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Training Studies with Compressed Air Breathing Apparatus – Methodology, Exercises

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Abstract **– The current article describes topics ranging from the respiratory physiology and the structure of compressed air breathing apparatus to the performance of practical training exercises in an unbreathable environment (hereinafter referred to as UE).**

The State Fire and Rescue Service (hereinafter referred to as SFRS) also carries out regular training studies in the UE, but these studies lack the methodology.

The research results could be used as a basis for the implementation of theoretical and practical training methods/exercises when training the SFRS officers.

Keywords **– Compressed air breathing apparatus (CABA), respiratory physiology, State Fire and Rescue Service (SFRS), unbreathable environment (UE).**

I. Introduction

The topic of the present research is chosen in relation with the need of the State Fire and Rescue Service to improve the theoretical and practical training in the UE for SFRS officers with special ranks (hereinafter referred to as the officers). This need is justifiable by the fact that the SFRS also carries out regular training studies in the UE, but these studies lack the methodology. Studies for personnel involved have no uniform and clear criteria to be tested during the studies. There are also no clearly defined methods of conducting the studies, or standards grouped or numbered in a certain order, as it is with the fire drill training.

The present research sets out themes ranging from respiratory physiology and the structure of compressed air breathing apparatus (CABA), which are to be used for the theoretical training, to the performance of practical training exercises in the UE, which in turn shall be applicable in practice.

It is essential to ensure the competence level of those firefighters who are assigned to use the respiratory equipment. This competence must be associated with the strictest procedures of equipment inspection, testing and maintenance. If the highest standards are not met and maintained through regular training, then not only the equipment can become ineffective and seriously threatening its users, but also a firefighter without regular enough practical training in a critical situation may turn out to be insufficiently competent to take the emergency response measures.

II. Breathing Physiology

A. Respiratory System

The respiratory system consists of:
- Mouth,
- Nose,
- Trachea,
- Lungs,
- Pulmonary alveoli.

The respiration ensures the breathing and the gas exchange (oxygen, carbon dioxide) in the lungs and body.

A human being breathes in order to deliver oxygen into the lungs and remove therefrom the excessive carbon dioxide. Air inhaled via mouth comes to lungs where it is divided further towards alveoli and capillaries, which convey oxygen further throughout the body. At the same time, carbon dioxide is removed from capillaries and exhaled into the atmosphere [7].

B. Respiratory Process

Breathing is one of the most important features of the human body. During breathing, gas exchange takes place between the body and the environment. During breathing, a person inhales oxygen and exhales carbon dioxide. If breathing disturbances occur, the gas exchange ceases and the body perishes. External respiration and internal respiration are distinguished.

As a result of external respiration, the gas exchange takes place in the human lungs between the outside air and the blood, which "transports" oxygen throughout the body. Internal respiration is the gas exchange taking place between the blood and body tissues.

Oxygen is necessary for a living body to provide the restoration of energy resources, which is ensured by a complicated process of biochemical nutrient conversion. The released energy plays an important role in thermal regulation of the body.

Respiratory cessation for even few minutes can have severe, life-threatening consequences.

Breathing is controlled by brain through autonomic nervous system. This system also helps to control the oxygen and carbon dioxide levels in the blood.

On average, an adult breathes 16 cycles per minute, a child – 20 to 30 cycles per minute. The number of cycles may vary (usually increase) if there are changes in a normal environment, such as stress, disease, injury, exercises, as well as increased oxygen and carbon dioxide levels in the air.

The respiratory cycle consists of the inhalation, pause, and exhalation. All the air is never exhaled from the lungs; therefore, oxygen is always continuously available for the body [7].

C. Air Composition

Air is a mixture of gases:
Nitrogen – 78 %,
Oxygen – 21 %,
Argon – 0.93 %,
Carbon dioxide – 0.04 %.
Expiratory air consists of:
Nitrogen – 78 %,
Oxygen – 17 %,
Argon – 0.93 %,
Carbon dioxide – 4 %.

As seen, oxygen content in the air has reduced along with the increased carbon dioxide content.

The amount of oxygen required by the body may vary depending on the workload. While at rest when only vitally important organs are working, the body only requires a minimum amount of oxygen. If the body becomes active and the volume of performed work is growing, the need for oxygen also increases as well as the amount of carbon dioxide discharged into the air.

Table below presents data from experiment carried out by Prof. J.S. Haldane from Minnesota State Fire Research Institute, showing the oxygen and air consumption amount during different body load periods (see Table I).

In heavier work conditions, such as running or climbing a slope, the amount of oxygen may grow up to 3 litres per minute, while the air consumption may rise up to 100 litres per minute [3].

TABLE I

LOAD DEPENDENCE OF OXYGEN AND AIR CONSUMPTION [3]

Process	Oxygen consumption, litres per minute	Inhaled air, litres per minute	Air volume in each breath, litres	Number of breathing cycles per minute
Lying in bed	0.237	7.7	0.457	16.8
Standing	0.328	10.4	0.612	17.1
Moving at a speed of 2 mph*	0.780	18.6	1.27	14.7
Moving at a speed of 3 mph	1.065	24.8	2.53	16.2
Moving at a speed of 4 mph	1.595	37.3	2.06	18.2
Moving at a speed of 5 mph	2.543	60.9	3.14	19.5

* 1 mile corresponds to 1.6093 km

III. RESPIRATION IN THE UNBREATHABLE ENVIRONMENT

Unbreathable environment is an ambience with reduced oxygen content or with human health and life-threatening biological, chemical, radioactive contamination, as well as with an increased temperature and humidity level.

A. Environment with Reduced Oxygen Content

Such situations may arise in fires, indoor areas, tunnels, underground communications, pipes, enclosed storage basins. Normal functioning of the body requires at least 20 % of oxygen content in the air while any changes in oxygen amount affect the body. The term “asphyxia” is used to denote the disturbed air entry into the lungs. Reduction in oxygen amount in the body is known as hypoxia. Hypoxia takes place if oxygen does not come to the body for more than 3 minutes, when brain cells begin to die. If hypoxia is not quickly eliminated, then the breathing and heart may stop. Most pronounced symptoms are rapid breathing, blue skin, confusion, nervousness, loss of consciousness, death. However, in many cases people do not realise the occurrence of hypoxia.

B. Hazardous Substances

Firefighters often receive calls for response to fires or accidents involving or suspecting the presence of hazardous substances. The hazard of these substances consists in a high toxicity or corrosive effect on the lungs, but there are also the risks of the presence of radioactive substances, which can cause cellular and genetic damage to the body. Exposure to biological agents can result in diseases.

C. Fires

Each year, about 60 % of deaths and 33 % of victims in fires are caused by smoke intoxication. There are three main factors of fires, which can cause damage to the respiratory system:

1) Heat – the human lungs are a relatively sensitive organ and at a temperature of 130 degrees (Celsius) irreversible damage to the lungs may occur. It is important that temperatures unbearable by skin may cause serious damage to the lungs.

2) Smoke particles – these are particles that can be very different in size while being not toxic, but when settling in the lungs they may block the airways and lead to fluid accumulation. They are able to involve the cancer-causing substances.

3) Toxic combustion products – these products arise during combustion. The most common of them are: carbon monoxide, hydrogen cyanide vapours, hydrogen chloride, and many other products of combustion in lower concentrations but also capable of causing a serious damage to the respiratory system and eyes.

Carbon monoxide (CO – white damp) in most cases rapidly increases its concentration in the air, in circumstances when the combustion process becomes short of the air oxygen. Combustion intensity decreases along with rapidly growing carbon monoxide concentration in the combustion area. Carbon monoxide is a highly toxic substance; its presence in the air in even minimum amount creates a high degree of hazard (see Table II).

TABLE II

CO EXPOSURE HAZARD DEPENDENCY ON CONCENTRATION AND EXPOSURE TIME [3]

No.	CO concentration in the air, %	Exposure time	Body response
1.	0.016	more hours	poisoning symptoms
2.	0.048	approx. 1 h	mild poisoning
3.	0.128	0.5–1.0	headache, nausea, buzzing in the ears, feeling of general weakness
4.	0.4	20–30 min.	life-threatening poisoning
5.	1.0	1 min.	loss of consciousness upon few breaths, very strong, even fatal poisoning degree

Nitrogen (N2) – gas slightly lighter than air – constitutes 2/3 of the total air mass, but is inert and under normal conditions does not affect the breathing process. Nitrogen has a feature: with increasing partial pressure, the gas saturates the human blood and tissues, thus, causing the narcotic effect (>5.5 kg/cm^2, dead faint). This phenomenon is known to divers and patients of barometric complexes, it is the direct cause of the caisson disease, most dangerous disease of divers.

Oxygen (O2) – colourless, odourless gas, heavier than air (1.43 kg/m^3), the main substance necessary for the life process. Disturbances or interruption of oxygen supply cause in the body the so-called acute oxygen insufficiency, which leads to the loss of consciousness or death. Combustion in a confined space quickly reduces the amount of oxygen and poses a threat to the human health. Fires in tunnels, subway stations, mines just due to this reason result in a great loss of life.

Carbon dioxide (CO2) – colourless, odourless gas, heavier than air (1.97 kg/m^3). Small presence of carbonic acid in the air stimulates the respiratory centre activity. With increasing gas concentration in the air, the human body responds individually.

TABLE III

CONCENTRATION DEPENDENCE OF CO_2 EFFECT [3]

No.	CO_2 concentration in the air, %	Body response
1.	0.04	no effect
2.	1.0–2.0	respiratory rhythm without changes
3.	4.0–5.0	increased respiratory depth and rhythm. Buzzing in the ears, temporal pulsation
4.	6.0	the same but in a more expressed form
5.	8.0	headache, dizziness, general weakness
6.	10.0	loss of consciousness
7.	20.0	respiratory paralysis, death

Hydrogen sulphide (H2S) – toxic, water-soluble gas, heavier than air (1.539 kg/m^3), with a characteristic smell of rotten eggs. It accumulates in low-lying areas, is flammable, its vapours in the air create an explosive mixture.

A serious threat to the human life, inhalation causes severe mucous membrane inflammation. Substance concentration of 0.08 % in the air leads to death in 5 to 10 minutes.

Hydrogen cyanide vapours (HCN) – a very dangerous substance, even negligible presence in the air at the scene creates a hazard to life. HCN concentration of 0.01 % may lead to loss of life. It is emitted by burning polyurethane foam; therefore, in the household sector it often causes serious poisoning, even at very low concentrations.

Ammonia (NH3) – water-soluble gas, lighter than air (0.597 kg/m^3), with a characteristic odour, vapours in the air create an explosive mixture (4:3). Liquefied ammonia in contact with the human skin causes frostbite (−68°).

Chlorine (Cl2) – substantially heavier than air (3.214 kg/m^3), greenish-yellow gas with a sharp odour. Its perception threshold of 0.003 mg/l means that feeling the presence of chlorine must entail the use of respiratory protective equipment [9].

IV. WORK IN CLOSED PREMISES

It has been proven in tests (Hampshire Fire and Rescue Service BA course) that a firefighter of medium build is able to enter a room through a hole of 25x40 cm, while upon use of the compressed air breathing apparatus the hole size should be increased up to at least 50x40 cm [4]. It means that the firefighter is restricted in movement within especially narrow areas. Therefore, removal of the compressed air breathing apparatus cylinder could be required in the following situations:

- The firefighter is trapped and needs to expect help from the outside;
- If rescue works are to be carried out in tight spaces and equipment is not available to facilitate these works.

In both these situations, removal of the compressed air breathing apparatus allows moving in a narrow space both horizontally and vertically.

The decision on removal of compressed air breathing apparatus shall only be taken by the group commander.

A. Horizontal Movement in Tight Spaces

If a decision is made to take off the compressed air breathing apparatus, then it should be considered whether the breathing apparatus shall be moved in front of or behind its wearer. As much as possible, the breathing apparatus should be moved behind. This method protects the breathing apparatus from damage taking into account that it is the only available means of respiratory protection, as well as it reduces the likelihood that the breathing apparatus may fall out or slip off from the rescuer, thus preventing the hazard for breathing.

B. Vertical Movement in Tight Spaces

This movement is much more dangerous and difficult. Weight of the apparatus interferes with the rescuer and such a movement results in only one free hand remaining to hold at the structures, as well as the space may be so narrow that the breathing apparatus should be held above the head or under the body. During the surveillance process, it is important to investigate whether it is possible to use the guy means, since in this case the entire body weight is supported by legs and the guy, while both hands become free to move the breathing apparatus into a more convenient position. However, if the rescuer has remained trapped as a result of structure collapse, such resources will not be available and the rescuer will need a great physical and spiritual strength to escape.

C. Movement with Removed Connected Compressed Air Breathing Apparatus

Standing:

- Whenever it is possible, the breathing apparatus shall be held at both shoulder straps.

Lying:

- The breathing apparatus shall be gently pulled behind.

D. Safety Aspects

- Members of the group shall help each other every time when going through narrow places;
- When crossing narrow spaces, every time they should try to expand them;
- Each time when putting on/taking off the breathing apparatus, members of the group must watch whether the facemask is securely positioned on the face;
- The breathing apparatus should be put on back as soon as possible prior to continuing the performance of a given task.

V. Search Technique and Fire Fighting in the Unbreathable Environment

Under normal circumstances, a human being uses five senses in the following percental distribution [4]:

- Vision 75 %,
- Hearing 13 %,
- Taction 6 %,
- Smell 3 %,
- Taste 3 %.

When doing work in a smoke-filled environment, the visual factor is substantially reduced; therefore, a rescue firefighter should comply with strict requirements when carrying out work in a smoke-filled environment. Two main requirements are:

- Ensuring firefighter's own safety;
- Searching for victims and fire location.

A rescue firefighter has to balance between his own safety and fulfilment of tasks in order to bypass all risks existing in fire locations. Therefore, the basic safety requirements should be followed:

- The rescuer should slip his feet and not move by normal steps. The body weight should be carried over to the back foot while the front foot examines the surface of movement in order to continue the forward movement. Feet should not be lifted from the ground, the foot should slip forward to find whether there are no weakened or collapsed structures on the way;
- Hands should be held in front, stretched out with palms outwards; thus, the rescuer should move along the structure, in case alive bare wire is touched, the electric shock will throw away;
- Direction of search should be chosen already before going to the unbreathable or smoke-filled environment. There are two main search directions: right-hand and left-hand.
  - Right-hand search direction – contact with a structure using the right hand;
  - Left-hand search direction – contact with a structure using the left hand.

To find a way out of the room, the direction of search should be reversed.

E. Direct and Indirect Search

Indirect search is used in cases when the group is instructed to look for victims or fire outbreak; members of the group should move so as to cover the largest possible area searched, maintaining a physical contact. Movement via space should be carried out at right angles; in case holes in walls or doors are discovered, the other side of the premises should be searched, and where it is not possible without interrupting the execution of the task, the SFRS should be informed.

Direct search is used when the group is instructed on performance of a particular task, then it shall move, applying the principles of the right-hand or left-hand search direction, towards the specified place to search for and rescue people and/or extinguish the fire. Direct search can be as well used to save other members of the group in case of structure collapse or communication failure.

Returning to normal conditions requires less air consumption, except for the cases when the group returns with a victim or the return path is blocked in case of collapse of structures.

VI. Exercises in Practical Operation of Firefighters with the Use of Protective Respiratory Equipment

Before beginning practical studies, each firefighter must be prepared theoretically.

The research authors suggest theoretical tests before commencement of the practical training, positive evaluation of which will allow assessing a person who has passed the test as knowledgeable and understanding enough to start practical training.

The test may consist of at least 40 questions, and the test shall be considered passed if at least 80 % of the questions asked are answered correctly. Timeframe provided for the test is 20 minutes, or 30 seconds for thinking over 1 question.

A. Description of Practical Training:

1. Each of the participants receives a fully charged (300 bar) compressed air breathing apparatus (hereinafter referred to as CABA).
2. Participants of training shall have valid mandatory health examination.
3. Participants are familiarised with the task to be performed and the procedure and sequence thereof.
4. CABA operational readiness check No. 1 is carried out and its results are documented.
5. Participants are instructed to perform as many tasks as possible without stopping – running is not allowed.
6. The participant puts on CABA.
7. The participant starts the exercise upon command "Start" from a starting point most convenient for him.
8. Fulfilment of the exercise continues until switching off the sound/physiological warning signal, then the execution is stopped, the results are documented and physiological indicators of the participant are recorded. Thereafter the participant continues execution of the exercise from a place where it was interrupted and goes on with execution until there is not air anymore in CABA or the participant suspends executing the task.
9. The participant's health state medical evaluation is carried out.
10. 15-minute break: rest / replacement of CABA cylinder(s)/ restoration of fluid in the body (sequence is not essential).
11. Participants will repeat the entire process using spare CABA cylinder(s).
12. If a participant suspends the work for health reasons, he shall give a hand signal: Work is over [4].

B. Practical Training No. 1: Compressed Air Breathing Apparatus (CABA)

Operational readiness check No. 1
Equipment required:

- CABA;
- Full facemask;
- Lung demand valve;
- Mask carrying case;
- Copy of Service Book.

Task execution time:

- 15 (fifteen) minutes.

Place of performance:

- Training class.

Performance conditions:

- CABA is on the table;
- Full facemask is in the carrying case on the table;
- A copy of the Service Book is on the table;
- Lung demand valve is connected to CABA;
- Performance of CABA Operational readiness check No. 1;
- The task is considered fulfilled if:
  - CABA Operational readiness check No. 1 is carried out correctly, not missing any one of the steps;
  - Entry is made in a copy of the Service Book.

After performance of the task:

- CABA shall be arranged as in the starting position;
- If pressure in CABA cylinder is less than 270 bar, it should be refilled immediately;
- If defects or imperfections are noticed in the equipment used during the task, they must be eliminated immediately, or the immediate superior should be informed about it.

Evaluation conditions:

Evaluation is performed by the immediate or higher commander. To consider the evaluation successful, the task has to be carried out according to the established execution conditions. If any of the execution conditions is not fulfilled or performed incorrectly, execution of the task shall not be considered successful. If in 6 months (10 days*) the repeated result is unsuccessful, then discussions are held as well as by-step performance evaluation of the practical training and the retraining** are applied.

TABLE IV

BY-STEP EVALUATION OF PERFORMED TASKS

No.	Task steps	First test fulfilled		Repeated test fulfilled	
		Yes	No	Yes	No
1.	Visual inspection of CABA and seamless mask				
2.	Air pressure check				
3.	Leakage check				
4.	Warning signal check				
5.	Making entry about check results in a copy of the Service Book				
Rating: successful / unsuccessful					

Note*: Frequency of repeated test of the exercise shall be determined depending on specificity of the task.

Note**: Conditions of exercise evaluation and conditions of approval/signature of the trainee employee are the same in all the exercises.

C. Practical Training No. 2

CABA Operational readiness check No. 2

Equipment required:

- Compressed air breathing apparatus;
- Full facemask;
- Lung demand valve;
- Mask carrying case;
- Protective firefighter clothing.

Task execution time:

- 1 (fifteen) minute.

Place of performance:

- Fire-fighting truck (FT).

Performance conditions:

- CABA is in FT, at place designed for this purpose;
- Full facemask is in the carrying case, in FT cabin;
- Lung demand valve is connected to CABA;
- Performance of CABA Operational readiness check No. 2;
- Time limit: 1 minute;
- The task is considered fulfilled if:
  – CABA Operational readiness check No. 2 is carried out correctly, not missing any one of the task execution steps.

After performance of the task:

- CABA shall be arranged as in the starting position;
- If pressure in CABA cylinder is less than 270 bar, it should be refilled immediately;
- If defects or imperfections are noticed in the equipment used during the task, they must be eliminated immediately, or the immediate superior should be informed about it.

TABLE V

BY-STEP EVALUATION OF PERFORMED TASKS

No.	Task steps	First test fulfilled		Repeated test fulfilled	
		Yes	No	Yes	No
1.	Put on CABA, adjust shoulder and waist straps				
2.	Open an air cylinder valve				
3.	Check lung demand valve operation				
4.	Check overpressure in a seamless mask				
5.	Fix pressure in an air cylinder				
6.	Confirm readiness for operation				
Rating: successful / unsuccessful					

VII. CONCLUSION

The SFRS carries out regular training studies in the UE, but these studies lack the methodology. Studies for personnel involved have no uniform and clear criteria to be tested during the studies. There are also no clearly defined methods of conducting the studies, or standards grouped or numbered in a certain order, as it is with the fire drill training. The present research sets out themes ranging from respiratory physiology and the structure of compressed air breathing apparatus (CABA), which are to be used for the theoretical training, to the performance of practical training exercises in the unbreathable environment (UE), which in turn shall be applicable in practice.

It is essential to ensure the competence level of those firefighters who are assigned to use the respiratory equipment. This competence must be associated with the strictest procedures of equipment inspection, testing and maintenance. If the highest standards are not met and maintained through regular training, then not only the equipment can become ineffective and seriously threatening its users, but also a firefighter without regular enough practical training in a critical situation may turn out to be insufficiently competent to take the emergency response measures.

In view of the foregoing, the authors believe that the performed research can be used as a basic material for improvement and perfection of training the SFRS officers in the field of UE.

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