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Study and Analysis of Human Survival Parameters in Mine Refuge Station

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Abstract: In order to study life support key techniques in mine refuge station, test the clinical emergency response of participants and human survival parameters in rescue state. A manned test with 50 miners for 48h in a real underground refuge station was conducted in Guilaizhuang gold mine. The experiment simulated rescue living environment of human and consisted of three stages (the passive stage, the compressed air supplying stage, and the compressed O_2 supplying stage). By monitoring environmental concentrations of O_2, CO_2, temperature, relative humidity， and human activity states during the test, the O_2 consumption, CO_2 production and respiration quotient was obtained and analysed in different activities, time quantum and O_2 concentration. On the basis, the minimum air supply volumes for the survival of test personnel were determined. That is 0.067m^3/min per person and is far lower than the national standard（0.3m^3/min per person）. During the test, no people experienced discomfort by health check and questionnaire. It is expected that the conclusions provide an important reference for the design of underground refuge stations and mine emergency rescue.

Keywords: Emergency rescue, mine, refuge station, respiratory quotient, survival parameters.

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1. INTRODUCTION

Refuge station provides a safe and secure living environment for miners who cannot evacuate in time after the accident. Ounanian shows that the mine emergency facilities can make the casualty rate reduce by 29%. The rescue of 33 Chilean miners trapped 700 m underground during 69 days has been considered the most successful case [1-2]. It is fatal important to control internal environment parameters for protecting health and safety of trapped miners [3-6]. In order to maintain the basic living conditions of the human in the chamber, and determine human survival parameters under the rescue state, both home and abroad have made corresponding study, for example, Li J. tested the O_2 consumption and CO_2 production of human under the different labor intensity states in the small-sized refuge chamber [7]; Brake and Venter confirmed that the air supply volumes is related to the CO_2 concentration in confined spaces, and the average CO_2 production was around 0.44 L/min per person during the 24 h test; Michael found that the effects of hypoxia and higher CO_2 concentration are larger than temperature and humidity on healthy [8-12]. In addition, domestic and international standards for confined space human survival indicators were proposed requirements [13-18].

Study of human survival parameters based on large space and long-time rescue in the underground mine is less, in order to determine the rescue time and life support control parameters, a 48-hour manned test with 50 miners was conducted in a refuge station under Guilaizhuang mine, located in Shandong Province, All trial subjects received health checks in forms of blood pressure, heart rate measurement and questionnaire investigation before, during, and after the test, to make sure every miner safety and healthy. And no subject experienced discomfort throughout the experiment. By monitoring environmental concentrations of O_2, CO_2, temperature, relative humidity，and human activity states inside the mine refuge station during the test. The influence rules of factors (including human activity states, time quantum, oxygen concentration, air supply volume etc.) on human survival parameters in emergency state were obtained and analysed. It is expected that the conclusions provide an important reference for the design of underground refuge stations and mine emergency rescue

2. TEST

2.1. Test Conditions

The refuge station is located the -150 level of Guilaizhuang mine. The chamber provides services for 50 people, its main functions consist of protecting mine floods, fires, poisoning and suffocation, it also can provide the living space for trapped miners and guarantee the safety. According to the different functions of the chamber`s area, it is divided into the transition zone and living zone. The transition zone can barrier of poisonous and harmful gas, hedge personnel metabolism and storage equipment; and the living zone equipped with oxygen supply, air purification, temperature and humidity control, communications and monitoring and other life-support systems protect trapped miners over 96 h.

The roadway of refuge station is 1/4 three heart arch , the width is 4.5 m, height is 3.5 m, length is 18 m, the net volume of about 250 m^3 of living zone. During the test, two people are in charge of operations equipment and data recording on both sides of the transition zone, 46 people stay the living zone. The test site and equipment layout are shown in Fig. (**1**).

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Fig. (1). Test site and equipment layout diagram.
A-Transition zone; B-Living zone; C-Roadway; 1-Waterproof closed doors; 2-closed door; 3-Multi-Drive mode air purifier; 4-Ice storage air-conditioning; 5-SWP-ASR209 Paperless Recorder; 6-CD7Mining multi-parameter sensor; 7-Communications equipment; 8-Webcam; 9-Outlet; 10-O_2 control cabinet; 11-Seat; 12-Diffuser; 13-Air pressure control cabinet; 14-O_2 bottles; 15-Battery (b) Test equipment layout

2.2. Test Method

2.2.1. Test Process

The time of manned test is 48 h, it divided into passive stage by the function of refuge`s design and protection, compressed air supplying stage, and compressed oxygen supplying stage. The aim of test is to test the clinical emergency response of participants and human survival parameters in rescue state, validate the design and test internal equipment operation of chamber. The chamber is closed during the test. Test procedures and content are shown in Table **1**.

2.2.2. Test facility

The internal equipment of refuge station mainly includes: Multi-Drive mode air purifier, ice storage air-conditioning, monitoring systems, communication system, and others. The environmental monitoring system is CD7 type mining multi-parameter sensor, it can monitor the environmental parameters (including CO, CO_2, CH_4, O_2, H_2S, temperature, and relative humidity) of chamber real time, and collect data uploaded to the dispatching center through the SWP-ASR209 paperless recorder. During the passive stage inside the devices of chamber rely on a battery which provides 24V DC power supply, to ensure the normal operation of equipment.

3. RESULTS AND DISCUSSION

3.1. Impact of Human Activity State

During the 48 hours test period, the statistics of participants' activity states are obtained. The state was divided into the following three levels: for example, sleep and sitting quietly were divided into the rest state; readings and watching TV were divided into the calm state, playing cards, talking, and walking were divided into the active state.

By monitoring internal environmental variables of the chamber during the test (Fig. (**2**)), the average O_2 consumption rate, CO_2 production rate, and respiratory quotient under the different activity states were obtained (see Table **2**). It shows a linear relationship between time and O_2 consumption and CO_2 production in confined space, with the testing personnel active increased, the oxygen consumption rate and CO_2 production rate also increase, The above calculated values are close to the results mentioned in Li J. [9] test, in which the test was carried out in small-sized refuge chamber (volume of about 8 m^3). This indicates that the O_2 consumption rate and CO_2 production rate is directly related to the active state, the size of the refuge station space or number of refugees has little effect on the respiratory parameters.

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Table 1. Experiment process.

Number	Test stage	Time quantum	Time	Content	Purpose
1	Passive stage	Daytime: 9:00-13:30 Nighttime: 2:30-6:00	8 h	Close the life support system of chamber including compressed air supplying, compressed O_2 supplying, air purification, temperature and humidity control system.	Test the response of rescue personnel under the emergency state and human survival parameters in the passive state
2	Compressed air supplying stage	13:30-2:30(next day) 6:00-12:00	19 h	Close temperature and humidity control, air purification system, regulate five kinds of air supply volumes, including 900, 600, 300, 200, 150 m^3/h.	Test environment parameters of chamber under different air supply volumes, and determine the minimum volume
3	Compressed O_2 supplying stage	12:00-9:00(next day)	21 h	Close compressed air supplying, turn Compressed O_2 supplying, open air purification, and temperature and humidity control system.	Test internal equipment operation of chamber and the impact of O_2 concentration on the parameters of human survival

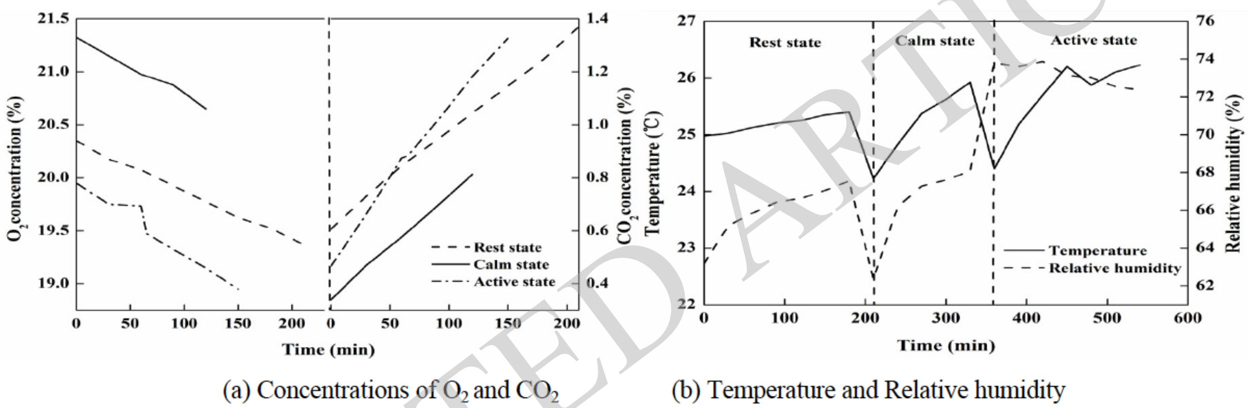

Fig. (2). Environmental parameters of refuge station under different activity state.

Table 2. Activity of test personnel in passive stage.

Activity state	Time/ min	Changes of O_2/%	O_2 consumption rate/ L/min per person	Changes of CO_2/%	CO_2 production rate/ L/min per person	Respiratory quotient
Rest state	210	20.4-19.4	0.258	0.61-1.37	0.197	0.764
Calm state	120	21.4-20.7	0.317	0.34-0.81	0.213	0.672
Active state	150	20.0-19.0	0.362	0.47-1.33	0.312	0.862

The temperature and relative humidity of chamber increase with the intensifying of activity state in the test. Compared to the humidity, temperature increases greatly, because of the heat exchange exists between rock and the chamber, so temperature and humidity are not properly described about human parameters.

3.2. Impact of Time Quantum

Fig. (**3**). depicts that the environmental variable concentrations of O_2, CO_2, temperature, and relative humidity during the passive stage inside the living zone of refuge station, It can be seen that, the concentrations of O_2 and CO_2 in the daytime and nighttime respectively decline and rise as a linear trend, by the straight slope, we can find that the O_2 consumption rate and CO_2 production rate during the daytime is higher than the results at night. In addition, O_2 concentration of the refuge station has reduced to 18.5% (the lowest level of national requirements) at the 270th minutes. It shows that the limit survival time of 50 people under the emergency state come up to 4.5 h, while CO_2 concentration rose to 1.0% at just 128th minutes. According to research, CO_2 can stimulate breathing, and if CO_2 and CO exists in the space, CO_2 will cause more serious joint damage than the single gas [19]. Therefore, according to the relevant provisions, which are "the concentration of CO_2 in emergency facilities is not greater than 1%", to ensure the safety of rescue people in the shelter, the main factors of the trapped miners' survival and emergency response of equipment are environmental concentrations of CO_2 in no thermal harm space.

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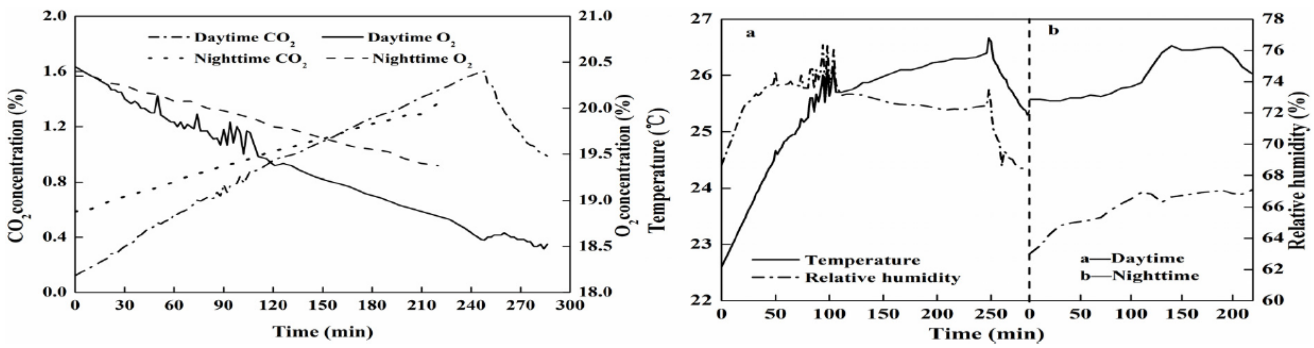

(a) Concentrations of O_2 and CO_2 (b) Temperature and Relative humidity

Fig. (3). Environmental parameters inside the living zone in passive stage.

Table 3. Respiratory parameters of human in passive stage.

Test stage	Time quantum	Changes of O_2 /%	O_2 consumption rate/ L/min per person	Time quantum	Changes of CO_2 /%	CO_2 production rate/ L/min per person	Respiratory quotient
Day-time	9:00-13:30	20.3-18.5	0.362	9:00-12:50	0.25-1.60	0.319	0.88
Night-time	2:20-6:00	20.4-19.4	0.247	2:20-6:00	0.58-1.40	0.203	0.82

Comparing the curve of temperature and relative humidity in the daytime and nighttime, the change trends indicate that the two parameters rose firstly and then stabilized, then temperature increasing was limited, environmental humidity in the daytime are higher than the results at night. Open purifier to control CO_2 concentration at the 246th minutes (12:50), as the duct of temperature control system was connected with air purification system, therefore, the temperature and relative humidity also drop. During the test process temperature and humidity of chamber eventually stabilizes. The main reason is that the temperature of surrounding roadway rock of refuge station is relatively low, it measured as around 20 ℃, during the test rock absorbed part of the heat.

According to the changes of O_2 and CO_2 concentration inside the living zone of refuge station, the average O_2 consumption rate, CO_2 production rate, and respiratory quotient in the daytime and at night were calculated. The results are shown in Table **3**. In the daytime, O_2 consumption rate, CO_2 production rate, and respiratory quotient were higher than the results at night. The reason is that most participants feel asleep at night. The biological clock has effect on respiratory metabolism parameters of human.

3.3. Impact of O_2 Concentration

3.3.1. Influence on Human Activity State

Select respectively two stages of compressed oxygen and compressed air stage, and compare the statistical data on human active number during the test Fig. (**4**), it can be seen that in the compressed O_2 supplying stage, with the increasing of the O_2 concentration, the active numbers gradually increase; Comparing two phases of personnel activity statistics at the same time, when the O_2 concentration inside the living zone is higher, the number of active personnel significantly increased, it shows that if O_2 concentration was higher, excitement level and activity states of participants were heightened.

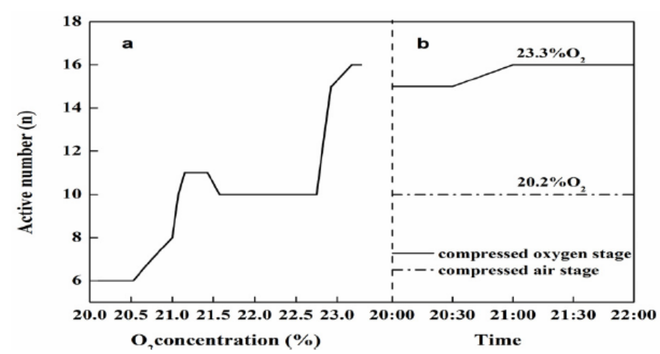

Fig. (4). Effect of O_2 concentration on human activity state.

3.3.2. Influence on Respiratory Parameters

As shown in Fig. (**5**), during the compressed oxygen supplying stage, air purifier was intermittent operation status in the refuge station. Air purifier opened when the CO_2 concentration raise to 1.0%, air purifier closes when CO_2 concentration reduce to 0.3%. Selecting environmental concentrations of CO_2 and O_2 under the purifier closed state. Analyze and calculate the oxygen consumption and CO_2 production under different O_2 concentrations, the results are shown in Table **4** Comparing test 1 and test 2 of Table **4**, With the increasing of O_2 concentration, average O_2 consumption rate and CO_2 production rate increase, the variation is the largest when O_2 concentration were close to oxygen enrichment, and leading to accelerating consumption of materials reserved in the

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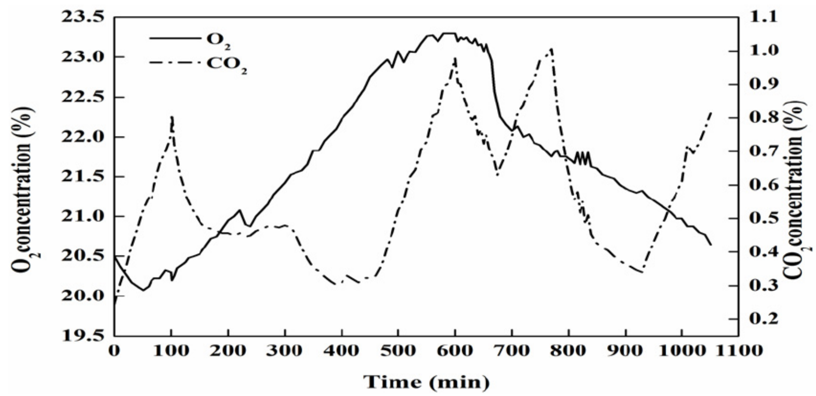

Fig. (5). Environmental parameters in compressed O2 stage.

Table 4. Influence of O_2 concentration on the human respiratory parameters.

Number	Time quantum	O_2/ %	O_2 supplying rate /L/min	Changes of O_2/ %	O_2 consumption rate/ L/min per person	Changes of CO_2 /%	CO_2 production rate/ L/min per person	Respiratory quotient
1	12:50-13:40	20.2	25	20.1-20.3	0.326	0.53-0.75	0.239	0.73
2	20:00-22:00	23.3	27.3	22.9-23.3	0.412	0.42-0.98	0.254	0.62
3	23:20-00:50	21.9	0	22.3-21.8	0.302	0.65-1.01	0.217	0.72
4	03:30-05:30	20.9	0	21.3-20.7	0.272	0.34-0.81	0.213	0.78

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refuge facilities. In the test 3 and test 4, the numbers of sleep state are increasing with time, oxygen consumption rate and CO_2 production rate are reducing, and when the concentration of O_2 is 20.9%, oxygen consumption rate and the discharge of CO_2 are the lowest. Therefore, in order to avoid personnel excitement, lead to increase O_2 consumption, CO_2 production, and rapid consumption of rescue materials in emergency environment, the concentration of O_2 in the refuge station should be controlled at about 20.9%. This conclusion is consistent with standard of Canadian [20] about refuge station and makes the national standard become more specific.

3.4. Impact of Air Supply Volume

According to the theoretical calculation, considering four aspects on the dilution of CO_2, balance of O_2, and reduction of the temperature and humidity [21-22], that the required pressure air volume for per person is $Q_{O2}<Q_{RH}<Q_{CO2}<Q_T$, Therefore, the CO_2 removal is the first task in the no thermal harm refuge station. By the CO_2 dilution equation, the compressed air volume for per person is related to time weighted threshold of required CO_2, the equation is as follow:

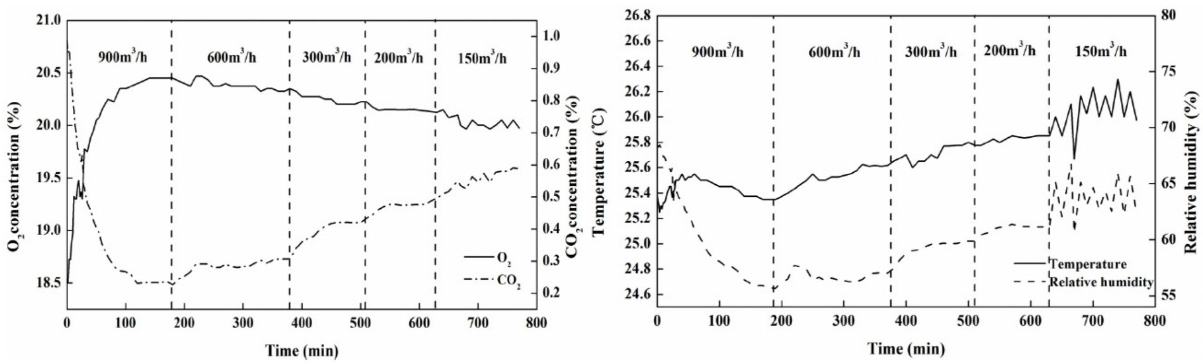
$$Q=\frac{60S_{CO_2}}{1000(y_{CO_2}-x_{CO_2})} \tag{1}$$

In the formula:Q—air supply volume, m^3/h; S_{CO2}—CO_2 production of per person, L/min; x_{CO2}—concentration of CO_2 inlet, %; y_{CO2}— time weighted threshold of CO_2, %.

In accordance with the relevant standards: the compressed air volume for per person is not less than 0.3 m^3/min [23] in the refuge station, by the calculation, the air supply volume required for this shelter is 900 m^3/h. In order to determine the minimum air volume required for human survival under limit rescue environment. The internal environmental variables of refuge station were monitored in different air supply volumes including 900, 600, 300, 200, 150m^3/h.

Fig. (**6**) depicts that the environmental variables of O_2, CO_2, temperature, and relative humidity under the above five kinds of compressed air volumes over time, the figure shows that, with the decreasing of air supply volume, the environmental concentrations of CO_2, temperature, and relative humidity gradually increased, the concentration of O_2 gradually decreased, the various parameters in each stage showed a trend of stability finally. When the compressed air volume is 150m^3/h, the volatility of environment parameters of the refuge station is larger. The main reason is lower compressed air volume and unstable of air pressure. Table **5** shows finally stable environment parameters of the refuge station under the different pressure air volumes state during the test, it is measured that, environmental noise decreased with the decreasing of pressure air volume. When the compressed air volume is 900m^3/h and 600m^3/h, the environmental noise is over 70 dB; the differential pressure between interior and exterior of cavern is decreasing with the decrease of pressure air volume. But it still remains in the range of 100 ~ 500 Pa. Which makes that the emergency facilities has always been a positive pressure requirement of more than 100 Pa.

By calculating CO_2 production of per person under the different pressure air volume based on the test data and formula (**1**), it is measured that, with the reduction of air supply



(a) Concentrations of O_2 and CO_2 (b) Temperature and Relative humidity

Fig. (6). Environmental parameters of refuge station in compressed air stage.

Table 5. Influence of air volumes on environmental parameters.

Air volume/ m^3/h	Time quantum	Environmental stabilization						Respiratory quotient / L/min
		Temperature/℃	Relative humidity /%	Noise /dB	Differential pressure /Pa	O_2/ %	CO_2/ %	
900	13:30-16:30	25.4	55.9	75.7	450	20.5	0.23	0.600
600	16:30-19:50	25.6	57.1	71.7	250	20.3	0.31	0.560
300	19:50-22:00	25.8	59.8	64.5	230	20.2	0.42	0.390
200	22:00-00:00	25.9	61.1	61.2	210	20.1	0.48	0.300
150	00:00-02:20	26.1	63.7	56.9	150	20.0	0.58	0.275

volume, the CO_2 production of per person will lessen. When pressure air volume is 900m^3/h and 600m^3/h, the CO_2 production rate respectively is 0.6L/min and 0.56L/min, which are greatly different from the experimental measured value; the compressed air volume is 150m^3/h and stable concentration of CO_2 is 0.58%, the each environmental parameter of cave floats very large. Therefore, the minimum air supply volume for the refuge is 200m^3/h. That is 0.067m^3/min per person. The environmental parameters of refuge station all meet human survival needs.

CONCLUSION

The main conclusions obtained from the above analysis and researches in this study are as follows:

(1) 50 people in the 250 m^3 space under the emergency state limit survival time is 4.5 h, the CO_2 production rate is faster than O_2 consumption. The main factors of the trapped miners' survival and emergency response of equipment are environmental concentrations of CO_2 in no thermal harm space.

(2) With the testing personnel active increasing, the O_2 consumption rate and CO_2 production rate also increase. The biological clock has effect on respiratory parameters of human, and then the size of the refuge station space or number of refugees has little effect.

(3) When environmental concentration of O_2 (up to 23.3%) was close to oxygen enrichment, the excitement level and activity states of participants were heightened. In order to avoid people excited and control rescue materials, O_2 concentration should be controlled at 20.9% in the refuge station.

(4) The compressed air volume for per person is related to time weighted threshold of CO_2. It is measured that the minimum air supply volume for meeting the survival is 0.067m^3/min per person in the refuge station by the test. It was far lower than the national standard (0.3m^3/min per person). It is expected that the conclusions provide an important reference for the design of underground refuge stations and mine emergency rescue.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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