# The Design of a Selfrescuer Simulator.


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## Simtars



**Abstract**
Since the introduction of self-contained self-rescuers the need for training methods has repeatedly been confirmed. When chemical self rescuers are used the process gives off heat and humidity and the flow of air is subject to resistance. When this is experienced for the first time, the wearer could be of the perception that the device is not functioning properly and might take the mouthpiece out of his mouth. This could cost the wearer his life if he is in a poisonous atmosphere. It is therefore deemed necessary to make the underground worker accustomed to the effects of breathing when using a self rescuer.

Following recommendations from the Fight or Flight Seminar, Simtars has embarked on an ACARP funded study to determine the specification of a simulator or simulators that can be used by the coal mining industry. Even though there are training self-rescuers available from manufacturers, a design for a prototype that can be used by mines at a relatively low cost has also been developed.

This paper sets out the rationale behind the design and specifications of such a breathing simulator and makes recommendations with regard to methods that could be used to train workers.


**Introduction**

From the beginning of the introduction of self-contained self-rescuers (SCSRs) in South Africa in 1987 and in Australia in 1997 the need for training has been realised. It has been stated by many that the life-saving potential of the SCSR was not determined solely by functional characteristics, but, amongst others, by realistic donning, activation and changeover training and the retention of these training skills.
This need for training was also identified locally in Queensland in the very first level one emergency exercise held in 1998 at the Southern Colliery. Here not only the need for training in the donning, but also the way in which self-contained self-rescuers worked, was identified. After a period of five years of emergency exercises this need was re-emphasized at a seminar in 2003 with an emphasis on changeovers and realism.
Over the years anecdotal reports have been noted, of users discarding chemical self-contained self-rescuers because they did not work only to find that on closer investigation that there was nothing wrong with the instrument. In these cases the user was not aware of the sensations that he would be subjected to as the self-contained self-rescuer was used. As there was no fatality that could be ascribed to such an occurrence all that was done was to re-emphasize the need for training.
In 2006 the Sago disaster caused the death of 12 mineworkers due to asphyxiation or poisoning by gas. This occurrence and the implications of the cause of the 12 deaths led to closer scrutiny of the need for training. It was highlighted that four self-rescuers were seemingly discarded due to the perception that they were considered to be unusable. However subsequent investigations found them to be sound and that they were thus needlessly removed. No death was ascribed directly to this discarding but the importance of the issue was brought to the fore.
This led not only to a refocussing of attention on training and training methods in the USA but also to the creation of a topic for study in the Fight or Flight Committees that were established in Queensland. With the support of the committee members Simtars was awarded an ACARP sponsored project to investigate the establishment of a simulator or simulators for use by the coal mining industry. The purpose of this investigation was to investigate the availability of

proprietary simulators, to evaluate those that were available, to investigate longer term simulators and to make recommendations with regard to the specification of simulators that can be used.

**Requirements**

The requirements for a simulator is that it should be suitable for training workers to make them aware of and experienced in the physiological burden that chemical self-rescuers place on the user. There are sufficient training models available for each model of self-rescuer currently being used that are suitable for training workers in the donning of the self-rescuer. Therefore the simulators do not have to replicate the actual self-rescuers closely. As the simulators are directed at training, rather than life saving, there is also no need for a supply of oxygen and the simulator could use normal air without detracting from its operation. Irrespective of the way the simulators are to be used they should allow the user to exert the necessary amount of effort to reach the required breathing rate. In the event of short term portable simulators the user can be made to walk but in the case of stationary longer-term simulators a treadmill would have to be used to enable the user to exercise by walking on it.

The performance limits of the chemical self-rescuer which cannot be exceeded has been clearly defined in the relevant standard, MDG 3006 MRT 9, (New South Wales Department of Primary Industries 2007) that is being used by both the Queensland and NSW mining industries. In this standard the following maximum allowable levels with regard to the physiological burdens are stated;

<u>For units with a rated duration of ≤ 30 minutes;</u>
Inhalation / exhalation resistance ≤0.75 kPa
Sum of inhalation and exhalation resistances ≤1.6 kPa
Inhalation temperature °C ≤55
Average $CO_2$ during rated duration 2%

<u>For units with a rated duration > 30 minutes;</u>
Inhalation / exhalation resistance ≤0.75 kPa
Sum of inhalation and exhalation resistances ≤1.3 kPa
Inhalation temperature °C ≤55
Average $CO_2$ during rated duration 2%

This standard also sets out the requirements for a training set. It should however be noted that these training sets are not sets that simulate the actions of a self-rescuer but are used to train users in the donning of sets. The requirements for these training sets are that they:

- Shall be clearly marked and coloured, in such a way that they cannot inadvertently be mistaken as functional escape devices.
- Shall not be registered.
- May simulate breathing resistance, temperature increase, donning and changeover, and weight.
- Should be resistant to cleaning and disinfectant fluids.

**Training units**

Most of the self rescuer manufacturers provide a training set. These sets are in conformance with the standard and are mainly used to train the user in the donning procedure. In most cases these sets are copies of the actual self rescuer and usually have the same weight and feel of the real set.
They are also good for the training of changeovers, an activity which has been identified as carrying a very high risk when taking place in a poisonous atmosphere.

**Short duration simulators**

Short duration simulators for filter self-rescuers have been available for quite a few years but since the advent of this project simulators for self-contained self rescuers[1] have been coming to the fore. There are presently single use short duration simulators available that provide oxygen by means of a chemical process similar to that used in self-rescuers. These simulators use small canisters that are disposable to generate the oxygen and provide the heat, the breathing resistance and the taste of the chemical in the mouth and a mouthpiece that can be cleaned and reused.. In the case of the longer duration set there is a breathing bag and a container so that the simulator can be worn just like a normal self-rescuer. Where the short duration simulators were generating oxygen it was assumed that they were tested to conform to the levels set by the standards and would, in normal operation, not exceed the levels as set for normal self-rescuers. These simulators however have not been designed to be used as self-rescuers and would therefore not be used in irrespirable atmospheres. In the event of one of them malfunctioning it can just be removed from the mouth without any adverse effects on the user.

In order to obtain a description of how the user could experience these simulators volunteers were each asked to use these simulators. A treadmill giving a specified rate of exercise was not available and the volunteers exerted effort by walking at a steady pace in an outside environment.
In the tests conducted with the oxygen generating simulator there did not initially appear to be a noticeable breathing difficulty or a noticeable increase in the temperature of the re-breathed air. Also the re-breather bag did not become fully inflated. However with time the bag became fully inflated resulting in air being expelled from the relief valve during exhalation. The canister became very hot, especially the tube connector and other metal parts. (This showed the need for the container around the metal canister)
During use, the heat of reaction slowly moved up the breathing tube so during the last 1/3 of the exercise noticeably warmer air was being inhaled. The inhaled air felt dry in the throat. The design of the simulator was such that it constrained the posture of the wearer requiring them to keep their neck bent down which caused a stiffening of the neck. It would have been very difficult to retain this posture for a whole hour without a prolonged exercise program. It was noted that no change in breathing difficulty was noticed over the duration of the exercise and the wearers were unaware of changes in the composition of the re-breathed air.
During the period of the tests there was no communication available for the wearers. A strange taste in the mouth was noted after cessation of the exercise.
In summary, it can be stated that this set would give the wearer an experience of wearing a SCSR but that it would not allow them to become aware of when to change such a set. There were both physical and psychological impacts on wearers. From the aspect of changeover, it was difficult for wearers to make a correct decision, based on what they experienced, regarding the right time for changeover.

The other simulator only gave off hot air. The breathing restriction was caused by orifices in the mouthpiece that went through to atmospheric air. This simulator however replaced the actual self-rescuer mouthpiece and as such could be installed so that the whole donning and breathing action could be exercised. It was an excellent simulacrum of the actual self-rescuer. On initial use of the simulator there did not appear to be a noticeable breathing difficulty or a noticeable increase in the temperature. The temperature of the air increased fairly rapidly thereafter. Although the temperature was high it was deemed not to be as hot as that with a real self-rescuer. The inhaled air felt dry in the same fashion as would be experienced by a user of a real self-rescuer.
As the self-rescuer was not connected to the simulator during the tests there was no effect on the user due to the weight of the set. If it was installed as part of the training self-rescuer the

[1] To ensure that this report is not perceived to endorse a mentioned product nor the non-mention of a product be seen as a non-endorsement, individual products will not be identified by name.

harness provided with the self-rescuer would take up most of the weight. The exercise was stopped when the temperature of the air through the simulator dropped. As the resistance was only obtained by means of holes there was no change in breathing resistance due to the chemicals. It was concluded at the end of these tests that this simulator gave a very good impression of the burden of a self-rescuer on a worker. To obtain a better experience of a self-rescuer it would be necessary to wear a real one.

In all of the tests there were noticeable discomforts while wearing the simulator. These included;

- Warm dry air inhalation
- Dry feeling in the throat
- Strange taste in the mouth in initial stage
- Saliva around mouth piece which could also cause concern about air leakage.
- Use of the nose clip was uncomfortable and unpleasant
- Facial muscles became sore and numb.
- Ears popped due to the wearing of nose clip
- Discomfort in jaw muscles as a result of holding onto mouth piece

Although not the intent of these simulators, an issue that has come to light is the fact that there is no clear way that the depletion of a self-rescuer can be identified or simulated. All that these simulators can do is make the user more accustomed to the feeling so that they do not remove the self-rescuer prematurely while it is still in working condition.

**Simulators for a long duration or multiple use.**

During a discussion with the Mines Rescue Service Limited in the United Kingdom (Brenkley, D pers. comm. To M Watkinson September 2007) the view was expressed that the initial requirements for a simulator would be best obtained by a fixed SCSR breathing simulator such as that developed for the Spanish mining industry.
This simulator was described by Fidalgo (2007) and further discussed through direct communications. In reviewing the information that has been gathered it would seem that this is a very comprehensive and able piece of equipment and is described below.

The simulator was designed to allow the user to experience the adverse sensations experienced when using a chemical self-rescuer. Chemical self-contained self-rescuers create a feeling of dryness in the respiratory tract. This chemical process also produces water vapour which, coupled with the heat, increases the relative humidity and can cause a sensation of suffocation in the user. These sensations are experienced in different ways by users and can also be dependent on the type and model of self-rescuer being used. The use of a nose clip to prevent air entering the nostril, as well as the increased breathing resistance caused by the chemicals, places further burdens on the user.
The simulator for the National Silicosis Institute has been designed to allow the user to be trained in these sensations so that they can become accustomed to them as being a normal characteristic of the self-rescuer and not as indicators of the self-rescuer not functioning.

The equipment consists of an air compressor that provides a flow of dry filtered air which is then heated by two heating elements. In one element an amount of water is introduced which evaporates and produces the required level of humidity. The rate at which the water is introduced determines the level of humidity and can be controlled by the operator. The airflow produced by this process is fed to a bag and mouthpiece that simulate the self-rescuer.
To simulate the process of walking and expending of effort the user walks on a treadmill. According to the description of the system the required breathing resistance is obtained by changes to the gradient of the treadmill. It is however considered that the required effort from the user could be better obtained in this way and the actual resistance in the ability to breathe could be obtained by placing a restriction in the breathing pipes.
While the system is being used, the outputs, in the form of temperature, breathing resistance and humidity, are being monitored by sensors. The whole process is controlled by a computer

which also shows how the parameters change over time. This allows the training programme to be altered if so required. This also allows changes to be made in the humidity as well as the level of effort required from the user.
To ensure the safety of the user, the equipment has been fitted with systems that control the maximum temperature and relative humidity as well as an emergency stop on the treadmill.
It has been found that the sensations experienced by using this simulator are very similar to that experienced by using a real self-contained self-rescuer.

Other longer duration simulators are described in reports by the Mines Rescue Service emanating from the Health and Safety Executive in the United Kingdom.
These reports (Jones et al, 2003) dealt with the use of self-rescuers and, as part of the study, investigated simulators that could be used to train users. It should be noted that the investigations were directed mainly at filter self rescuers (FSR)
The FSR, which removes CO from the air through a chemical reaction, creates higher temperatures in the supplied cleaned air. As the level of CO in the air increases so does the temperature of the air that is breathed. The unit that was designed and proposed however could be used to provide inspirable air that had a temperature of 50°C. The unit also had significant safety measures like a water trap and controls to safeguard the user against excessive heat and hot water being inhaled in the event of the failure of the hot water heating system.
In this report the SCSR simulator developed in Spain is also discussed as a good example of a long duration simulator that would replace the use of either out of date SCSRs as training sets or other types of long duration trainers.
It is quite evident that the Spanish simulator is perceived as a benchmark in the provision of such a training facility.

Work conducted in Japan (Takahashi *et al.* 1998) to investigate the effects of breathing resistance while inhaling carbon dioxide required a simulator type of instrument to enable the test to be conducted. The system consists of a blower feeding air to a conditioning chamber and breathing bag from which air is channelled to a breathing mask. Exhaled air was taken out of the system to a point where it could be analysed for purposes of the test regime. The necessary breathing resistance was obtained by placing orifices in both the inhalation and exhalation tubes. The correct gas mixture was obtained by feeding oxygen and carbon dioxide into the air stream just before the blower and by monitoring the gas mixture in the conditioning chamber. The volunteers breathed through a half mask that had a pressure gauge attached to measure the breathing resistance.
Even though this instrument was designed to determine the effects of gas mixture and resistance on users, the principles used to design it can be used to good avail in the design of a simulator to train workers.

## Design of a simulator

In designing a simulator for use in Queensland two main aspects were considered. The first was the availability of the short duration training units that can be obtained from the suppliers of the self rescuers that are being used in the mines. As these are proving to give a representative feeling to the user it would be a wasted effort to try and invent a unit to replace them. These manufacturers are so well advanced on the experience curve that there would be no benefit in either cost or quality in trying to develop an alternative universal short duration set.
The second aspect was the ability to change the parameters of the physiological burden to suit the requirements of training at the time. This necessitated that the oxygen in the simulator could not be chemically generated but would have to come from normal air. To be able to change the oxygen generating chemical reaction was considered to be very complicated and would not have contributed much to the outcomes of the training except to possibly give the additional effect of the taste of the chemicals in the air.

It was therefore decided that for a longer duration simulator a stand alone simulator would be developed using normal air as the oxygen supply. This simulator would be used in association with an exercise method so that the user can expend physical effort while staying in one place. It is anticipated that a treadmill would be the most suitable. Other methods of exercise such as a bicycle ergometer or rowing machine would in all probability also suit the purpose. By using normal air as the oxygen supply, any ethical problems caused by the user experiencing a lack of oxygen in the blood due to the addition of an inert gas will also be removed completely. It is anticipated that under such conditions the equipment could be used without requiring any medical staff to be present.

Although the design of such a long duration simulator would incorporate the ability to change the various parameters, the instrument will be directed at a set of conditions that would simulate the worst-case situation that would be allowable under the standard.
These conditions are;

- Inhalation temperature should be ≤55 $^{o}$C
- Inhalation and exhalation resistances should be ≤1.5 kPa
- As chemical oxygen SCSR produces warm humid air, the humidity should be able to be set to reach ≥90% relative humidity.

The breathing resistance will be obtained by means of orifices in the breathing airway. By varying the size of the orifice differing resistances will be able to be obtained with ease.
The air coming into the simulator from the atmosphere will be drawn into the apparatus by means of a pump with a volume well exceeding that of the expected air usage of 35 l/min. This air will be heated by an inline heater before being bubbled through a heated water bath. In this way the humidity of the air can be increased without cooling the air down but at the same time it will cause a dampening effect in the event of a failure of the heating system that could cause a rapid increase in the temperature of the air.
The heated and humid air will then flow into a breathing tube to be conveyed to the user's mouthpiece. With regard to the airflow requirements the flow of the generated hot humid air should exhaust unrestricted to the mouthpiece and it should do so irrespective of whether breathing occurs or not. Excess air will flow out of a release valve. The exhaust air flow rate is to exceed the maximum volume breathing rate, so as to ensure that the air to be breathed, which is supplied by the simulator, exceeds the amount required for breathing and prevents room air being sucked in through the exhaust.
Breathing is to be performed though a non-returning t-valve just prior to the attached mouth piece, which will ensure that the simulator beyond this valve remains free of viruses and bacteria that could otherwise be re-breathed into the simulator. This removes the need to clean the simulator after each use. The t-valve and mouth piece is to be made sterile or disposable.
To ensure the safety of the user with regard to excessively high temperatures, a continuous temperature measurement will be taken just before inhalation point. This will activate an alarm or shutdown mechanism should the temperature of the inhalation air exceed 50 $^{o}$C, As the heat load of saturated humid air increases rapidly above ~50 $^{o}$C it is deemed to be dangerous to the user over extended periods.
The air expired by the user will be exhausted to atmosphere.

With regard to the overall design of the apparatus it is foreseen that it would be made portable so that it can be moved from one venue to another. The linking of the simulator to the exercise machine as has been done in other instances is not deemed to be necessary just as it is not deemed necessary to link any reading like heart rate , temperature or breathing rate to the system.

Simtars has developed a prototype laboratory system in keeping with the aforementioned design criteria. This system will be used to gain experience and determine possible shortcomings in the overall design.
The prototype system is fully portable and will be able to be transported to any required venue. It is foreseen that this ability would be an important factor in the final design of such a system.

**Risk and usage considerations.**

The use of these simulators will reduce the overall risk to a worker as it will equip him or her better to cope with the effects of the aftermath of an underground occurrence. However the simulator itself will pose a degree of risk to the user. These risks can be broadly classified into two categories which are the medical/ ethical risks, and the risk of actually using the simulator.

In considering the ethical issues there are four main tenets to keep in mind:

- Beneficence - "the practitioner should always act in the best interests of the patient (in this case the worker)".
- Non-malificence - "First do no harm".
- Autonomy - the person has a right to refuse the treatment.
- Truthfulness and honesty - the concept of informed consent.

In terms of beneficence the practitioner is required to take all possible precautions against doing harm but there can be little doubt that conducting simulation exercises is in the best interests of the worker. There is a high degree of risk for workers in an asphyxiant atmosphere if they do not know what to expect when wearing a self rescuer in an emergency situation

Non-malificence is a legally definable concept. Litigation for malpractice may occur when non-malificence is violated. In the case of simulation training in a physically active workforce, the risk of a serious adverse effect appears small, especially when weighed against the possibility of multiple fatalities if self-rescuers were to be removed prematurely in a hazardous atmosphere. The risk appears to far outweigh that posed by the simulation.

The degree of risk of an adverse event is considered small for the following reasons:-

- The "healthy worker effect" should apply - workers are generally healthier than the overall population;
- Coal mine workers have all been subjected to a medical assessment within the previous five years;
- Underground mining is physically demanding, requiring reasonable cardiovascular fitness. Also, the worker can cease the simulation if any symptoms occur. It would be advisable for the worker to be instructed to stop the simulation if there is any concern about his or her health, particularly chest tightness & / or chest, neck or arm pain, breathing difficulty, headache, dizziness, pins and needles, weakness or visual disturbance. In the event of any of these occurring, the person should be returned to a cool place to rest under supervision and be advised to see their medical practitioner urgently
- Longer duration simulators should have controls that prevent dangers such as too high temperatures as part of the system.

If the tenet of autonomy, where the person has the right to refuse the treatment, is applied to the work situation, this principle would suggest that a coal mine worker should have the right to refuse to undertake the simulation. However, should this right be invoked, the employer may have good reason to refuse to accept the risk of employing the worker underground.

Under the tenet of truthfulness and honesty it is required that the person is properly informed about their situation and the treatment (in this case the details of the simulation) they are to receive. An uninformed person is in danger of making choices which do not reflect their personal values. In the work situation a full explanation of the simulation exercises, the risk (though slight) and the unpleasant sensation induced by the self-rescuer ought to be provided, before requiring the worker to sign a form, if required, consenting to undertake the simulation.

From the above it is thus clear that there are very few ethical considerations that would stop simulators from being used as a training tool. The necessary safeguards to minimise risk can very easily be introduced into a system in the mine or wherever training is to happen.

With regard to the risks of actually using the simulators only a few have been identified. These have mainly do to with what the user will be breathing and the risk of hurting himself on the exercise machine.
In the development of the short term simulator filters have been fitted that would stop the inadvertent breathing of chemicals and as the exercise is being carried out in a safe atmosphere the user can remove the simulator at any stage they feel uncomfortable. It is actually the purpose of the simulator to make the user become used to the sensations. In the design of the longer duration simulator a sensor that monitors temperature with safety switches has been fitted. The use of a water bath also reduces the possible impact of any catastrophic failure.
The other issue of being hurt on an exercise machine is seen to be of such low likelihood, in comparison with mine workers being required to walk out of a mine under adverse conditions, that it does not require further attention.

### Conclusions

The need for a method to train workers has again been confirmed and has led to the establishment of this ACARP project. This study has found that there are sufficient suitable single-use short term simulator sets available that will allow workers to be adequately trained. Even though not all self-rescuers have simulators provided by the manufacturers, those that are available should enable training to be done by the mines.
In the event of the mines requiring a multi-use simulator there are sufficient designs and prototypes available that can be used by a manufacturer to provide a product, or to allow a mine or organisation to have such a device manufactured on their behalf.
It is evident that there is presently no constraint due to the availability of equipment to stop workers from being trained with regard to the adverse effects they might encounter when using a self-contained self-rescuer in a real situation.
The best method of training workers would be one that would incorporate both a long duration simulator as well as short duration sets.


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### References


Fidalgo, M., Madera, J. & Solar, B. 2007, 'Realistic training programme for the safe use of chemical oxygen self-rescuers in the coal mines', *Proceedings of the 32nd Conference of Safety in Mines Research Institutes: September 28-29, 2007 Beijing China, National Center for International Exchange and Cooperation on Work Safety, Beijing China*, pp. 215-218.

Jones, B., Brenkley, D., Jozefowicz, R. R., Whitaker, D., Shotton, J. & Booth, A. P. 2003, 'Use of self rescuers in hot and humid mines' *Research report(Great Britain. Health and Safety Executive),* no. 180, HSE books, pp. 27-37.

New South Wales Department of Primary Industries 2007, 'Escape breathing apparatus for underground coal mining applications: Requirements for registration and monitoring guidelines for compressed air refill stations' [DRAFT] **.** *MDG 3006 MRT 9,* N.S.W. Department of Primary Industries..

Takahashi, M.,Mano, Y., Shibayama, M. & Yamami, N. 1998,. **'Effects of breathing resistance while inhaling 3% carbon dioxide during steady-state exercise',** *Journal of Occupational Health,* vol. 40, no. 3, pp. 213-217.