

The Oxygen Cost of an Escape from an Underground Coal Mine

ELIEZER KAMON , DIANE DOYLE & JOHN KOVAC

To cite this article: ELIEZER KAMON , DIANE DOYLE & JOHN KOVAC (1983) The Oxygen Cost of an Escape from an Underground Coal Mine, American Industrial Hygiene Association Journal, 44:7, 552-555, DOI: [10.1080/15298668391405292](https://doi.org/10.1080/15298668391405292)

To link to this article: <https://doi.org/10.1080/15298668391405292>



Published online: 13 Aug 2012.



Submit your article to this journal [↗](#)



Article views: 11



View related articles [↗](#)



Citing articles: 6 View citing articles [↗](#)

The Oxygen Cost of an Escape from an Underground Coal Mine

ELIEZER KAMON, DIANE DOYLE and JOHN KOVAC

The Noll Human Performance Research Laboratory, The Pennsylvania State University, University Park, PA 16802;
Foster-Miller Associates; Bureau of Mines, U.S. Department of the Interior

Six 27- to 63-year-old coal miners performed an "escape" maneuver from an underground mine along a passageway that required walking and running erect or stooped, duckwalking and crawling. The miners traveled at different speeds, for each mode of locomotion. The minute pulmonary ventilation (\dot{V}_E), O_2 uptake (\dot{V}_{O_2}) and heart rate (HR), recorded continuously on a magnetic tape via lightweight meters carried on the miners' waists, indicated similar average and peak values for all modes of locomotion. The mean \dot{V}_E , \dot{V}_{O_2} ($L \cdot \text{min}^{-1}$, STPD) and HR ($\text{b} \cdot \text{min}^{-1}$) were, respectively, 49, 1.63 and 143 for the average values, and 52, 1.92 and 161 for the peak values. Compared to the aerobic capacity obtained during graded treadmill test to exhaustion, the average effort of the "escape" was performed at 64% and the peak effort at 70% of the miners aerobic capacity for an "escape" time of 58 minutes.

Introduction

Information on the oxygen requirement and the cardiac strain of various occupational activities is of practical importance to physiologists, industrial hygienists, engineers and physicians who are concerned, respectively, with fitness for work, safety, productivity and health of workers. Consequently, systematic measurements of O_2 uptake and of heart rate have been conducted for most common activities of humans at work.^(1,2) Uncommon human physical activities which are performed under emergency situations, such as escape from disaster and firefighting, have been less investigated.⁽³⁾ One important emergency activity which was not studied in terms of the physiological responses is the escape from an underground mine following an explosion. Such an escape is a physically demanding muscular activity and, depending on the terrain and roof conditions, may involve running, stoop walking and crawling. Also, since explosion results in contamination of the ambient air with toxic gases, escaping miners must use self-contained respirators which

are expected to supply the oxygen needed for the escape. The O_2 demand and cardiac strain during an escape are of interest to the physiologist and clinician. However, the information on the O_2 cost of an escape could be useful to those involved with the certification of (it could also be applied to the design of) adequate self-contained respirators. This report is a summary of a field study undertaken to measure the O_2 cost and heart rate during an escape maneuver from an underground mine.

Methods

Miners

Six miners volunteered for the study. Their ages, years of underground experience, and physical characteristics are shown in Table I. They were mostly foremen who, after giving their consent, were given a physical examination and a graded stress test (treadmill) to exhaustion, while cardio-

TABLE I
Age, Physical Characteristics, Maximal Heart Rates (HR beats/min), O_2 Uptake (\dot{V}_{O_2}), and Pulmonary Ventilation (\dot{V}_E) for Each Miner

Miner	Age (yr)	Underground Experience (yr)	Ht. (cm)	Wt. (kg)	HR (bpm)	Maximal		
						\dot{V}_{O_2} (L/m)	\dot{V}_{O_2} (mL/kg·min)	\dot{V}_E (L/m)
1	61	41	185	71.2	156	1.60	22.5	33
2	54	35	160	77.6	155	2.39	80.8	64
3	49	6	166	78.0	168	2.87	36.8	54
4	49	10	172	80.7	200	2.70 ^A	33.5 ^A	---
5	34	10	166	81.3	200	3.17	38.9	97
6	24	6	183	82.9	182	3.48	42.0	86
X	45.2		172	78.6	176.8	2.47	34.1	62.3
S.D.	13.6		10	4.1	20.4	0.88	10.2	25.5

^AEstimated by extrapolation to the HRmax from the \dot{V}_{O_2} -HR relationship during the escape.

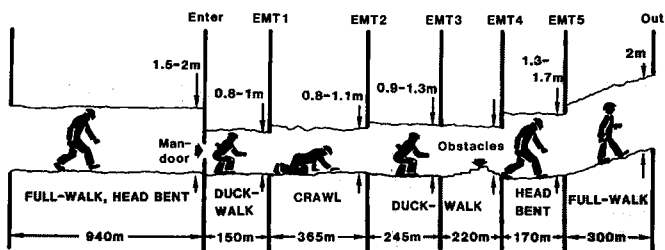


Figure 1 — Schematic of the "escape" route indicating the distance and roof height for each section between the Emergency Medical Technicians (EMT).

grams were taken and expired gas was collected to derive their maximal heart rate (HR_{max}), ventilation (\dot{V}_E _{max}) and aerobic capacity (\dot{V}_{O_2} _{max}). Because of technical problems, no gas collection was obtained for miner #4. His \dot{V}_{O_2} _{max} was estimated by extrapolation of O₂ uptake and heart rate during the escape maneuver (Table I).

The Escape Route

The escape route was inside an underground coal mine in western Pennsylvania. The distance was chosen for an estimated escape time of one hour. The mine was selected because the route included sections of different terrain and roof heights enforcing the following modes of locomotion: walking and/or running erect or with the head bent, and crawling and duckwalking. A schematic of the route including its roof heights and the length of each section is shown in Fig. 1. The first section included 940 m of smooth ground alongside the entry tracks and a roof height of 1.5 m, up to 2 m in some parts, allowing mostly head-bent, but some erect walking (or jogging). From this relatively comfortable section, the miners entered, through a one-meter high door (man door, Fig. 1), a passageway with a roof height of 0.8 to 1.1 m. For 150 m of this section, from the man door to the first emergency medical technician (EMT-1, see below), the floor was covered with slate from roof falls, making duckwalking the best mode of locomotion. The next 365 m to EMT-2 had a smoother ground surface, allowing crawling. The section between EMT-2 and EMT-3 included 245 m of roof height of 0.9 to 1.3 m, allowing duckwalking. This was followed by a similar section with two obstacles of water

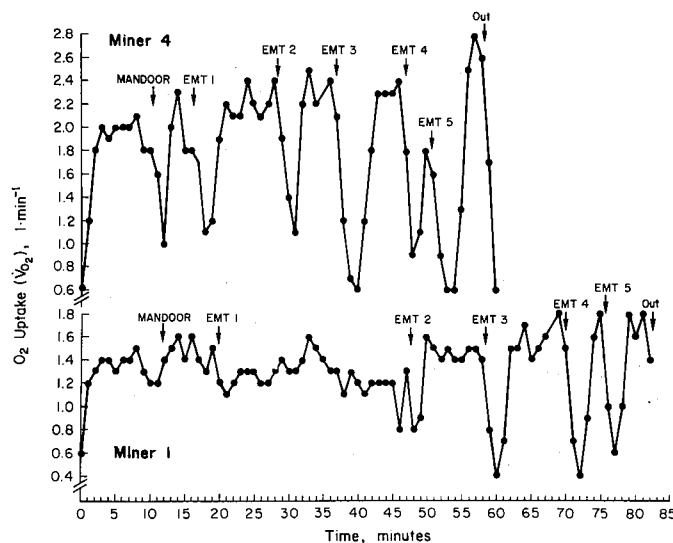


Figure 2 — The time course of O₂ uptake for two miners during the "escape" with brief stops at each Emergency Medical Technician (EMT).

puddles. It was 220 m long and the miners preferred to mix the duckwalking with crawling. The following short section to EMT-5 included a distance of 170 m of smooth terrain and a roof height of 1.3 to 1.7 m, allowing head-bent or erect walking. Finally, the last 300 m of the passageway out was at a 9% grade with a smooth ground surface alongside the entry tracks, and a high roof (2 m or more), permitting full upright walking or running. Since the section to EMT-5 was very short and the responses to the head-bent walking did not differ from that of the last section (out), the data for the two were combined.

Measurements

Pulmonary ventilation and O₂ uptake were measured using an Oxylog (P.K. Morgan Ltd.)^A unit encased in a 20 × 18 × 18 cm box, weighing 3 kg, and made to be hung from the shoulder and belt fastened to the waist. A face mask, cover-

^AReference to specific products does not imply endorsement by the Bureau of Mines.

TABLE II
Mean and Standard Deviation of the Pulmonary Ventilation (\dot{V}_E),
O₂ Uptake (\dot{V}_{O_2}) and Heart Rates (HR) for Each Section of the Escape

Section Reaching:	Average Values			Peak Values		
	\dot{V}_E (L·min ⁻¹) n=5	\dot{V}_{O_2} (L·min ⁻¹) n=5	HR (b·min ⁻¹) n=6	\dot{V}_E (L·min ⁻¹) n=4	\dot{V}_{O_2} (L·min ⁻¹) n=5	HR (b·min ⁻¹) n=6
--Man door	38±10	1.63±0.17	148±16	43±12	1.90±0.42	159±13
--EMT-1	44±12	1.52±0.26	128±13	48±11	1.80±0.36	153±12
--EMT-2	42±11	1.53±0.44	144±17	50±12	1.86±0.40	162±13
--EMT-3	46±14	1.72±0.43	152±18	52±13	2.01±0.48	167±14
--EMT-4	51±13	1.65±0.41	145±15	56±13	1.94±0.41	164±17
--Out	53±14	1.70±0.42	143±14	53±15	2.00±0.54	158±13
Whole route	49±13	1.63±0.36	143±12	52±13	1.92±0.44	161±14

TABLE III
Mode of Locomotion by Section, Speed of Travel, Mean of the Average and the Peak Values of % \dot{V}_{O_2} max and % HRmax

Mode of Locomotion	Sections	Speed (m·min ⁻¹)	Average Values		Peak Values	
			\dot{V}_{O_2} (% \dot{V}_{O_2} max)	HR (%HRmax)	\dot{V}_{O_2} (% \dot{V}_{O_2} max)	HR (%HRmax)
Walk-run	to Man door EMT4-Out	63±10	67± 7	82±7	78±12	90±8
Duckwalk	Man door to EMT 1 EMT2-EMT3	32±10	64± 8	80±5	76±11	91±5
Crawl	EMT1-EMT2	24±10	61±11	84±6	74±10	92±8
Crawl and duckwalk	EMT3 to EMT4	27±12	66± 9	83±4	77± 9	93±6
Mean for escape		41± 9	64± 9	82±5	76± 4	91±3

ing the nose and mouth, with a two-way valve was connected to the Oxylog meter for recording of the ventilatory rate and for sampling expired gas for the measurement of O₂ concentration.

The heart rate (HR) was measured using chest electrodes and an amplifier which was also attached to the waist belt (Respironics Inc.).

The output of the pulmonary ventilation, the derived O₂ uptake and the heart beats from the meters were recorded on a miniature magnetic tape recorder (Medilog, Oxford Medical) which was attached to the waist belt. The recorded data were then digitized, using a replay unit, which was connected to a computer (PDP-8) programmed to derive minute-by-minute volume of ventilation (\dot{V}_E), O₂ uptake (\dot{V}_{O_2}) and HR. The Oxylog included a display of minute or total \dot{V}_E and \dot{V}_{O_2} . The display was taken by the technician stationed at each EMT (Fig. 1) for double checking the data (see below).

Procedures

Each miner traveled the escape route once daily for four days. The first day was used for familiarization with the route. The next three days were used for escape: 1) without donning any equipment, 2) with breathing through the Oxylog, and 3) with use of a self-contained breathing apparatus (respirator). Since we used two Oxylog units and two respirators each day, the use of each was randomized between the six miners. The data for this paper were only those of the days when the Oxylogs were used.

Upon arrival to the mine's office at 8 a.m., the miners prepared for the escape maneuver by placing the chest electrodes and fitting the Oxylog, their coveralls, and mine gear, which included a hardhat with a cap lamp, and a cord connected to a 3 kg battery attached to the waist belt. They then rested sitting for 30 min. The preparation and resting lasted 60 to 90 min.

Entry to the escape starting point was done by walking along the smooth ground of the entry tracks. The entry lasted 27 min after which the miners waited their turn to "escape," either sitting or standing leaning against the wall. Each miner performed the "escape" by himself with a 15-min interval between miners.

The escape started along the entry track (940 m of the first section to the man door, Fig. 1). Thereafter started the low passage of the escape route. Emergency medical technicians (EMT, Fig. 1) were stationed at the end of each section. They stopped the miners for 2 to 3 min to measure blood pressure, read the displays of \dot{V}_E , \dot{V}_{O_2} and HR, and record the subjective evaluation of the miners' well-being. The miners were asked to perform the escape maneuver as rapidly as they possibly could.

Results

The minute-by-minute time course of the \dot{V}_{O_2} is shown in Fig. 2 for two miners. It can be seen that: 1) the \dot{V}_{O_2} cycled between a relatively steady state and one or two peak values for each section between the EMT stations, and 2) there was an obvious drop in \dot{V}_{O_2} during the stop at each EMT station. These responses were also seen for the \dot{V}_E and the HR. Therefore, the escape data were summarized for the "escape"

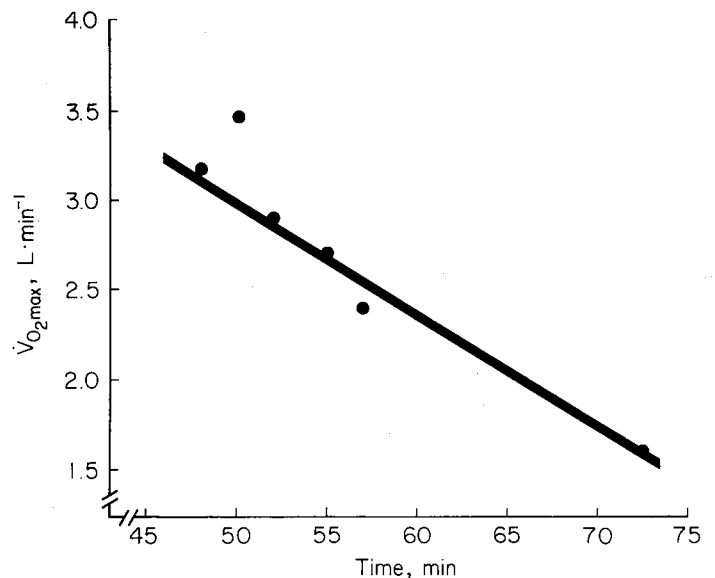


Figure 3 — The relationship between the "escape" time and the maximal aerobic capacity (\dot{V}_{O_2} max) for the six miners.

only, excluding the resting periods at each EMT. The analysis was done in terms of the average value and the peak value for each section. The means for all the available data on the miners are given in Table II. Because of technical difficulties, the \dot{V}_E was not recorded on the magnetic tape for miner #4, but the average values could be derived from the display on the Oxylog, and no gas analysis was available for miner #6. Consequently, the mean \dot{V}_{O_2} and \dot{V}_E values are for five miners and the peak \dot{V}_E is for four miners only.

The speed of travel was similar for the sections in which the same mode of locomotion was used. The average \dot{V}_{O_2} and HR per section and the laboratory-measured \dot{V}_{O_2max} and HRmax (Table I) provided for the evaluation of the relative demand with respect to the mode of locomotion. The mean travel speed, % \dot{V}_{O_2max} and % HRmax are given in Table III for all the miners. For all practical purposes, the absolute, as well as the relative, demand was the same throughout the escape route (Tables II and III).

Discussion

Judged by the miners' subjective evaluation and considering the competitive spirit that developed between the miners, they indeed made their best effort to travel the escape route as fast as possible. Yet, the peak \dot{V}_{O_2} and HR did not, at any time, reach the maximal values obtained in the laboratory (Table I). This could be attributed to external and internal factors. Three external factors could be identified: 1) the darkness, 2) the terrain and roof conditions, and 3) the mode of locomotion. The two internal factors were most likely: 1) the limits of muscle involvement due to the mode of locomotion and, 2) fatigue because of the restricted locomotion. The underground darkness limited the miner's vision to the distance covered by his cap light. Roof falls, over time, covered the ground with debris and exposed the bolts and plates of the roof supporting system. These hazardous extensions from the roof, and the floor conditions, restricted the travel speed and prevented the miners' \dot{V}_{O_2} from reaching a peak of more than about 76% \dot{V}_{O_2max} . Finally, the muscular involvement in crawling and duckwalking could not provide the full dynamic action needed to develop maximal cardiovascular responses. The limited muscle action resulted in local fatigue. However, in the last section, the room was high, the terrain was smooth, and vision was adequate because light penetrated from the surface opening. Yet, the peak \dot{V}_{O_2} for this section was also below the \dot{V}_{O_2max} , even though the miners could run at their best. This could be attributed to the development of fatigue during the period of restricted locomotion. Crawling and duckwalking did tax the leg muscles to their capacity, although without full taxation of the cardiovascular system. Therefore, later, when enhanced cardiovascular involvement was possible, the leg muscles became the limiting factor.

Fatigue could be a determining factor in the escape only if the average \dot{V}_{O_2} was close to the limit of endurance. Indeed, peak \dot{V}_{O_2} and HR below the maximal values did not mean that the average \dot{V}_{O_2} was below its limit. Judged by the appearance and expression of their feeling, the miners were fatigued at the end of the "escape." Unfortunately, no systematic study of state of fatigue could be conducted. However, fatigue due to prolonged muscular work at submaximal level can be judged objectively by evaluating the individual as well as the group performance.

Individual "escape" time was expected to be \dot{V}_{O_2max} dependent. As can be seen in Fig. 3, there was a linear inverse relationship between the "escape" time and the individual \dot{V}_{O_2max} . In general, there is a power inverse relationship between endurance and the % \dot{V}_{O_2max} at which muscular work is performed, such that for untrained persons, 60 min can be endured at 50 to 60% \dot{V}_{O_2max} .⁽⁴⁾ An attempt to quantify the relationship between \dot{V}_{O_2} as a fraction of \dot{V}_{O_2max} and endurance in minutes (t) led Bink⁽⁵⁾ and Bonjer⁽⁶⁾ to suggest the formula: % \dot{V}_{O_2max} = [(log 5700 - log 5)/3.1] · 100.

The mean travel time of the six miners was 58 min. Using this value as -t in the above formula yielded an effort of 65% \dot{V}_{O_2max} , which is in perfect agreement with the actual value obtained for the "escape" (Table 3). However, endurance as a function of % \dot{V}_{O_2max} is higher for trained than for untrained persons.⁽⁴⁾ For example, a group of marathon runners performed the 42.2 km run at 65 to 76% \dot{V}_{O_2max} for a mean time of 2.5 hours.⁽⁷⁾ Thus, to improve their capacity for escape, miners should be encouraged to train for better physical fitness.

Acknowledgement

This study was supported by Bureau of Mines contracts No. J0199110 and No. J0100092. We wish to thank the Rochester and Pittsburgh Coal Company for providing the mine and personnel, without which this study could not have been accomplished.

References

1. Åstrand, I., P. Fugelli, C.G. Karlsson, K. Rodahl and Z. Vokac: Energy Output and Work Stress in Coastal Fishing. *Scand. J. Clin. Lab. Invest.* 31:105-113 (1973).
2. Durnin, J.V.G.A. and R. Passmore: *Energy, Work and Leisure*. Heineman, London (1967).
3. Barnard, R.J. and H.W. Duncan: Heart Rate and ECG Responses of Fire Fighters. *J. Occup. Med.* 17:247-250 (1975).
4. Åstrand, P.-O. and K. Rodahl: *Textbook of Work Physiology*, p. 292. McGraw-Hill, New York, NY (1970).
5. Bink, B.: The Physical Working Capacity in Relation to Working Time and Age. *Ergonomics* 5:25-28 (1962).
6. Borjer, F.H.: Temporal Factors and Physiological Load. In *Measurement of Man at Work*, W.T. Singleton, J.G. Fox and D. Whitfield, eds., pp. 41-44. Taylor and Francis Ltd., London (1971).
7. Costill, D.L. and E.L. Fox: Energetics of Marathon Running. *Med. and Science in Sports* 1:81-86 (1969).

18 October 1982; Revised 18 March 1983