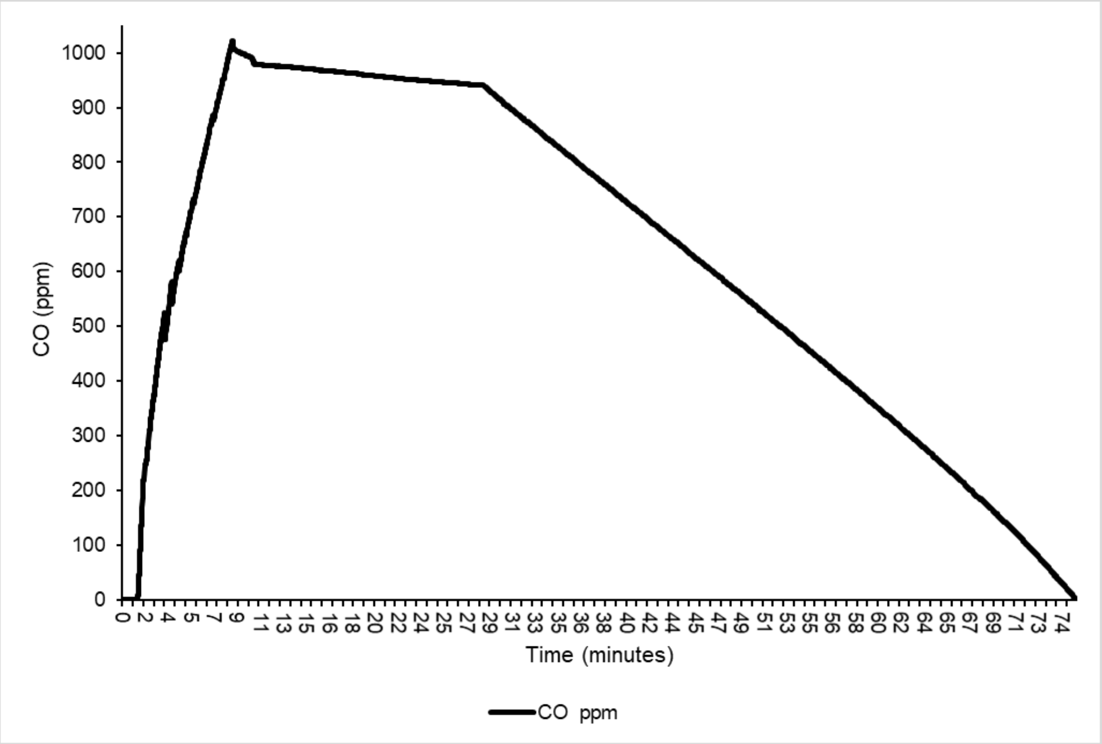


Figure 6. CO concentration over time curve in the selected CO monitoring location during the fire scenario

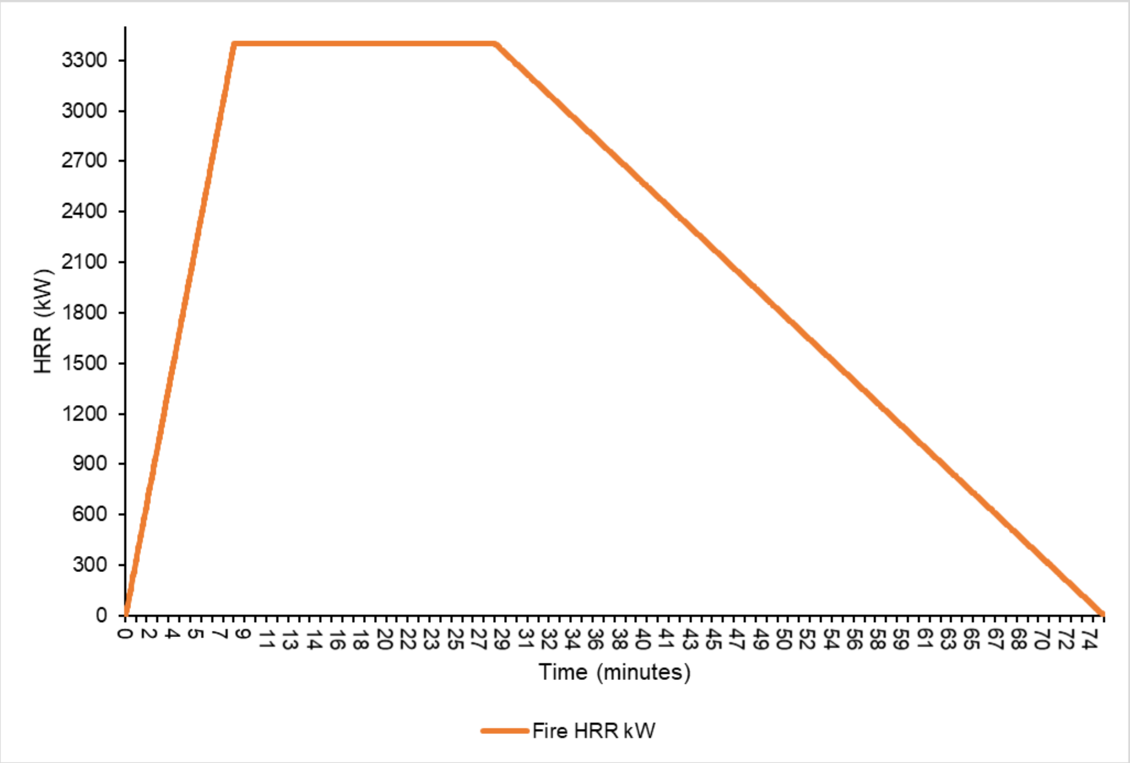


Figure 7. HRR from fire scenario

The results of the modeled fire scenario from which we used the CO concentration over time curve (Figure 6) gave the corresponding results from the smartphone app for the predicted COHb (%) formation. The results are shown in Figure 8.

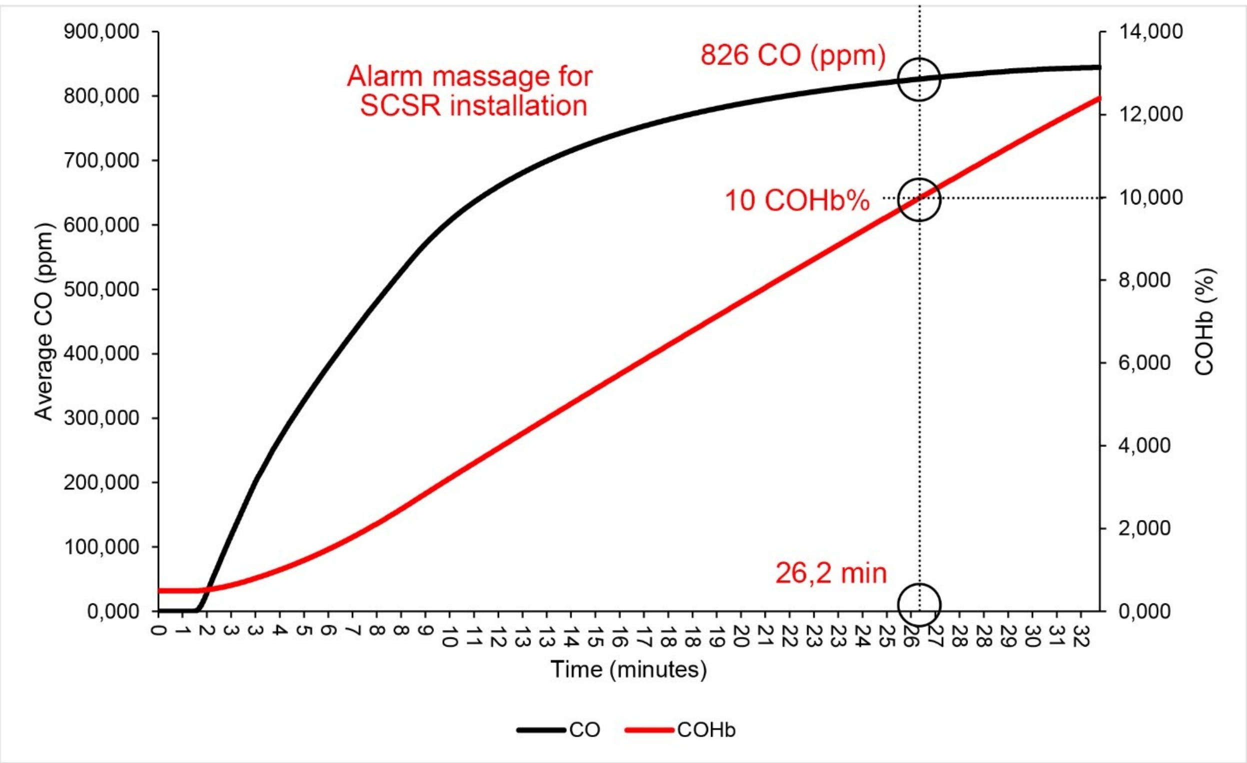


Figure 8. Results obtained from the smartphone app, based on the modeled hypothetical fire scenario

The results of this simulated scenario demonstrate the idea behind the proposed system. In the presented scenario in which we import the CO curve from a hypothetical fire model, the proposed system generated an alarm on the smartphone when the CFK model programmed into a smartphone app, predicted ≥ 10% COHb at 26.2 minutes after the monitoring layer of the system began recording the presence of CO in the air. For its use in the smartphone application, the CO concentration needs to be averaged over time to better present the accumulating effect of a time-changing exposure.

4.2 System performance testing with a real scaled-down fire experiment (Scenario 2)

A real scenario in safe conditions to test the system performance between the monitoring and processing layer is done in this section. For safety reasons and due to the fact that the system is in a developmental phase, it is costly and difficult at this stage to carry out experiments in operational mines. The testing of the proposed system was conducted using a scaled-down model, shown in Figure 9. The intention in using a scaled-down model for a real fire experiment was not to represent a full-scale mine section, but rather to safely test the system within the budget that was available to us. All the walls of the model were made of fire resistant glass to enable observation.

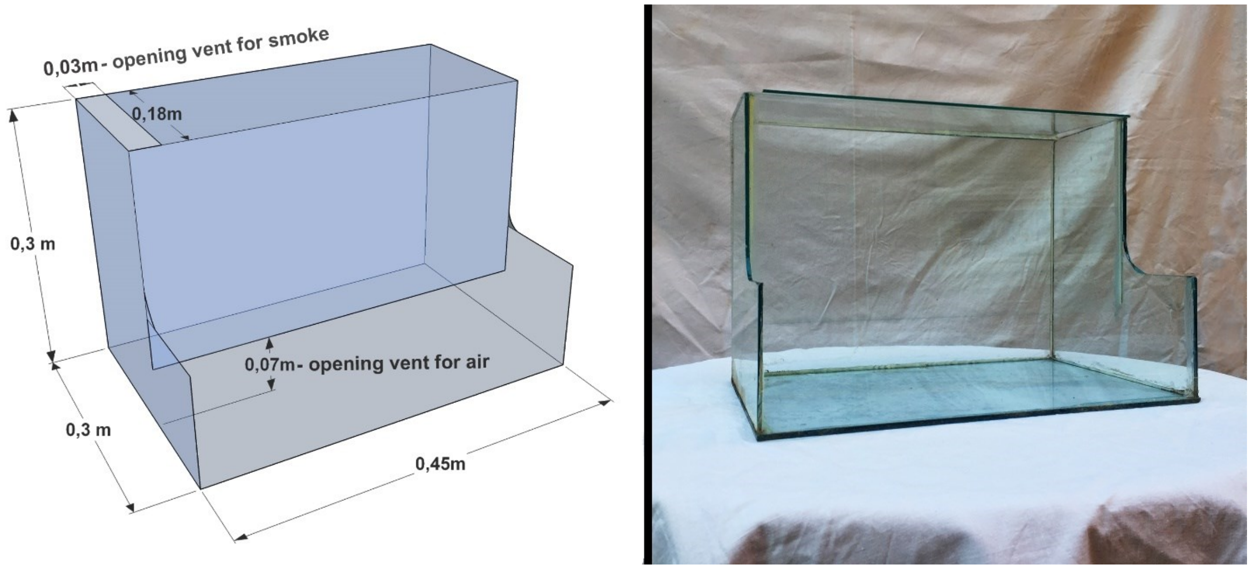


Figure 9. Scaled-down model for testing the performance of the proposed system

Smoke was produced by burning a rubber inside the model in a well-ventilated condition. The proposed Arduino system which represents the monitoring layer was strategically placed to record the generated CO concentration and send the collected data through Bluetooth to the processing layer. The distance between the monitoring and the processing layer in real conditions will not exceed 1.5 m, but for the testing purposes we will set the distance of 5 m between the layers.

To test the connection and the strength of the signal in the range of 5 m, we measured the Received Signal Strength Indicator (RSSI) between the monitoring and the processing layer. RSSI is a measurement of the power present in a received radio signal and it is measured in decibel-milliwatts (dBm) and has typical negative values ranging between 0 dBm (excellent signal) and -120 dBm (extremely poor signal) [23]. Figure 10 shows RSSI values over the distance of 5 m between the monitoring and the processing layer.

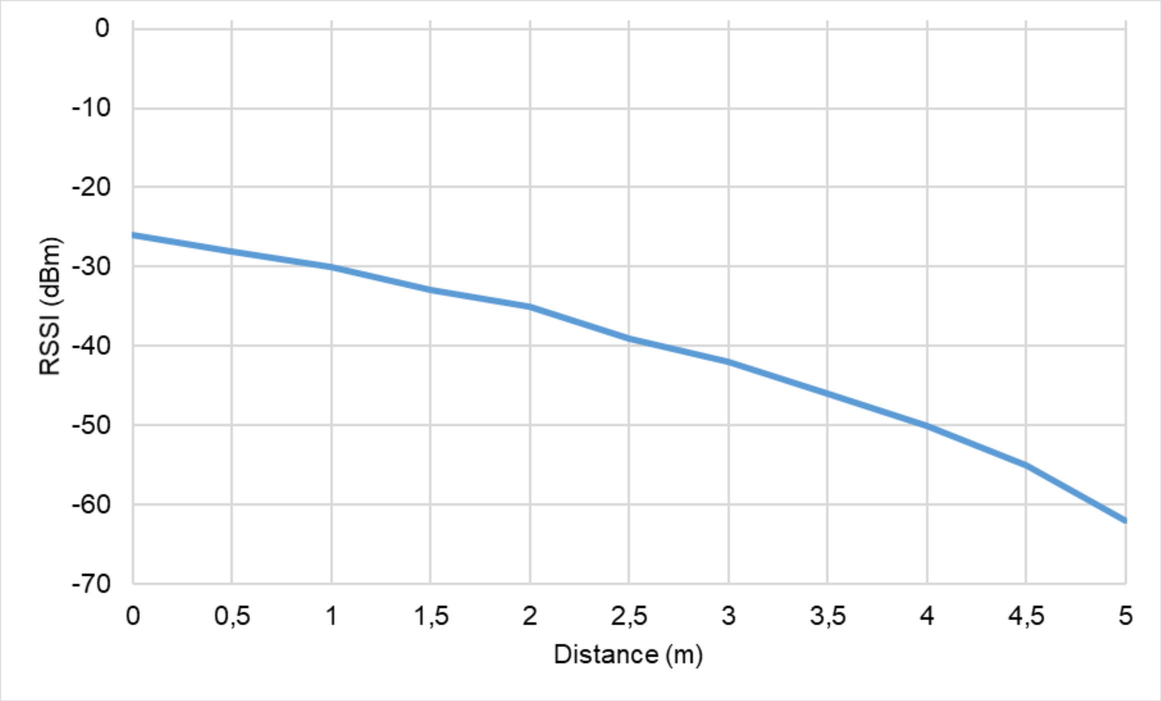


Figure 10. Results from RSSI values over the distance of 5 m between the monitoring and the processing layer of the proposed system

Video clips of the scaled-down fire model were recorded for analysis. Figure 11 (a,b) shows a setup and snapshot of the fire experiment.

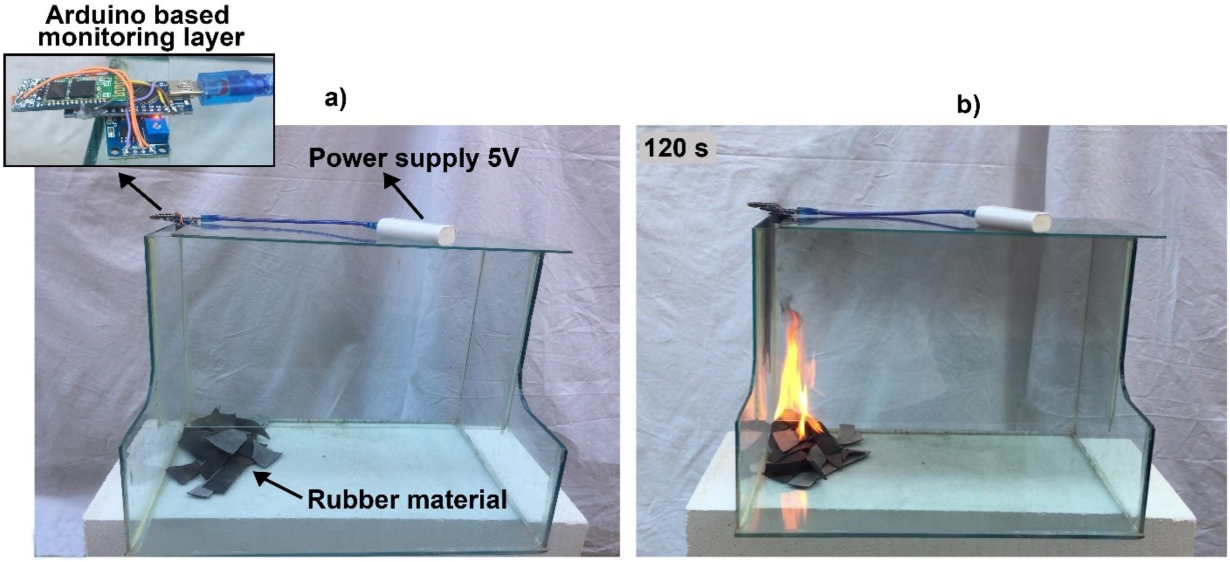


Figure 11. a) Setup of the fire experiment with positioning of the monitoring layer of the proposed system; b) Snapshot at 120 s, from the start of the fire experiment

The setup for the experimental fire procedure for the scaled-down model was as follows:

- The lower opening of the model is constructed to provide sufficient ventilation for the fire scenario
- The rubber material is used as burning fuel to generate smoke and CO rich environment
- Fire resistant glass was used for safety purpose and for better observation
- The monitoring layer of the proposed system was placed at the top opening of the scaled-down model to record and send the collected CO data from the fire experiment to the processing layer
- The connection and the strength of the signal in real time were tested between the monitoring and the processing layer with the RSSI parameter
- The recording of data in a sufficient time interval was done between the monitoring and the processing layer for the purposes of the analysis.

As can be seen from Figure 12, critical levels of the predicted COHb % concentration to trigger an alarm message by the processing layer were not reached due to the small proportions of the burning material (fire experiment) inside the scaled-down model.

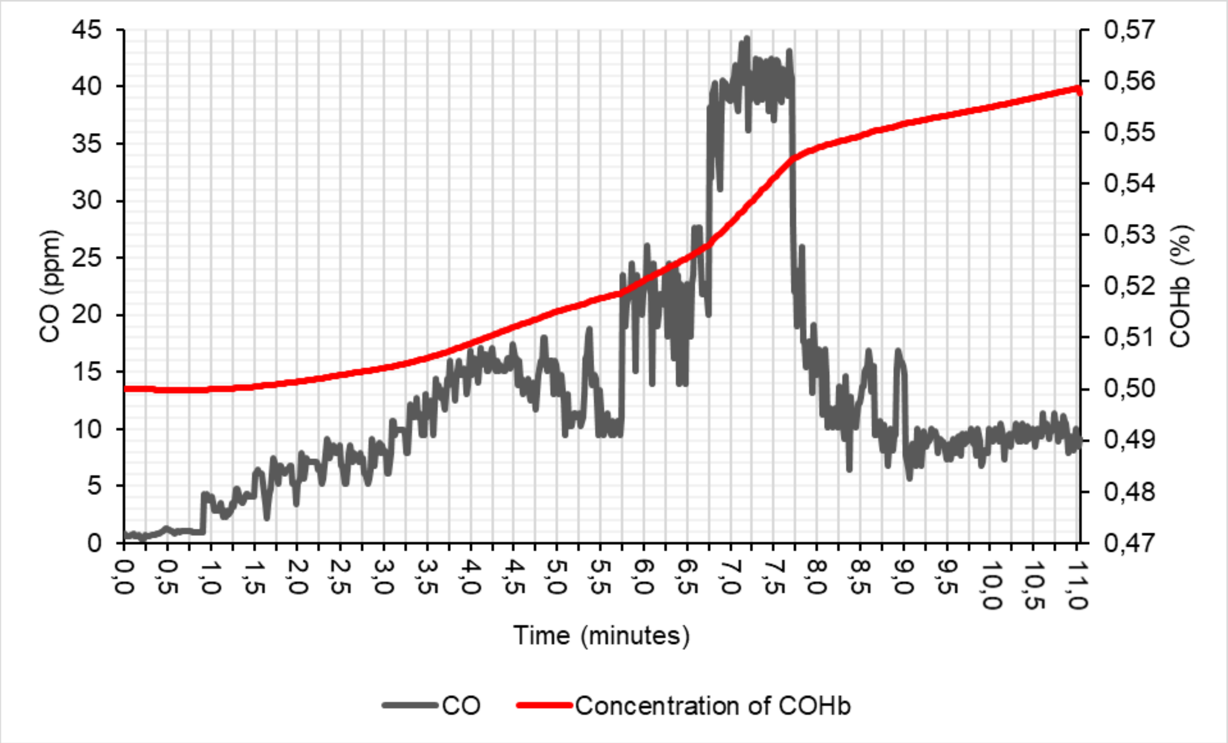


Figure 12. Results obtained from the proposed system, tested in real fire experiment inside the scaled-down model

5 LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

As previously discussed, it is important to note the current limitations in the proposed system involved in this paper. All of the identified limitations of the proposed system will be the scope of future work and modification to the system.

Firstly, we will start with the calibration of the MQ-7 sensor. To calibrate the MQ-7 sensor we will use a calibration cylinder with known CO (ppm) value as a standard value. This reference/standard value will generate resistance values from the MQ-7 sensor. Using the resistance values obtained from the known reference/standard value (R_0) and the resistance of the sensor at different CO concentrations (R_1) present in the air, a ratio is calculated. Based on the ratio values (R_1/R_0), the CO concentration in ppm can be calculated using the sensitivity characteristics of the MQ-7 sensor [24].

Another identified limitation in the proposed system is the physiological variables which are needed as input upon launching the smartphone app. The physiological variables in the form of endogenous production of CO, blood volume and pulmonary diffusing capacity, which are needed for the CFK model inside the smartphone app, are difficult to measure every time the miner uses the system.

After an extensive literature search, possible models have been found that can help to improve the accuracy of these input data. The proposed models are based on user gender, age, weight and height to determine the mentioned physiological variables. A study conducted by Coburn et al. (1963) [25] showed an increase in the endogenous production of CO with age in healthy males, and also in the same study, the relationship between endogenous production of CO and weight was found to be non-significant. Their best estimate for the endogenous production of CO is given by:

$$V = 0.0028a + 0.3351\ (males) \tag{5}$$

where

V - endogenous production of CO in mL/h

a - age in years

Gibson and Evans (1937) [26] conducted a study in 90 healthy adults aged 16 to 89 years, looking at the relationship between gender, body mass, height and age on blood volume. Based on their research, blood volume can be estimated as:

$$V_b = 61.8m + 1074\ (males) \tag{6}$$

$$V_b = 27.3m + 2293\ (females) \tag{7}$$

where

V_b - blood volume in ml

m - body mass in kg

A study by Ogilvie et al. (1956) [27] shows the relationship between pulmonary diffusing capacity and body mass and their best estimate is:

$$D = 0.39m + 1.22\ (males) \tag{8}$$

$$D = 0.24m + 8.08\ (males) \tag{9}$$

where

D - pulmonary diffusing capacity in (min mmHg)$^{-1}$

m - body mass in kg

Before deciding to implement these models inside the processing layer of the proposed system, the models need to be tested and compared against real physiological measurements from the users (mineworkers).

For the implementation of the proposed system inside the harsh mining environment, there is need for a specially designed protective casing for the monitoring layer of the system. The future work for this part will include designing 3D models for the protective casing that will be 3D printed to test their integration inside different parts of the PPE. The identified limitations of the proposed system laid foundations for future work and testing. Possible improvements in the proposed system will increase with certainty the accuracy of the system and therefore its primary goal of informing the user about the on-time installation of SCSR in case of fire in an underground mine.

6 CONCLUSION

In this research paper we introduced an initial effort to develop a safety system, which in case of underground mine fire, will predict the concentration of COHb (%) in human blood and use this information as an indicator to alert the user about the on-time installation of SCSR.

The proposed system is based on Arduino, sensor board and smartphone with a specially developed app to integrate the underground mine environment in case of a fire scenario with the prediction of the COHb (%) levels in human blood as a result of the inhaled CO. The monitoring layer of the system is designed to be easily integrated as part of the PPE and to continuously measure the CO exposure of the user in case of a fire scenario or other related emergency situations. The system architecture uses this CO exposure data as an input to the processing layer which in its core is a user friendly smartphone app based on the CFK model.

To test the idea behind the proposed system, a number of scenarios were created and the system was tested under a hypothetical simulated fire scenario and a real scaled-down fire model. These tests showed that the proposed system is robust and also located parts for which improvements are possible. The system was able to continuously monitor CO, and at the same time to effectively communicate and send the collected data to the smartphone app for its processing. The system provides the user with information about the real time CO exposure and the predicted COHb (%) levels. Thus, the mineworkers using the proposed system not only get the concentration of the CO present in air, but also the health hazards associated with the predicted COHb (%) levels.

Overall, the proposed system not only monitors, but also activates an alarm message on the smartphone when the COHb (%) levels are abnormal, which is an indicator for the on-time installation of SCSR. The idea behind this system is to act as the last safety barrier, which means there is no optimal time to install SCSR because of the many variables that exist in the event of a fire. The user may decide to instantly install the SCSR when senses or sees visual fire indicators, but in case of panic and confusion when the rational action process is significantly reduced as stated in the Sago mine explosion report, the proposed system may be crucial for safe evacuation.

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