

Competency-based training for mine emergency response

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Mine workers are exposed to hazards that can cause injuries or fatalities, including fires, underground explosions, irrespirable atmospheres, falls of ground, and mobile machinery. Emergency preparedness is important for improved safety outcomes and includes the deployment of self-contained self-rescuer (SCSR) devices, effective escape routes, and adequately located refuge bays. The need has been identified for improved training solutions for mine worker escape situations, which should provide some exposure to the stressors that would be experienced. The CSIR Mining Cluster has developed innovative multi-modal competency-based training modules to improve the emergency response of mine employees. The modules include interactive e-learning, virtual reality training, SCSR donning and breathing simulation, and competency-based assessments. A pilot study was successfully completed with participation from a major coal mining operation. The competency-based approach improves the overall efficacy of the training and is especially well-suited to training for high-consequence, low-frequency scenarios.

Keywords: competency-based training, emergency preparedness, expectation trainer, experiential learning, immersive training

INTRODUCTION

The need for improved training solutions has been identified to improve health and safety awareness and performance, and to reduce the occurrence of injuries and fatalities in the South African mining industry (SAMI). Training capability for emergency scenarios in the industry could be improved through the application of technology. Improved training approaches that have been identified include experiential training, which may involve the use of computer simulation and virtual reality (VR) technology, to improve the level of engagement, quality and effectiveness of safety training. Immersive training can recreate – in a safe and controlled environment – the physical, cognitive, and psychological stressors and behavioural responses that are experienced in emergency situations. These stressors are likely to have an adverse effect on recall and execution of emergency response procedures. By including immersive simulation of emergency scenarios in the training, the retention and performance outcomes in real emergencies can be improved.

The CSIR Mining Cluster has developed innovative multi-modal competency-based training modules to improve the emergency response of mine employees in scenarios that include risk of irrespirable atmospheres. The immersive and experience-based training interventions supplement existing safety awareness training provided by the Kloppersbos fires and explosions test facility. This paper provides a description of the potential application of technology to enhance training capability for emergency scenarios in the SAMI and the development of the immersive training modules by the CSIR. These modules include e-learning, VR training involving simulation of an escape route scenario, simulation of SCSR donning and breathing, and competency-based assessments. Although the training methods employed in this project are not novel, the application of the combination thereof to emergency response training in the SAMI is unique.

REVIEW OF LITERATURE

Emergency preparedness

The mining industry is inherently dangerous, with numerous fatalities and injuries resulting from mining accidents (Andersen *et al.*, 2020; Daniels and Salisbury, 2000; Grabowski and Jankowski, 2015; Hui, 2017; Tichon and Burgess-Limerick, 2011; van Wyk, 2015). Mining industry hazards include fire, underground explosions, toxic gases, geotechnical hazards, and working in close proximity to equipment (Tichon and Burgess-Limerick, 2011). Emergency preparedness is important for improved safety outcomes (Ablah *et al.*, 2009; Cohen *et al.*, 2013; Feng *et al.*, 2018 and 2020; Sermet and Demir, 2019).

A self-contained self-rescuer (SCSR) is an emergency breathing apparatus which allows the user to isolate their respiratory system from an irrespirable atmosphere and which provides a safe source of oxygen for a finite duration. The use of SCSR devices has become common in underground mines in South Africa with approximately 287 000 SCSR units deployed in 201 mines in 2023 (Sehlabana, 2023). When an irrespirable atmosphere occurs, for example as a result of a fire, each worker must don (deploy) their body-worn SCSR and proceed to a place of safety such as an underground refuge bay. The deployment of SCSR devices, the location of refuge bays, and effective escape routes form part of emergency evacuation procedures (Biffi and Sehlabana, 2018). In an emergency, SCSRs provide breathable air and protect the wearers against potentially toxic gases and oxygen deficient atmospheres, to enable them to reach a place of safety (such as a refuge bay) where respirable air is available. Biffi and Sehlabana (2018) note that workers must be proficient in the donning of SCSRs and familiar with emergency evacuation procedures to achieve the life-sustaining capacity of the SCSR. Previously reported failures in donning SCSRs in emergencies included mine workers forgetting to don nose-clips or goggles, not being able to activate the oxygen supply, straps getting tangled with cap-lamp cords, delayed donning, or removing the mouthpiece when experiencing breathing resistance (Biffi and Sehlabana, 2018).

The high rate of accidents and fatalities in the SAMI has frequently been attributed to ineffective training methods and material, and the need for new solutions has been identified, such as the use of VR technology (Daniels and Salisbury, 2000; Grabowski and Jankowski, 2015; Squelch, 2001). More specifically, improvements to the nature and level of mine worker training in escape and rescue operations has been highlighted, including “novel training procedures that will provide an indication of the physical, cognitive, psychological stressors and behavioural responses that would be experienced in traumatic escape situations” (Biffi and Sehlabana, 2018). Biffi and Sehlabana (2018) highlight the application of experiential training for the use of refuge bays and underground emergency procedures, and the potential for the SCSR Expectation Trainer. Additionally, a recommendation arising from a project funded by the Mine Health and Safety Council was to “Implement, as a matter of urgency, experiential and expectation training for the donning and use of SCSRs” (Hodgskiss *et al.*, 2017).

Experiential training methods

Experiential training is considered an effective means to improve mine emergency training. Computer simulation and VR can provide immersive training, in which the trainee has a realistic experience of the simulated scenarios, without the associated risks (Tichon and Burgess-Limerick, 2011; van Wyk, 2015; Zhang, 2020). The use of VR has been cited as an effective method of training in a number of industries and activities, including safety and hazard or risk awareness, emergency response, and evacuation (Chen *et al.*, 2008; Daniels and Salisbury, 2000; Feng *et al.*, 2018; Makransky *et al.*, 2019; Squelch, 2001). The use of VR technologies has also been increasing in the SAMI (Solomons, 2015).

Traditional emergency preparedness training approaches include seminars, posters, manuals, videos, and drills (Andersen *et al.*, 2020; Daniels and Salisbury, 2000; Feng *et al.*, 2018 and 2020; Makransky *et al.*, 2019). Traditional methods of training in the SAMI, in particular, include class-room style learning, video-based training programs, instruction in physical mock-ups of underground workplaces, and on-the-job training (Squelch, 2001). However, limitations to conventional approaches include that they are not highly engaging, and limit sensory reflection of real-life emergency scenarios (Feng *et al.*, 2020;

Tichon and Burgess-Limerick, 2011). Additionally, factors that make training under actual working conditions difficult or impossible include the need to interact with equipment that is expensive, unavailable, or inaccessible; the expense of downtime; dangerous conditions; and that it is not always possible to simulate real dangers or conditions (Andersen *et al.*, 2020; Hui, 2017; Sharma *et al.*, 2017; Squelch, 2001). Further challenges include skills degradation over time, difficulties with skills assessment and feedback, and the evaluation of the effectiveness of training (Cohen *et al.*, 2013; Ford and Schmidt, 2000; Tichon and Burgess-Limerick, 2011).

As an example, VR can be used to supplement or replace traditional methods of training (Squelch, 2001). Potential benefits of VR training noted in previous research (e.g. Bednarz *et al.*, 2010; Cohen *et al.*, 2013; Crichton and Flin, 2004; Daniels and Salisbury, 2000; E&MJ, 2019; Grabowski and Jankowski, 2015; Makransky *et al.*, 2019; Sermet and Demir, 2019; Squelch, 2001; Tichon and Burgess-Limerick, 2011; Zhang, 2020), include:

- Provision of realistic experiences for improved quality of training
- Cost-effectiveness
- Safe environment (e.g. to prevent risk of injury or material damage)
- Possibility for a wide range of scenarios, including those that are rarely experienced in real-life
- Flexibility (e.g., to modify and customise)
- Acquisition and transfer of tacit knowledge
- Training sessions can be conducted for multiple participants
- Trainee interaction (e.g., for physically distant individuals and teams)
- Training can be provided at any location
- Monitoring of progress and understanding during training sessions
- Ability to precisely record and reproduce simulated training exercises; and
- Provision of accurate and immediate feedback.

As such, immersive training experiences can increase mine workers' ability to retain and recall information, and to execute the correct emergency response procedures swiftly and accurately. The physical or virtual immersive training environment can simulate a high consequence scenario without exposing the trainees to the actual safety hazards. Additionally, creating a virtual environment can be achieved at a fraction of the cost of constructing and maintaining a traditional physical environment. Changes in the digital environment are also far more cost-effective.

Competency-based training

There are various definitions for competency-based education (CBE) or competency-based learning (CBL). Within the context of this paper, CBE or CBL is referred to as competency-based training.

Gervais (2016) defined CBE as "an outcome-based approach to education that incorporates modes of instructional delivery and assessment efforts designed to evaluate mastery of learning by students through their demonstration of knowledge, attitudes, values, skills, and behaviours required for the degree sought." Henri *et al.* (2017) broadly defined CBE as "a pedagogical approach that focuses on the mastery of measurable student outcomes." Oroszi (2020) defined CBE as "an innovative approach in higher education that organises academic content or delivery according to competencies, what a student knows and can do, rather than following a more traditional scheme, such as by course."

In essence, CBE is a learner-centred approach (Dyke, 2009) that enables learners to practise the learnings to attain specific skills, as opposed to extensive time spent in a classroom in traditional learning approaches (Oroszi, 2020). Some of the key characteristics of CBE include self-paced learning and flexibility, the use of technology for experiential learning, tailored learning styles (based on student age group and student experience), interactive sessions and assessments, and predefined outcomes. These characteristics are also aligned with those of experiential learning. In addition, CBE aims to improve the retention of knowledge and to impart skills to students that meet the needs of industry (Henri *et al.*, 2017; Oroszi, 2020; Gervais, 2016).

The Republic of South Africa (2000) highlighted three pillars of competence in its National Education Policy Act, 1996:

- Foundational (or theoretical) competence – the learner shows an **understanding** of the knowledge and thinking behind what they are doing
- Practical competence – the learner is able to **do** what they have learned in a real-world environment and is able to **make good decisions** on how to do it; and
- Reflexive competence – the learner is able to **connect** their actions and decisions with their understanding, are able to **adapt to changes** and can **explain** why certain choices are made.

These pillars strongly suggest that theory, practise and reflection play a crucial role in CBE (Dyke, 2009) and are collectively referred to as “applied competence” (Republic of South Africa, 2000). Dyke (2009) inferred that CBE is an enabler for more informed decision-making that would guide a learner’s actions. Dyke (2009) included “interaction” as a fourth pillar for CBE in his framework for “reflexive learning.” Interaction is related to engaging with others in a social or learning context.

The literature indicates that CBE is becoming more widely adopted for various competencies in various industries, including engineering and mining competencies. CBE has become an effective mode of learning to impart skills that meet industry’s needs and to accommodate learners from different backgrounds and circumstances through its flexible approach (Henri *et al.*, 2017).

METHODS

The CSIR hosts weekly mine fire and explosion safety awareness training seminars at the Kloppersbos facility. The seminars are considered an important part of worker safety training, especially for coal mine workers. The seminars include a lecture on fire and explosion risk and prevention, small-scale demonstrations, and large-scale fire and explosion demonstrations. The CSIR has been offering the safety awareness training for many years and approximately 4500 mine workers attend annually. Despite the safety awareness training and the mines’ internal operational and engineering controls, underground fires and ignitions of flammable gas still occur. Mines Rescue Services (MRS) reported a total of 17 fire incidents occurring in South African mines in 2024, of which six were classified as major fires (Mines Rescue Services, 2025).

CSIR invited key industry stakeholders to participate in a workshop to explore how the training in underground mine fire and explosion safety could be enhanced. The broad aim of the workshop was to explore opportunities to increase the effectiveness of mine safety training interventions through experiential training and use of appropriate technology. One of the significant outcomes of the workshop was recognition of the need for better training of mine workers in mine emergency response. Once an incident, such as a fire or explosion occurs, which results in an irrespirable atmosphere, each worker must be able to self-rescue by rapidly donning their SCSR and following the designated escape route to reach a place of safety from where they can be taken to surface by MRS rescue teams. The stakeholder workshop indicated that the quality of existing training of workers in self-rescue procedures varied greatly across the mining industry. Following this outcome, the CSIR partnered with an industry-leading company specialising in the development of technology-enabled training solutions to develop the Competency-based Training in Mine Emergency Response. This novel training framework incorporates e-learning and VR modules as well as experiential training to ensure high learner engagement during the training, resulting in good recall with rapid execution of the emergency response procedure while under the psychological and physical stress of an emergency situation.

The CSIR then did a roadshow with the new training offering to demonstrate it to selected clients and solicit their feedback and recommendations for future developments and improvements.

A pilot study was conducted with a coal mine in November 2023, to test the equipment, process, and programme, and obtain feedback from the learners. The programme was attended by a ventilation and occupational hygiene engineering specialist, training specialist, technician, and learner.

Ethics approval to conduct this project was granted by the CSIR Research Ethics Committee (Ref: 340/2020).

OUTPUTS

The newly developed modules that are described in this section include:

- Interactive e-learning modules on basic emergency response procedures
- Real-life experiential training in SCSR-donning procedures
- SCSR breathing simulation using the CSIR Expectation Trainer device
- VR training involving simulation of an escape route scenario; and
- Competency-based assessments.

Interactive e-learning modules on emergency response procedures

The training course starts with the transfer of the basic knowledge on which the rest of the training will build. This knowledge transfer is achieved by allowing the trainee to work through five interactive e-learning modules at their own pace. The e-learning modules make use of realistic video animations, text captions and voice-over to convey the learning content. This engages both visual and auditory senses of the learner and ensures that it caters for learners with different learning styles. In addition, each component includes an introduction and assessment section. Three primary interactive e-learning components were developed in the Learning Management System (LMS), namely:

- Catastrophic explosions – explosion prevention (two modules)
- Awareness campaign for everyone – lifeline and refuge bay (two modules); and
- Self-rescue (one module).

Table 1. E-learning modules and content

Topic	Content
Overview of Catastrophic Explosions	<ul style="list-style-type: none"> • Methane Gas (Firedamp) • Coal Dust • Ventilation Issues • Ignition Sources • Structural Failures • Spontaneous Combustion • Human and Systemic Errors • Environmental Factors
Catastrophic Explosion Prevention Tools	<ul style="list-style-type: none"> • Monitoring and Detection Systems • Ventilation Systems • Explosion-Proof Equipment • Dust Suppression and Control • Barriers and Containment • Spontaneous Combustion Prevention
Explosion Prevention Strategies	<ul style="list-style-type: none"> • Effective Ventilation Management • Regular Dust Control • Ignition Source Elimination • Training and Safety Protocols • Emergency Preparedness

	<ul style="list-style-type: none"> • Legislation and Standards Compliance • Continuous Improvement Programs
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Topics covered in the e-learning modules, relating to catastrophic explosions and the prevention thereof, are listed in Table 1. Examples of content relating to the lifeline procedure and SCSR modules are shown in Figures 1 and 2. Benefits of the e-learning modules are that it is self-paced, and can be completed anywhere, provided there is access to a device with internet connectivity.



Figure 1. Example of content in the lifeline and rescue bay training module.

Let's review: Using Your Short duration SCSR | AfroxPac 35i - The 7 Donning Steps

Fit and adjust neck and waist strap

Lift your *hard hat*, fit neck strap and *immediately* replace hard hat. Tilt head back and *adjust strap* to prevent mouthpiece pulling out. Clip in waist strap and adjust.

Figure 2. Example of a step in the SCSR donning procedure module.

An assessment is required following the completion of the e-learning modules. A score of at least 90% is required to pass each assessment. Three attempts are permitted. The e-learning system further includes components for uploading the assessment results from the practical components, namely the

SCSR simulation and VR training. A certificate is provided upon the successful completion of all the required components.

Experiential SCSR training and breathing simulation

SCSR training is important as it has been identified that individuals do not follow correct donning procedures in an emergency and lack the experience and feel of real units. As such, in addition to the e-learning training, the SCSR training includes the use of training units obtained from SCSR original equipment manufacturers and the use of the CSIR Expectation trainer device. Training units, or expired SCSR units used in a safe environment, can be used for individuals to practise donning and to learn what to expect when breathing from an SCSR. The use of the Expectation trainer is detailed further below. It is recommended that regular, practical training takes place every six to 12 months.

The purpose of the SCSR Expectation trainer is to improve the training and preparedness of underground mine workers in the use of SCSRs during emergency escapes. The unit simulates the experience of breathing from an SCSR, including factors such as elevated inhalation temperature, elevated resistance, and fitting of nose clips and goggles. The unit provides a realistic inhalation temperature ranging from 40°C to 60°C and a breathing resistance of approximately 1000 Pascal (10 mbar) for both inhalation and exhalation, simulating conditions similar to those encountered when using a real SCSR in an escape scenario. The Expectation trainer does not require chemicals and can be disinfected and reused. Images of the training unit are shown in Figure 3. Overall, the application of the Expectation Trainer serves to enhance miners' understanding of and proficiency in using SCSRs during underground emergencies, improving their chances of successful escape.



Figure 3. Expectation trainer (left) and components (right).

VR training for an emergency escape scenario

The VR experience covers three areas of an emergency escape scenario, namely:

- Donning of the SCSR unit
- Finding the lifeline and route to the refuge bay; and
- Refuge bay procedures.

Examples of images from the VR training are provided in Figures 4 and 5.

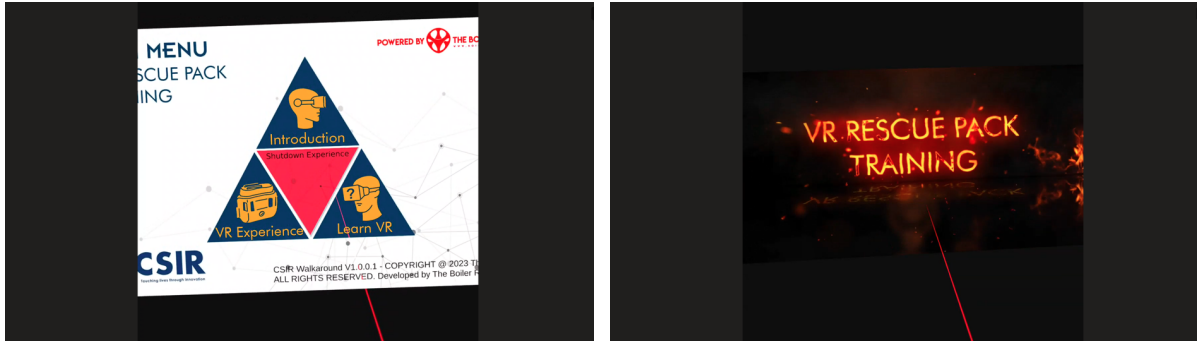


Figure 4. Main menu of VR training module.



Figure 5. Example of VR training for an escape route scenario.

During the training, the facilitator needs to ensure that the following activities have been completed by the learners once having entered the refuge bay in the VR environment:

- Check and test for methane gas
- Activate the positive vent flow at the borehole
- Instruction to remove SCSR units
- Check and apply first aid to any individual in need
- Take register of team numbers
- Inform control room of status and needs of the team
- Check status of toilet facility
- Keep only one headlight on to preserve and save energy of other lamps; and
- Stay calm and wait patiently for rescue team to arrive.

These modules train the workers to rapidly respond to emergency situations. By including an appropriate level of assessment in each module the trainer can confirm if each trainee is competent or needs further training.

Pilot study feedback

Feedback on the training was provided following a pilot study of the modules with participants from a mine, in terms of the e-learning modules, VR modules, and use of the Expectation trainer. Images taken during the pilot study are shown in Figure 6.

Each of the learners completed at least one of the e-learning modules and assessments that followed. All of the learners indicated that the content was exciting, interesting, and easy to follow. They indicated that the way it was presented captured their attention and kept them engaged to the end. The LMS structure and layout was considered easy to navigate and manage.

The VR module provided an underground mining experience. Some of the learners battled to find their way through the course from donning the SCSR to getting to the rescue bay. It was clear that experience at an underground operation and the emergency response procedure played a major role. The learner who did not have mining experience battled more than the other learners to complete the module. All learners had to repeat a section or module more than once to get to the rescue bay. In addition, the following aspects played a major role in the success of the module:

- Previous experience playing computer games
- Familiarisation with VR technology
- Computer and technology orientation; and
- Experience in dealing with nausea.

Despite the above challenges, all the participants reported the training to be exciting and that it was good to use technology to enhance the training experience and they would explore and use the headset.

The Expectation trainer provided the learners with the heat and breathing resistance typically associated with the use of SCSR units. All candidates used and tried the Expectation trainer with great anticipation. The trainees indicated that the experience was different to only using a training unit and felt much more uncomfortable, warm, and more like the real-life units. The nose clip provided some challenges for individuals with a small nose construction as it kept slipping off.

The pilot program was considered a valuable experience and opportunity to test the equipment. It also captured feedback from the learners in terms of the content and process. The program is expected to add value and increase competency in emergency response training. Moreover, the following aspects need to be considered when nominating individuals for this course:

- **Literacy level:** It is recommended that individuals need at least a Grade 10 or equivalent literacy level to cope with the course content and instructions
- **Mining experience:** It was clear that the individuals with underground mining experience followed the content and instructions a lot better than those without experience; and
- **Computer and technology exposure:** Individuals need a basic level of computer and technology exposure to navigate through the LMS and VR headset.

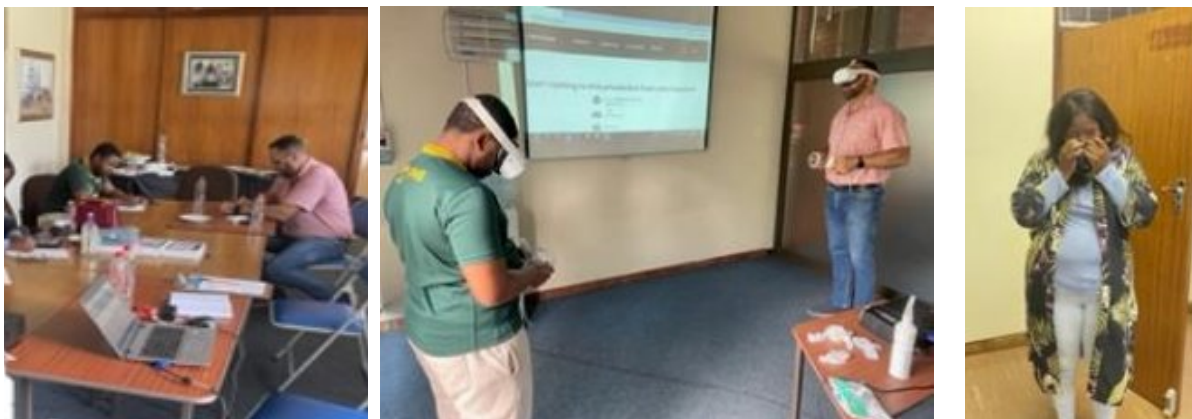


Figure 6. Pilot study participation.

Implementation of competency-based training for mine emergency response

The multi-modal competency-based training can be completed in a single day and can be offered at the Kloppersbos facility or at the mine's training centre. However, access to SCSR devices, Expectation trainers, and VR headsets will be required for the related simulations. The cost of the training will be comparable to the current mandatory annual mine fire and explosion safety awareness training.

Certificates of competence will be provided upon successful completion of all the training components, including assessments.

CONCLUSION AND RECOMMENDATIONS

The multi-modal competency-based training approach is a transformative solution to safety challenges in the SAMI, where workers face high-risk environments daily. This approach is particularly effective in preparing personnel for high-consequence, low-frequency scenarios – such as underground rockfalls, methane explosions, and machinery-related incidents – by immersing learners in realistic, high-pressure training environments that develop critical decision-making skills, risk awareness, and emergency response capabilities. The high level of learner engagement results in improved efficiency in terms of learning outcomes achieved vs investment in training time and money. It is also expected that improved retention of learning content will be achieved, although this could not be measured within the timeframe of the pilot study. It is expected that this immersive and experiential training approach will improve learning outcomes, and lead to improved safety of mine workers in South Africa.

Key safety benefits of multi-modal competency-based training in the SAMI include:

- Improved training outcomes when compared to conventional lecture-based training
- Reduction in workplace fatalities and injuries
- Improved hazard recognition and risk mitigation
- Greater knowledge retention, recall and practical application; and
- Alignment with regulatory and industry safety standards, such as the Mine Health and Safety Act.

To drive measurable safety improvements across the South African mining sector, it is recommended that this multi-modal competency-based training approach be systematically implemented across all mining operations. By adopting cutting-edge training methodologies, the South African mining industry can achieve higher safety performance, lower incident rates, and a more resilient workforce, ultimately saving lives and fostering a sustainable mining environment. The CSIR developed the competency-based training in mine emergency response to address a confirmed gap in emergency response and self-rescue training in the SAMI. The CSIR can develop similar multi-modal competency-based training solutions to suit the specific training needs of the user.

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Jodi Pelders is a researcher in the CSIR's Mining Cluster. She has been involved in conducting research relating to human factors, health and safety in the southern African mining sector for over a decade. Jodi obtained her Master's degree in Ergonomics from Rhodes University, and completed a PhD in Public Health at the University of the Witwatersrand. Her research interests include fatigue management, workplace stress, physiological strain, incident analysis, women in mining, socio-economic and living conditions, and ergonomics, as this relates to mine workers in South Africa. More recently, much of her research involvement has related to modernisation of the mining industry. The research project clients include the Mine Health and Safety Council, Mandela Mining Precinct, and mining houses. Jodi aims to contribute to improving the health, safety, and productivity of individuals, and increasing sustainability in and around mines.