

MINESAFE 2025

MINE HEALTH AND SAFETY CONFERENCE

SAFE MINES,
HEALTHY LIVES,
AND SUSTAINABLE
FUTURES

19-20 NOVEMBER 2025 — CONFERENCE
EMPERORS PALACE CONVENTION CENTRE



MINERALS COUNCIL
SOUTH AFRICA



SAIMM
THE SOUTHERN AFRICAN INSTITUTE
OF MINING AND METALLURGY



SANIRE
SOUTH AFRICAN NATIONAL INSTITUTE OF ROCK ENGINEERING



Proceedings Book

**THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY
JOHANNESBURG 2025**



**19-20 NOVEMBER 2025
EMPERORS PALACE CONVENTION CENTRE**

SAIMM PUBLICATIONS

THE MONOGRAPH SERIES

- M1 Lognormal-De Wijsian Geostatistics for Ore Evaluation**
(2nd ed 1981) D.G. Krige
- M2 An Introduction to Geostatistical Methods of Mineral Evaluation**
(2nd ed 1981) J.-M.M. Rendu
- M3 Principles of Flotation**
(1982) (3rd imp. 1986) Edited by R.P. King
- M4 Increased Underground Extraction of Coal**
(1982) Edited by C.J. Fauconnier and R.W.O. Kersten
- M5 Rock Mechanics in Mining Practice**
(1983) (3rd imp. 1986) Edited by S. Budavari
- M6 Assay and Analytical Practice in the South African Mining Industry**
(1986) W.C. Lenahan and R. de L. Murray-Smith
- M7 The Extractive Metallurgy of Gold in South Africa,**
2 volumes (1987) Edited by G.G Stanley
- M8 Mineral and Metal Extraction — An Overview**
(1994) L.C. Woollacott and R.H. Eric
- M9 Rock Fracture and Rockbursts—an illustrative study**
(1997) Edited by W.D. Ortlepp

THE SPECIAL PUBLICATIONS SERIES

- SPI Proceedings, Underground Transport Symposium**
(1986) Edited by R.C.R. Edgar
- SP2 Backfill in South African Mines (1988)**
- SP3 Treatment and Re-use of Water in the Minerals Industry (1989)**
- SP4 COREX Symposium 1990**
(1990) Edited by H.M.W. Delpont and P.J. Holaschke
- SP5 Measurement, Control, and Optimization in Mineral Processing**
(1994) Edited by H.W. Glen
- SP6 Handbook on Hard-rock Strata Control**
(1994) A.J.S. Spearing
- SP7 Rock Engineering for underground coal mining**
(2002) J. Nielen van der Merwe and Bernard J. Madden
- SP8 Second Edition: Rock Engineering for underground coal mining**
(2010) J. Nielen van der Merwe and Bernard J. Madden
- SP9 Theoretical Rock Mechanics for Professional Practice**
(2016) M. Handley
- SP10 Johannesburg and its Holey Mining Heritage 2021**
(2021) T.R. Stacey
- SP11 Mineral and Metal Extraction — An Overview**
(2021) L.C. Woollacott and R.H. Eric
- SP12 The Fall of a Giant: The story of the disintegration of the South African Mining Industry**
(2022/2023) Dr I. Robinsoin
- SP13 COMRO's Legacy: Research and Development of Stopping Mining Machinery and Technologies**
(2023) B. Protheroe

SUPPLEMENT TO THE SAIMM JOURNAL

The Metals and Minerals Industry in South Africa - Part 1 (1989)
Edited by H.W. Glen

THE SYMPOSIUM SERIES

- | | | | |
|-----|---|------|---|
| S1 | Mathematical Statistics and Computer Applications in Ore Valuation (1966) | S18 | The 8TH International Platinum Symposium (1998) |
| S2 | Planning Open Pit Mines (1970) (4th imp.)
Edited by P.W.J. van Rensburg | S19 | Mining in Africa '98 |
| S3 | Application of Computer Methods in the Mineral Industry (APCOM 1973) Edited by M.D.G. Salamon | S20 | Extraction Metallurgy Africa '98 |
| S4 | Infacon 1974 Edited by H.W. Glen | S21 | Sixth International Symposium for Rock Fragmentation by Blasting (1999) |
| S5 | Proceedings of the 12TH CMMI Congress 2 volumes (1982)
Edited by H.W. Glen | S22 | Metallurgy Africa '99 |
| S6 | Rockbursts and Seismicity in Mines (1984)
Edited by N.C. Gay and E.H. Wainwright | S23 | Heavy Minerals 1999
Edited by R.G. Stimson |
| S7 | The Planning and Operation of Open Pit and Strip Mines (1986) Edited by J.P. Deetlefs | S24 | Tunnels under Pressure
Technical Editor T.R. Stacey |
| S8 | GOLD 100: Proceedings of the International Conference on Gold (1986)
Volume 1: Gold Mining Technology
Edited by H. Wagner and R.P. King
Volume 2: Extractive Metallurgy of Gold
Edited by C.E. Fivaz and R.P. King
Volume 3: Industrial Uses of Gold
Edited by G. Gafner and R.P. King | S25 | Mine Hoisting 2000 |
| S9 | APCOM 87: Proceedings of the Twentieth International Symposium on the Application of Computers and Mathematics in the Mineral Industries (1987)
Volume 1: Mining
Edited by L. Wade, R.W.O. Kersten and J.R. Cutland
Volume 2: Metallurgy
Edited by R.P. King and I.J. Barker
Volume 3: Geostatistics
Edited by I.C. Lemmer, H. Schaum and F.A.G.M. Camisani-Calzolari | S26 | Coal—The Future (2000) |
| S10 | International Deep Mining Conference (1990)
Volume 1: Innovations in Metallurgical Plant
Edited by G.A. Brown and P. Smith
Application of Materials Engineering in the Mining Industry Edited by B. Metcalfe
Volume 2: Technical Challenges in Deep Level Mining
Edited by D.A.J. Ross-Watt and P.D.K. Robinson | S27 | The Fifth International Symposium on Rockburst and Seismicity in Mines (RaSim 5) (2001) |
| S11 | Infacon 6 (Incorporating Incsac) (1992)
Edited by H.W. Glen | S28 | 6TH International Symposium on Mine Mechanization and Automation (2001) |
| S12 | Massmin 92
Edited by H.W. Glen (out of print) | S29 | XIV International Coal Preparation Congress and Exhibition |
| S13 | Minefill 93
Edited by H.W. Glen | S30 | Surface Mining 2002—Modern Developments for the New Millennium |
| S14 | XVTH CMMI Congress Publications (1994)
Volume 1: Mining
Edited by H.W. Glen
Volume 2: Metals Technology and Extractive Metallurgy (1994) Edited by H.W. Glen | S31 | IFSA 2002, Industrial Fluidization South Africa |
| S15 | Surface Mining 1996
Edited by H.W. Glen | S31a | APCOM 2003—Application of Computers and Operations Research in the Minerals Industries |
| S16 | Hidden Wealth (1996)
Edited by H.W. Glen | S32 | ISSA/Chamber of Mines Conference—Mines and Quarries: Prevention of Occupational Injury and Disease |
| S17 | Heavy Minerals 1997
Edited by R.E. Robinson | S33 | ISRM—Technology Roadmap for Rock Mechanics |
| | | S34 | Heavy Minerals Conference 2003 |
| | | S35 | Safety in Mines Research Institutes (2003) |
| | | S36 | VII International Conference on Molten Slags, Fluxes & Salts (2004)
Tenth International Ferroalloys Congress INFACONX 2004 |
| | | S37 | Deep and high stress mining 2004 |
| | | S38 | ‘Platinum adding value’ 2004 |
| | | S39 | Base Metals—Southern Africa’s response to changing global base metals market dynamics 2005 |
| | | S40 | Strategic <i>versus</i> Tactical approaches in mining 2005 |
| | | S41 | Best practices in rock engineering SARES 2005 |
| | | S42 | IFSA 2005, Industrial Fluidization South Africa |
| | | S43 | Southern African Pyrometallurgy 2006 International Conference |
| | | S44 | Stability of rock slopes in open pit mining and civil engineering situations |
| | | S45 | ‘Platinum Surges Ahead’ 2006 |
| | | S46 | Hydraulic Transport of Solids - Hydrotransport 17 (2007) |
| | | S47 | Fourth Southern African Base Metals Conference ‘Africa’s base metals resurgence’ |
| | | S48 | Heavy Minerals Conference, 2007 |

S49	Cave Mining Conference, 2007	S88	AMI–Nuclear Materials Development Network 2015
S50	International Symposium on Lead and Zinc processing – Lead & Zinc 2008	S89	MPES–23rd International Symposium on Mine Planning & Equipment Selection 2015
S51	Surface Mining 2008	S90	Diamonds still Sparkling Conference 2016
S52	Platinum in transformation 2008	S91	The SAMREC/SAMVAL Companion Volume Conference 2016
S53	IFSA 2008, Industrial Fluidization South Africa	S92	New Technology and Innovation in the Minerals Industry Colloquium 2016
S54	Hydrometallurgy Conference 2009	S93	Theoretical Rock Mechanics for Professional Practice (Special Publications Series 9) by M. Handley - 2016
S55	Shotcrete for Africa 2009	S94	Hydrometallurgy Conference 2016
S56	Base Metals Conference 2009	S95	10 TH Heavy Minerals Conference 2016
S57	Heavy Minerals Conference, 2009	S96	MineSafe Conference 2016
S58	Hard Rock Safe—Safety Conference 2009	S97	AMI-Ferrous and Base Metals Development Conference 2016
S59	Sampling and Blending 2009	S98	3rd Young Professionals Conference 2017
S60	World Gold 2009 Conference	S99	Proximity Detection and Collision Avoidance Systems in Mining Colloquium 2017
S61	Physical Beneficiation Conference 2010	S100	6 TH Sulphur and Sulphuric Acid Conference 2017
S62	Second Hardrock Safe—Safety Conference 2010	S101	Mine Planning Colloquium 2017
S63	Platinum in Transition ‘Boom or Bust’ 2010	S102	Chrome Colloquium 2017
S64	South African Pyrometallurgy 2011 International Conference	S103	4 TH Mineral Project Valuation Colloquium 2017
S65	Minefill 2011 (10 TH International Symposium on Mining with Backfill)	S104	Water Conference 2017
S66	Base Metals Conference 2011	S105	Rapid Underground Mine and Civil Access Engineering 2017
S67	MineSafe 2011 Conference	S106	MineSafe Conference 2017
S68	Iron Ore and Manganese Ore Metallurgy 2011	S107	Uranium 2017 International Conference 2017
S69	Percolation leaching: The status globally and in Southern Africa 2011	S108	IFSA 2017–Industrial Fluidization Conference 2017
S70	IFSA 2011, Industrial Fluidization South Africa	S109	AfriRock 2017–ISRM International Symposium 2017
S71	Southern Hemisphere International Rock Mechanics Symposium 2012	S110	AMI Precious Metals 2017–The Precious Metals Development Network (PMDN) Symposium
S72	Platinum Conference ‘A catalyst for change’ 2012	S111	7 TH International Platinum Conference 2017
S73	Ferrous 2012—Ferrous and Base Metals Development Network Conference	S112	Infacon XV: International Ferro-Alloys Congress 2018
S74	Diamonds - Source to use 2013	S113	SOMP–Society of Mining Professors 6 TH Regional Conference 2018
S75	Sampling and analysis: Best-practice in African mining 2013	S114	Digitalization in Mining Conference 2018
S76	Base Metals Conference 2013	S115	Diamonds – Source to Use 2018 Conference 2018
S77	Precious Metals 2013 Conference—The Precious Metals Development Network (PMDN)	S116	The 9 TH Southern African Base Metals Conference 2018
S78	Physical Beneficiation 2013 Conference	S117	Geometallurgy Conference 2018
S79	21st Century challenges to the southern African coal sector 2014	S118	Mine Safe Technical Conference and Industry Day 2018
S80	Furnace Tapping Conference 2014	S119	ASM Conference 2018
S81	Platinum Conference ‘Platinum—Metal for the Future’ 2014	S120	4 TH Young Professionals Conference 2018
S82	IFSA 2014, Industrial Fluidization South Africa	S121	Furnace Tapping 2018 Conference 2018
S83	Copper Cobalt Africa 2015	S122	7 TH Sulphur and Sulphuric Acid Conference 2019
S84	The Danie Krige Geostatistical Conference 2015 - Vol. 1	S123	Mine Planner’s Colloquium 2019
	The Danie Krige Geostatistical Conference 2015 - Vol. 2	S124	9 TH International Conference on Deep & High Stress Mining 2019
S85	World Gold Conference 2015	S125	New Technology Conference and Trade Show 2019
S86	Slope Stability 2015	S126	Smart Mining Smart Environment Smart Society Conference 2019
S87	2nd Annual Young Professionals Conference 2015	S127	The Eleventh International Heavy Minerals Conference 2019

S128	Surface Mining Masterclass 2019	S151	COMRO's Legacy: Research and Development of Stopping Mining Machinery and Technologies (Special Publications Series 13) by B. Protheroe - 2023
S129	International Mine Health and Safety Conference 2019	S152	Copper Cobalt Africa in Association with The 10TH Southern African Base Metals Conference 2023
S130	Tailings Storage Conference 2020	S153	Digital Transformation in Mining Conference 2023
S131	IMPC2020 XXX International Mineral Processing Congress	S154	Diamonds Source to Use 2023 Online Conference
S132	Johannesburg and its Holey Mining Heritage (Special Publications Series 10) by T.R. Stacey - 2021	S155	12TH International Heavy Minerals Conference 2023
S133	Mineral and Metal Extraction — An Overview (Special Publications Series 11) by L.C. Woollacott and R.H. Eric - 2021	S156	Geometallurgy Conference 2023
S134	Diamonds - Source to Use - 2021 Online Conference 2021	S157	Next Generation Tailings Opportunitiy or Risk? Conference 2023
S135	WorldGold Online Conference 2021	S158	6TH Young Professionals Conference 2023
S136	APCOM 2021 Minerals Industry4.0-The next digital transformation in mining	S159	Southern African Pyrometallurgy 2024 International Conference
S137	5TH Young Professionals Online Conference 2021	S160	The 11TH World Conference of Sampling and Blending 2024
S138	Southern African Rare Earths International Online Conference 2021	S161	SANIRE Symposium 2024 Technical Applications in Rock Engineering
S139	SAMCODES Conference 2021	S162	2ND International Conference 2024 Southern African Rare Earths
S140	Global Tailings Standards and Opportunities'For the Mine of the Future Conference 2022	S163	2ND Battery Materials Conference 2024
S141	The Fall of a Giant: The story of the disintegration of the South African Mining Industry (Special Publications Series 12) by I. Robinson - 2022/2023	S164	Hydrometallurgy Conference 2024
S142	Battery Materials Conference 2022	S165	Environmental Social Governance Sustainability Conference 2024
S143	32ND SOMP Annual Meeting and Conference 2022	S166	MineSafe Mine Health and Safety Conference 2024
S144	SDIMI (Sustainable Development in the Minerals Industry) 10TH International Conference 2022	S167	Mintek@90 Conference 2024
S145	THANOS International Conference 2022	S168	Mine Closure Conference 2025
S146	Mine Impacted Water Online Conference 2022 (Abstract Book Only)	S169	2ND Southern African Hydrogen and Fuel Cell Conference 2025
S147	8TH International PGM Conference 2022	S170	9TH Sulphur and Sulphuric Acid Conference 2025
S148	SANCOT Symposium 2022	S171	4TH Digital Transformation in Mining Conference 2025
S149	8TH Sulphur and Sulphuric Acid Conference 2023	S172	AfriRock 2025 Pioneering Progress Conference
S150	Southern African Hydrogen and Fuel Cell Conference 2023	S173	Thirteen International Heavy Minerals Conference 2025
		S174	International Mineral Asset Valuation Conference 2025
		S175	Geometallurgy Conference 2025
		S176	9TH International PGM Conference 2025

Published by The Southern African Institute of Mining and Metallurgy
Minerals Council South Africa, 7th Floor, Rosebank Towers, 19 Biermann Avenue, Rosebank, 2196
Republic of South Africa

© The Southern African Institute of Mining and Metallurgy, 2025

ISBN 978-0-6398820-6-2

The papers in this volume have been for the most part prepared from Word documents supplied by the authors,
with additional typesetting and formatting by The Southern African Institute of Mining and Metallurgy.

Organising Committee

G. van Greunen, Conference Chairperson

T. Balfour	L. McMaster
J. Böning	A. Muller
W. Deysel	L. Ndelu
E. Kleinhans	Z. Ndese
C. Legodi	S. Phakathi
M. Letebele	H. Prinsloo
N. Mahwasane	O. Rakumakoe
S.C. Mashile	G. Sekwati
D. Masilela	S. Sepetla
S. Masanabo	B. Shirindza
X. Mbonambi	R. van der Berg

The Organising Committee would like to thank the reviewers listed below for the efforts in the reviewing process

T. Balfour
W. Deysel
J. Fourie
D. Labuschagne
F. Magweregwede
L. McMaster
N. Moyo
L. Moorosi
Z. Ndese
G. van Greunen

FOREWORD

As an industry built on the strength, skill, and resilience of its people, mining's most important responsibility remains the protection of life. Every life lost represents a profound tragedy that must renew our determination to do better — to lead, to innovate, and to care.

This year, the South African mining industry recorded **39 fatalities**, compared to 33 during the same period in 2024. This regression reminds us that safety is not an achievement that can be claimed once, but a continuous journey requiring relentless focus, leadership, and accountability. Each number represents a colleague, a family, and a community forever changed — and each must inspire us to redouble our efforts to make 'zero harm' not just an ambition, but a lived reality.

The **MineSafe Conference** stands as a central pillar of this collective journey. It brings together all who share responsibility for the well-being of the sector — from the **Department of Mineral Resources and Energy** and the Minerals Council South Africa, to organised labour, health and safety practitioners, and the many men and women who make mining possible. It is here that we pause to reflect, to learn, and to strengthen our commitment to safer, healthier, and more sustainable mining operations.

The 2025 theme — *Safe Mines, Healthy Lives, and Sustainable Futures* — speaks directly to our shared purpose. It challenges us to expand our view of safety beyond compliance and statistics, towards a holistic culture that values health, human dignity, and environmental care as inseparable parts of sustainable performance. It calls on us to recognise that sustainable futures are only possible when every miner works in an environment that is both safe and empowering.

Over the past three decades, collaboration among industry partners has delivered remarkable progress in risk reduction, technology adoption, and health outcomes. These achievements prove that we can make lasting change when we work together. Yet, they also remind us that the journey is far from over. The task ahead demands courageous leadership, practical innovation, and an unwavering belief that every fatality is preventable.

The **Industry Awards Day**, to be held on **21 November 2025**, will celebrate individuals and organisations who have demonstrated excellence in safety, health, and sustainability. Their achievements reflect what is possible when passion and purpose align — and they serve as a powerful reminder that safe, responsible, and sustainable mining is within our grasp.

Let MineSafe 2025 be a time not only to recognise progress but to recommit ourselves to the future we all want to build — one where **every mine is safe, every worker thrives, and every community benefits**. Together, we can and must deliver on the promise of **safe mines, healthy lives, and sustainable futures**.

G. van Greunen
Chairperson: Organising Committee

Contents

Page No

Real-time temperature profiling in underground mines: A proof of concept using distributed temperature sensing based on optical fibre Y. Hleta, M. Mochubele, P.D. Seroba	1
Identifying safety risks and future research directions in the pursuit of zero harm in South African mines: A review of mine health & safety council initiatives L.A. Maseko	15
Efficiency and sustainability: Evaluating the performance of lime-based expansive agents in hard rock mining – A field study M. Mekgwe, T. Mmola, H. Grobler	27
Eliminating fall of ground incidents in underground mines: Lessons from Australia for the Southern African mining industry A. Mapuranga	43
Beyond compliance: Addressing psychosocial risks in Southern African mining - integrating ubuntu, systems thinking, and innovative practices for a sustainable workforce A.K.B. Chigwada	53
Understanding battery chemistries, safety considerations, and suppression challenges in the mining industry A.K. Townsend, J. van Rensburg, H. Olivier	63
Bridging gaps in mining safety understanding: Leveraging visual animations to overcome language and literacy barriers A.K.B. Chigwada	81

The organisers of the conference thanks the following sponsors for their support

PREMIUM CONFERENCE EXHIBITORS



CONFERENCE EXHIBITORS



INDUSTRY DAY EXHIBITORS



INDUSTRY DAY BANNER SPONSOR



Real-time temperature profiling in underground mines: A proof of concept using distributed temperature sensing based on optical fibre

Y. Hleta¹, M. Mochubele², P.D. Seroba²

¹PositionNXT, South Africa

²University of the Witwatersrand, South Africa

In response to the September 2024 directive by the Mine Health and Safety Inspectorate in South Africa, mandating continuous monitoring of environmental conditions, specifically temperature, noise, and airborne pollutants, this study explores the viability of adopting real-time technologies as a regulatory necessity. This paper presents a proof of concept evaluating the application of Distributed Temperature Sensing (DTS), based on optical fibres, for real-time monitoring of thermal conditions in underground mining environments. The experimental results demonstrate that Distributed temperature sensing offers high-resolution, continuous dry-bulb temperature profiling with an accuracy of up to $\pm 1^\circ\text{C}$, as validated against standard thermometers over a six-hour monitoring session. Notably, DTS enables the generation of spatially rich 3D thermal maps, allowing ventilation engineers to visualise airflow patterns, temperature gradients, and potential thermal hotspots in real time. By extending temperature monitoring over several kilometres using fibre-optic cables, distributed temperature sensing significantly outperforms traditional point-based sensors in both spatial and temporal resolution. The study establishes distributed temperature sensing as a promising tool for enhancing thermal risk management, ventilation control, and regulatory compliance in underground mines.

Keywords: Distributed temperature sensing, real time, fibre, thermal map, underground

INTRODUCTION

The real time profiling of temperature variations is a critical aspect in safeguarding the mineworker's health and safety against risks such as heat stress and underground fires which can ultimately lead to fatalities. A study by Aminossadati et al. (2010) looking into the applicability of Distributed Temperature Sensing in underground environments, stated that in underground mines most safety concerns are due to temperature rises and the lack of proactive monitoring which can lead to serious disasters. A plethora of environmental conditions monitoring strategies have been employed in the mining industry including scheduled workplaces walk-through inspections and daily workplace measurement by the personnel as a regulatory enforcement, which clearly lack the principle to provide reliable and consistent real-time temperature variations. This hampers the ability to provide and maintain the ventilation supplied in response to the real time underground environmental conditions.

Recognising the health & safety implications, and the need for proactive control, the Department of Mineral and Petroleum Resources (DMPR) issued a directive in September 2024 mandating continuous real time monitoring of temperature, air velocity, noise, and airborne pollutants. Mines that fail to comply risk penalties and Section 54 stoppages under the MHSA, with significant production and financial consequences. This regulatory pressure highlights the urgent need for technologies capable of providing reliable, real-time environmental data.

By deploying Distributed Fibre-Optic Sensing (DFOS) also commonly known as distributed temperature sensing (DTS), mine operators can establish a real-time, spatially continuous thermal monitoring system that informs ventilation control, maintains safe dry-bulb temperature thresholds, and supports regulatory compliance. DTS enables early detection of abnormal heat signatures associated with equipment fires or spontaneous combustion by tracking the movement and intensity of hot gases along mine passages, capabilities that far surpass traditional point sensors. This study presents a laboratory proof-of-concept to evaluate DTS accuracy, sensitivity, and deployment considerations for underground applications.

LITERATURE REVIEW

Current Mining Industry Environmental Monitoring Practices

Regulation 9.2(2) of the MHSA 29 of 1996 read with Section 11(4)(a) and 12 compels the employer to establish and maintain a system for occupational hygiene measurements. In response to the regulatory requirements, mines conduct walk-through inspections at intervals of 30 days for temperatures above 27.5°C wet-bulb in all underground working areas. During these audits, personnel measures wet-bulb and dry-bulb temperature, air velocity and wet-kata cooling power of air. In addition, there are daily environmental audits conducted as part of workplace safe declaration, although these are limited to only the wet air velocity, bulb and dry bulb temperature measurements. These assessments are carried out using cost effective and simple to use instruments such as whirling hygrometers and vane anemometer.

A significant limitation of manual monitoring is its reliance on human intervention, which introduces inconsistencies in data collection. This dependency often results in data gaps or inaccuracies, making it difficult to obtain a reliable and continuous representation of environmental conditions, particularly at critical monitoring points. periodic audits in nature provide only snapshots of environmental conditions at specific times, failing to capture the dynamic and rapidly changing nature of underground environments. This reactive approach delays the identification of potential risks, especially those associated with heightened heat levels, and hampers timely corrective actions.

A key issue arises in the investigation of heat-related incidents, which is not conducted immediately after an event occurs. Given the dynamic nature of underground environments, delays in investigation compromise the reliability of retrieved data. This reactive approach can delay the detection of heat-related hazards and postpone corrective actions. For instance, if a heat incident is caused by a non-operational ventilation fan, remedial actions may be implemented before the investigation takes place. Consequently, measured conditions may not accurately reflect those present at the time of the incident, underscoring the limitations of manual environmental monitoring.

Current mine ventilation monitoring methods suffer from several critical limitations. Manual inspections provide data only at discrete locations and times, leaving extensive airway segments unmonitored and risking undetected hotspots or airflow irregularities between measurement points, or buildup in between measurements. Routine walk-through surveys are labour-intensive and prone to transcription errors and inconsistent measurement techniques, further delaying hazard detection and undermining data reliability.

Real Time Monitoring Technologies Available in the Market

Several technologies have been explored for underground real-time environmental monitoring, including thermal imaging, infrared cameras, point-type sensors with SCADA integration, and Distributed Temperature Sensing (DTS). Their suitability depends on accuracy, coverage, redundancy, cost, and maintenance.

Thermal imaging cameras measure surface temperature and can trigger alarms when thresholds are exceeded. However, they require line of sight and are highly affected by dust, which scatters infrared radiation and causes false readings (Visagie & Pearton, 2018; Francis, 2023). Their reliance on object temperature rather than ambient air conditions further limits effectiveness in humid or wet environments where water can mask heat signatures. Coverage is also localized, creating blind spots in complex tunnels, while multiple installations increase cost and maintenance.

Infrared cameras detect heat signatures and are effective for fire detection, but their range is limited; fires must grow larger with distance before being detected (Visagie & Pearton, 2018). Like thermal imaging, they require a clear line of sight and are compromised by dust, moisture, and wear, making them unsuitable for underground mining despite successful use in industrial facilities. Point-type sensors linked to SCADA are widely used to monitor parameters such as gas levels, humidity, barometric pressure, and temperature. They provide continuous logging and alarms but cover only their immediate vicinity, requiring extensive networks for broader coverage. Installation is complex, maintenance is high, and accuracy is affected by airflow, dust, and diesel fumes.

Distributed Temperature Sensing (DTS) transforms an optical fibre into a continuous linear sensor, providing seamless temperature profiles across long distances. Unlike point-based systems, DTS offers intrinsic safety, resistance to fire, radiation, electromagnetic and radio frequency interference, and enables secure and self-calibrating data transmission in hazardous environments (Aminossadati et al., 2010). With wide-area coverage from a single location and minimal maintenance, DTS offers a practical and scalable solution for real-time underground monitoring (Luna Innovations, undated).

Visagie & Pearton (2018) developed a comparison framework between the various real time temperature monitoring technologies such as DTS, thermal imaging, EMS and bearing temperature. These systems were assessed for application on a conveyor belt installation based on reliability, survivability, and availability. The scoring matrix uses a 0–2 scale, where 0 = Poor (does not meet the criterion), 1 = Average (partially meets the criterion with limitations), and 2 = Good (fully meets the criterion effectively). Weighted scores are then calculated across categories of reliability, survivability, and availability to give an overall Control Quality Score for each technology. The DTS technology emerged as the most favourable system for adoption based on the comparison and scoring mechanism applied, see Figure 1.

CONTROL QUALITY CALCULATION:		Thermal Imaging	Linear Heat (DTS)	EMS	Bearing Temperature
Reliability	Will the control detect heat/gas prior to a flame?	2	2	0	1
	Is the technology proven?	2	2	2	2
	Is the technology proven for early detection on underground conveyors?	1	0	0	2
	Is the system failsafe/ have redundancy?	1	2	1	0
	Is the design practical for full length of belt?	0	2	2	0
Survivability	Can it be damaged, impaired?	1	1	1	1
	Can the control be maintained during normal operating hours?	2	1	2	1
	Is failure automatically detected?	1	2	1	2
Availability	Can the system operate without mains power?	1	1	1	1
	Is the system easy to maintain?	1	2	1	2
	Can the control be tested to confirm correct operation?	2	2	2	1
Weighted Score		14	17	13	13
Control Quality Score		64%	77%	59%	59%
* Scoring: Good = 2; Average = 1; Poor = 0					

Figure 1. Control quality comparison

Distributed Temperature Sensing Working Principle

Principles of Operation

Distributed Temperature Sensing (DTS) uses an optical fibre as a continuous sensor by launching pulsed laser signals into the cable and analysing the Raman backscattered light along its length. The time-of-flight of the return signal, similar to optical time domain reflectometry (OTDR), determines the location of each measurement, while the ratio of the temperature-independent Stokes signal to the temperature-sensitive anti-Stokes component provides the local absolute temperature. In this way, DTS generates continuous temperature profiles with typical spatial resolutions of 0.25–0.5 m and measurement ranges of up to 8–10 km. Modern interrogators can scan an entire fibre in intervals of 5–10 seconds, enabling near real-time monitoring.

Key Equations

Temperature at distance z :

$$T(z) = \frac{\gamma}{K - \Delta\alpha z - (\ln I_s(z)/I_{as}(z))} \quad [1]$$

Where γ is a system constant set by the Raman energy shift, K is a calibration offset, and $\Delta\alpha$ accounts for differential attenuation between Stokes and anti-Stokes signals along the fibre.

Location (time-of-flight / OTDR):

$$z = vt/2 \quad [2]$$

with v the speed of light in the fibre ($\approx 2 \times 10^8 \text{ m.s}^{-1}$) and t the measured round-trip time.

The ratio I_{as}/I_s largely cancels common-mode signal losses, but because the Stokes and anti-Stokes components occupy different wavelengths, they experience different attenuation which is captured by the $\Delta\alpha z$ term in the temperature equation. Accurate temperature retrieval therefore depends on calibration, the constants K , γ and $\Delta\alpha$ must be determined for single-ended or double-ended methods, with double-ended configurations particularly effective at compensating for non-uniform attenuation along the cable. Because Raman backscatter is intrinsically weak, system signal-to-noise is improved by pulse stacking and temporal or spatial averaging. Consequently, temperature resolution improves with averaging but degrades with distance due to attenuation (typical resolution ≈ 0.01 – 1°C). Once a system is properly calibrated, however, its absolute accuracy is largely independent of distance.

Performance

Visagie and Pearton (2018) note that DTS can sample every 0.25–0.5 m and sense temperature changes as small as $\sim 0.1^\circ\text{C}$ with high-quality systems, over continuous lengths of several kilometres. The entire length of the fibre can be monitored in real time, providing a continuous temperature profile and heat-flow estimate at once, hence this dense spatial and temporal data is far beyond what discrete point sensors (thermocouples, etc.) can offer in a mine.

Installation

In mining applications, the fibre cable is typically installed along the excavation or equipment to be monitored (e.g. attached to or embedded in airways, declines, or conveyor frames). The fibre's path should be chosen to be as close as practical to potential heat sources, since small, localized fires or hotspots require the fibre to be nearby for detection. As noted by Visagie & Pearton, "when the heat source is small, the position of the cable is crucial to ensure that the cable detects the radiated, convected or conducted heat". In other words, DTS is inherently a linear heat detector it senses heating where the cable is placed, so careful routing ensures coverage of critical areas.

Mining ventilation applications and test findings

Several studies have demonstrated the use of DTS in underground ventilation contexts. Notably, Aminossadati et al. (2010) conducted an underground mine trial using DTS. In the trial fibre was installed along mine tunnels and used the system to map the entire air temperature profile. This experiment showed that DTS could serve as a powerful ventilation monitoring tool: the fibre-based DTS system provided valuable information for the mine safety control and the mine ventilation system. In their tests, the DTS measured air temperature throughout the mine with $\sim 1^\circ\text{C}$ accuracy and 1 m spatial resolution. The system clearly detected both heating and cooling fronts in the airflow and could quantify heat generation at any location for example, from geological sources or equipment using the distributed temperature data. In practice, this means a ventilation engineer can see exactly where the mine is heating up or cooling down, in real time, rather than relying on sparse point sensors. Aminossadati et

al. (2010) even suggest that integrating DTS with other mine monitoring like gas sensors and ventilation controls could lead to a safer, automated ventilation control regime.

Industry experts have similarly recognized DTS for fire and heat detection in mines. At a Mine Ventilation Society of South Africa (MVSSA) conference, Visagie & Pearton (2018) reviewed DTS as a proactive detector especially for conveyor belt fires and tunnels. They highlight that DTS is already used in many tunnel and conveyor applications (“metro and train tunnels, manufacturing and warehouses, and conveyor belt systems”), effectively giving continuous coverage along long linear structures. By monitoring the entire cable length, DTS can provide early warning of temperature rises anywhere along a belt or airway. In fact, for belt conveyors which is a leading fire risk in mines, DTS has been deployed to continuously scan the belt for hot spots. The system can trigger an alarm or suppression long before a flame develops, simply by detecting a rising temperature zone. Its millimetre-scale resolution means even small local heat (e.g. a bearing overheating) can be seen if the fibre passes nearby. Overall, these studies show that DTS yields richer thermal information than traditional sensors, covering wide areas and capturing subtle changes in ventilation behaviour.

Limitations and considerations

While DTS offers many advantages, the literature also notes some practical limitations. First, fibre placement is critical: if the cable is too far from a small heat source (say, off the conveyor or away from a drift wall), a developing fire may not raise the local fibre temperature enough for early detection. This means system designers must plan fibre routes to “hug” potential hazards (rollers, motors, power cables, interfaces between airways, etc.).

Second, DTS systems require careful support infrastructure. For reliability, redundancy is recommended: for example, Visagie & Pearton discuss dual controllers and dual fibres as backup. Importantly, they note that any redundancy requires uninterrupted power (UPS) for the DTS units and their communications links. In other words, the DTS measurement loop must remain live even during power outages. Fiber optic cables themselves are passive and immune to electrical interference, but the interrogator electronics need a continuous power source.

Another challenge is calibration and drift, fibre attenuation and connector losses can change over time, though modern Raman-DTS systems often use double-ended or referential calibration to compensate. In practice, one must occasionally verify that the DTS readings match fixed thermometers at key points. This is noted in broader DTS literature (e.g. advanced DTS systems include continuous calibration routines) even if not highlighted in the mine studies. Finally, DTS measures only temperature it does not directly detect toxic gas or smoke. Mine safety still requires separate gas monitoring (CO, methane, etc.). The idea, however, is that temperature data enriches ventilation management, for example, a sudden temperature rise might indicate a methane ignition or a ventilation failure, prompting further action. Aminossadati et al. (2010) foresaw linking DTS to gas sensors and control systems for an integrated safety approach.

Currently the optical fibres DTS only measures the dry bulb temperature. Dry-bulb temperature monitoring aids in determining whether the situation calls for official heat stress management (HSM) initiatives. Temperatures below 37°C are seen to be part of the optimum environment to decrease the danger of heat stress, routine work is advised not to be permitted if the dry-bulb temperature exceeds this number. Although wet-bulb temperature is the primary driver of evaporative cooling in hot, humid conditions, dry-bulb temperature remains a critical parameter both as a direct measure of ambient heat load in indoor settings and as an integral component of heat stress. With a maximum deviation from wet bulb under extreme conditions not exceeding 5 degrees and an average of 3, a good correlation can be drawn between the two, especially when considering fluctuations over time.

EXPERIMENTAL DESIGN

Study Site and Physical Layout

The proof-of-concept was conducted in a university computer laboratory measuring 14 m in length, 7 m in width, and 3 m in height, see Figure 2. The room was enclosed on three sides by solid walls and on one side by glazed windows. Air-conditioning diffusers were located at floor level along the window wall, and fluorescent luminaires were ceiling mounted. Computer workstations occupied the central floor area and generated localized heat sources during occupancy tests.

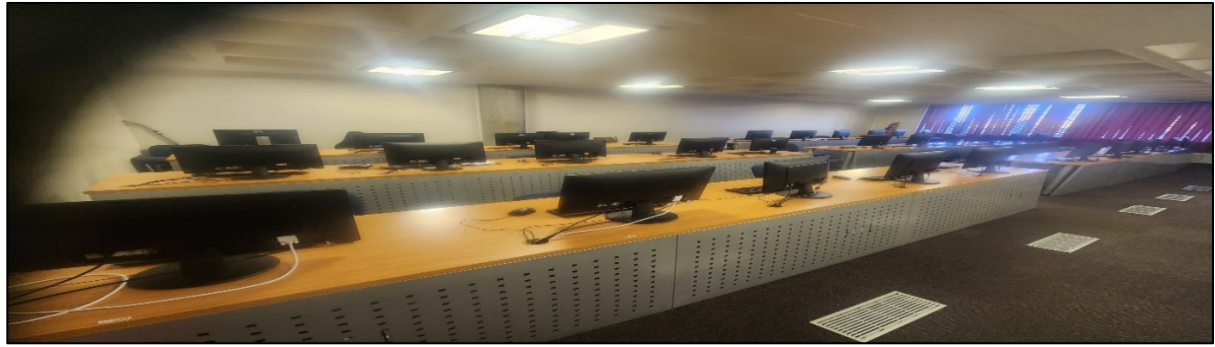


Figure 2. University computer laboratory

Fiber Optic Cable Routing and 3d Model

A steel-armoured multimode fibre optic cable (total length 60 m) was routed as follows; Ceiling run: 15 cm below the ceiling along half the room perimeter, to capture room temperature. Window sill run: 50 cm above the floor adjacent to the wall, to monitor heat exchange due to solar gain and convective airflow. A 3D building information model was produced to document the cable routing and lab geometry. The model was used to generate plan and elevation views for precise cable placement. The cable was sectioned into 8 zones along the length of the room as depicted in Figure 3 and Table I.

The zones were created to easily monitor the temperature values across the room. A temperature gradient was set for the cable with red indication the highest temperature value and blue indicating the lowest temperature value. The data was analysed in five-minute intervals from a temperature profile.

Table I: Zone Configuration

Zone	Interval (m)
1	0 – 9.5
2	9.5 – 17
3	17 – 29.5
4	29.5 – 37
5	37 – 42
6	42 – 44.5
7	44.5 – 49
8	49 – 60

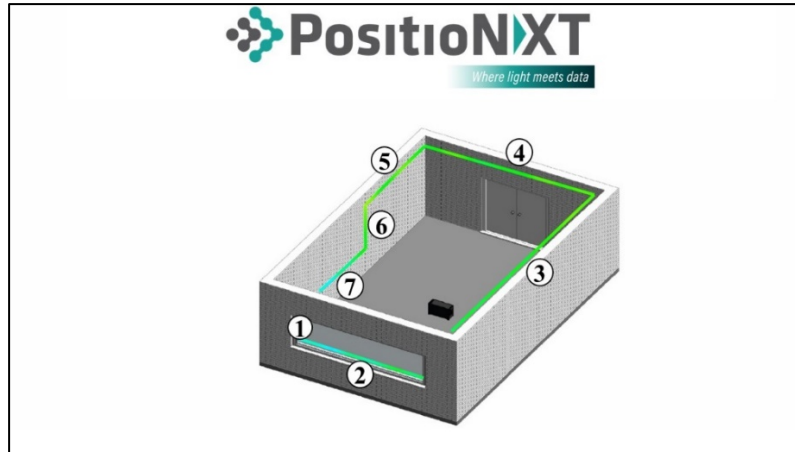


Figure 3. 3D heat map of the lab with zones labelled

Environmental Conditions and Baseline Measurement

Prior to any intervention, the laboratory was conditioned to static environmental settings with the air-conditioning disabled, windows closed and lighting off. Under these baseline conditions, temperature profiles along the fibre were recorded continuously for 60 minutes. This established reference temperature gradients.

Regulated Environmental Disturbances

To evaluate system responsiveness, a series of timed interventions was introduced. Windows were opened for one hour and then closed for one hour in two cycles, the air-conditioning was alternately enabled and disabled for one-hour periods, and lighting was toggled on and off at one-hour intervals. All interventions were time-stamped and logged, and the sequence was varied in replicate runs to assess repeatability and minimise sequence effects.

Simulated Occupancy and Thermal Load

To simulate peak human and equipment heat loads, 50 occupants entered the lab and operated workstations for 60 minutes under the following conditions: windows closed, air-conditioning disabled, and lighting at full output. Continuous temperature monitoring via the fibre cable captured transient thermal responses associated with metabolic and equipment heat flux.

Data Acquisition and Processing

Temperature was sampled along the fibre at 1 m spatial resolution and 30 s temporal resolution. Data was exported for post-processing, which involved generating line plots to compare temperature evolution at representative ceiling and windowsill segments and correlating anomalies with environmental triggers such as air-conditioning status, lighting, and occupancy. System performance was assessed in terms of response time to interventions, thermal distribution along the fibre, and the stability and accuracy of DTS against reference thermometer readings.

RESULTS AND DISCUSSION

Room temperature

A thermometer was located at zone 7 (Figure 3), this was the location that was chosen to monitor the room temperature and check how that value corresponded to the temperature measured by the fibre cable at that location which was at 48m. Over the course of 6 hours of continuous monitoring, the difference between the two measured temperatures was 1°C which was an acceptable difference.

Heat sources

The lights were turned off at 10:16 am and the screenshot in Figure 4 was recorded at 11:28 am. The lights were turned on at 11:28 am and the screenshot in Figure 5 was recorded at 12:06 pm. It is evident that the radiation from the light source influenced the temperature in the vicinity. When comparing the two images, there are two hotspots in zone 5 which correspond to the two sources of light that were in this area. In Figure 6 encircled in red, the two hotspots are registered as two peaks on the graph at 38.5m and 41.5m reading 26.78 °C and 26.62 °C respectively.

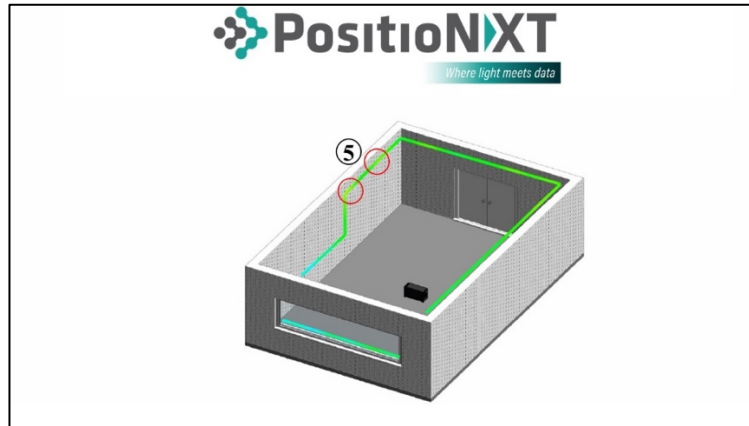


Figure 4: Zone 5 with the lights turned off



Figure 5: Zone 5 with the lights on

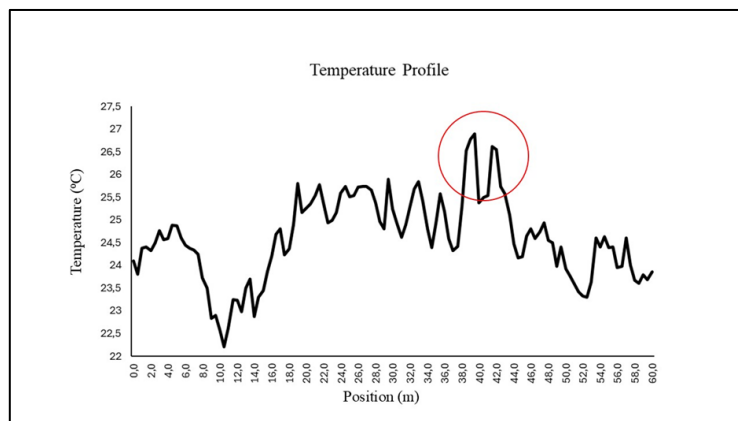


Figure 6: Temperature profile at 12:31 pm

The section of the cable in zone 2 installed on the window sill was in contact with the concrete by means of duct tape, see Figure 7. As seen, zone 2 has a lower temperature than the rest of the room, this is because the windows were open and there was airflow into the lab. The direct contact with the surface also contributed to the low temperature as the other zones were clipped to the wall using adhesive clip-ons rather than duct tape. In Figure 8, encircled in red is the section of the cable that was duct taped to the window sill. As seen the temperature in this zone is lower than the entire length of the cable. This is because of direct contact with the concrete surface and the proximity to the open windows.



Figure 7: Zone 2 with windows open at 09:51 am

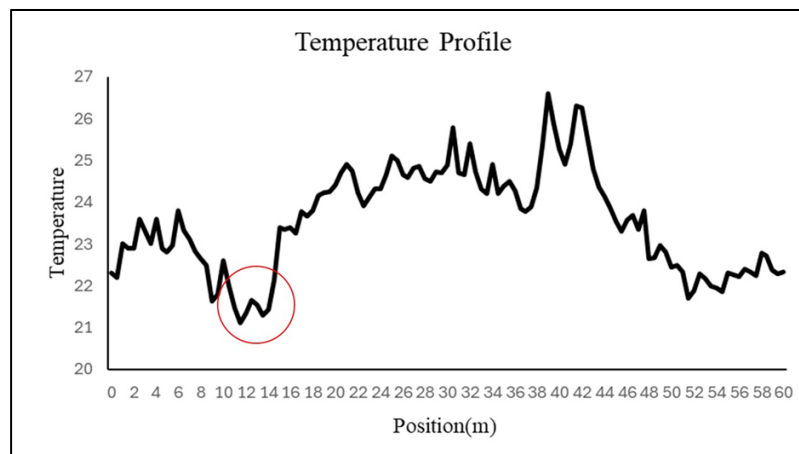


Figure 8: Temperature profile at 09:51 am

Occupancy

One of the objectives of the proof of concept was to investigate whether the fibre optic cable could detect a temperature in the lab because of the number of people inside. 50 students entered the lab at 12:30 pm and a lecture was conducted whilst the air conditioner was off, but the windows were open. There was a noticeable increase in the dry bulb room temperature during the duration of the lecture.

Table II below shows the lowest and highest temperatures recorded along the cable at different times, the lowest temperatures mainly came from zone 2 which was the location of the cable laid next to the window. The highest temperatures were recorded at the location of the ceiling lights which is located at Zone 5. The room thermometer was placed in zone 7, which is a 2.5m long segment.

Table II: Range of temperatures

Time	Room dry-bulb Temperature (Thermometer)	Room Temperature (DTS)	Lowest Temperature (Zone 2)	Highest Temperature (Zone 5)
11: 31 am	23.1	23.69	22 °C	25.8 °C
12:01 pm	23.4	23.81	22.16 °C	26.36 °C
12:31 pm	23.7	24.24	21.98 °C	26.79 °C
1:01 pm	24	24.66	22.52 °C	26.87 °C
1:31 pm	25.2	25.76	23.13 °C	27.35 °C
2:01 pm	22.4 °C	23.78	21.36 °C	25.82 °C

The temperature profiles were thirty minutes apart and room temperature increase was evident from the progression. When the lab was evacuated at 1:31 pm, the air conditioner turned on and the door opened, a drastic drop in temperature was noticed. The maximum dry bulb temperature recorded was 25.2 °C and the minimum 22.4 °C, registered at 2:01 pm. Figure 9 below shows the location of the hotspots at 1:31 pm which proved the radiation of the lights had a significant effect on the temperature of their surroundings.



Figure 9. Hotspot location

Figure 10 below provides a visual of the difference in temperature profiles over a span of two hours from 12:01 pm to 2:01 pm. Each line represents the temperature along the cable that was recorded at a particular time. The lab was occupied with students at 13:01 pm and as expected, there was an increase of room temperature as seen on the graph above. The decrease in room temperature at 2:01 pm was because the lab was empty and the windows and air conditioner was on. The lab was also empty at 12:01 pm but windows were closed, and the air conditioner was off hence the difference in temperature profile compared to the profile at 2:01 pm.

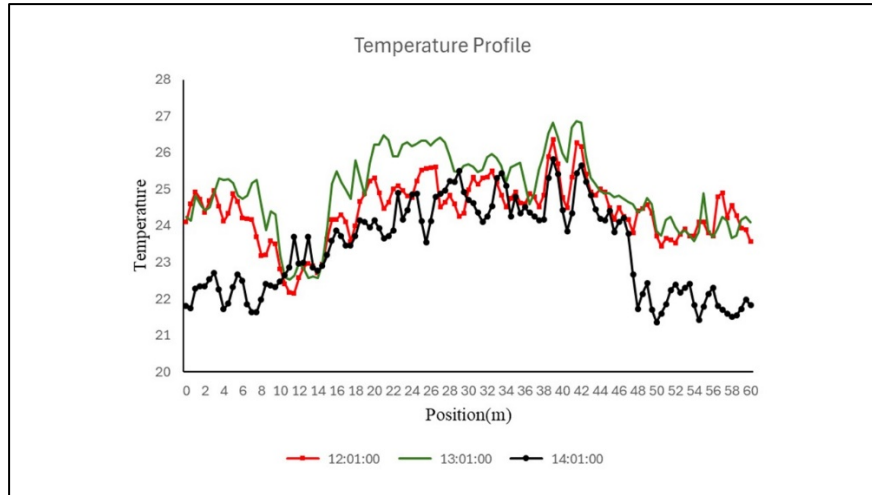


Figure 10. Temperature profile comparison

Validation of temperature measurements

The close agreement between the fibre-derived temperature at 48 m (zone 7) and the reference thermometer with a maximum deviation of 1 °C over six hours confirms the overall accuracy and stability of the DTS system under quasi-steady laboratory conditions. This level of agreement falls well within acceptable limits for mine-safety applications, where ± 1 °C resolution can reliably detect ventilation anomalies and localized hot spots. The slight offset likely reflects small calibration differences and the thermal lag inherent in the steel armoured cable, which were consistent over time and did not compromise detection of dynamic events.

Detection of localized heat sources

The controlled lighting experiments in zone 5 demonstrated the ability of the DTS to resolve discrete thermal peaks separated by as little as 3 m along the cable (peaks at 38.5 m and 41.5 m, Figure 6). The measured peak temperatures of 26.87 °C and 26.79 °C, rising from a 25 °C baseline, illustrate the system's sensitivity to modest heat inputs on the order of 1–2 °C. In underground mining tunnels (3–4 m $\times$ 3–4 m), similar radiative or convective heat inputs such as vehicle exhaust, lamp banks, or localized rock strata heating could be detected if the fibre is routed within 0.5–1 m of the heat source.

Influence of surface contact and airflow

Zone 2 measurements highlighted the impact of direct contact with the mounting surface and proximity to open windows: duct-taped cable segments exhibited temperatures 1–2 °C lower than ceiling runs under free-air conditions (Figure 7;8). In a mining context, close coupling of the fibre to the rock surface (e.g., clipped or bonded to the tunnel wall) would similarly enhance detection of rock-mass temperature variations, but may introduce bias if airflow currents are uneven. Careful mounting using clip-ons or adhesive anchor points to maintain a minimal air gap can mitigate thermal conduction effects while preserving spatial resolution of ventilation patterns.

Response to occupancy and ventilation changes

During the simulated occupancy test, the DTS system captured the progressive rise in dry-bulb temperature from 23.7 °C to 27 °C and back down to 22.4 °C following evacuation and air-conditioning activation (Table II, Figure 10). The measured response time on the order of minutes, confirms that the system can track transient ventilation changes, such as those induced by shifts in airflow rates or stoppage of fans. In underground mine roadways, where airflow velocities are higher and thermal inertia lower, the response times may be even shorter on the order of seconds to tens of seconds allowing near-real-time monitoring of ventilation performance and early detection of air-quality hazards.

Durability and terrain endurance

The steel armouring proved robust against routine handling and simulated interference in the lab; however, underground mining environments subject cables to abrasion, rock fall, and chemical exposure (e.g., diesel soot, moisture). To ensure long-term durability, the cable jacket should be rated for cut resistance and chemical inertness, and installation should include protective conduit or angled rock bolts in areas of high mechanical stress. Periodic visual inspections and automated integrity checks (e.g., optical backscatter loss monitoring) will further safeguard against damage.

CONCLUSION

This proof-of-concept demonstrates that Distributed Temperature Sensing (DTS) based on optical fibre is a practical tool for real-time thermal monitoring in confined environments, with strong potential for underground mine ventilation and thermal-risk management. In controlled laboratory tests, DTS produced stable temperature profiles with ± 1 °C accuracy, 1 m spatial resolution, and sub-minute responsiveness. It reliably detected localized heat inputs of 1–2 °C and tracked transient changes caused by occupancy and ventilation, confirming its ability to capture operational events and precursors to hazardous conditions.

For mining operations, these results translate into three benefits: wider spatial coverage than point sensors, real-time visualisation of ventilation behaviour, and enhanced early-warning of fires or thermal events when fibre is routed near heat sources. Correlation with thermometer readings further supports the use of DTS dry-bulb profiles in heat-stress and ventilation decisions. Practical limitations remain, including sensitivity to cable placement, calibration needs, and durability in abrasive, wet, or high-vibration environments. Addressing these requires protective installation, redundancy, and rigorous calibration protocols. We recommend phased field validation in representative underground settings, with integration into existing AMS and ventilation control systems.

In conclusion, DTS is a mature and deployable technology that meets DMPP requirements for continuous monitoring and can materially improve ventilation control, early warning, and compliance. Early adoption through pilot trials will reduce operational risk and build the experience needed for large-scale underground deployment.

REFERENCES

- Aminossadati, S. M., Mohammed, N. M., & Shemshad, J. (2010). Distributed temperature measurements using optical fibre technology in an underground mine environment. Elsevier, 220-229.
- Francis, B. (2023, December 30). Infrared for health. Retrieved from Infrared for health: <https://infraredforhealth.com/infrared-sensor-issues-can-dust-cause-interference/> [accessed 27 July. 2025].
- Visagie, C., & Pearton, J. (2018). Applicability of a DTS as a proactive detection system. MVSSA Annual Conference 2018: Doing more with less: Future challenges for the Ventilation professional (pp. 19-24). Johannesburg: The Mine Ventilation Society of South Africa.



Muthusi Marumo

Principal Technician
Mintek

Muthusi Marumo holds a National diploma in Biotechnology from University of Johannesburg (2009). Baccalaureus Technologiae (Btech) degree in Biotechnology from University of Johannesburg (2023). BSc Honours Environmental monitoring and modelling from University of South Africa (current). Over the past 15 years, I have gained considerable working experience in a mining and metallurgical research and development institution, Mintek. This experience has been developed in the areas of mineral extraction and environmental remediation. My mineral extraction experience involves project and operational management of lab scale and pilot plant heap and tank bioleaching projects on various base metals and gold. I have played an integral role in the commissioning and operation of mine impacted water treatment plants. I have received an achievement award for my role in the successful demonstration of our Biological Sulphate Reduction (BSR) process on a mine site. I am results orientated, adaptable and good at handling and resolving problems on the spot. I consider myself pragmatic and resourceful, capable of quickly learning as I go by being practically involved in the work.



Andre Veldsman

Director
PositionNXT

Andre Has spent the last 15+ years working as a test and measurement specialist focussing on sensors and sensing technologies across industries. From measuring explosions to bottle caps, he built up invaluable experience and custom sensing solution capabilities.

Identifying safety risks and future research directions in the pursuit of zero harm in South African mines: A review of mine health & safety council initiatives

L.A. Maseko

University of South Africa, South Africa

Although efforts continue to eliminate or reduce the harm to mine workers in South African mines, there are still accidents and occupational diseases on the job. Understanding the factors that lead to hazards remains the most important part of addressing safety risks to achieve zero harm. However, there remains limited research that systemically explores these causal factors.

The main objective of this study was to assess the progress towards zero harm by analysing research output funded by the Mine Health & Safety Council. This was done to identify research areas that may need attention through the lens of system safety. This research paper was intended to help the mining industry improve occupational safety and health outcomes.

Seventy funded projects covering the following areas were evaluated: occupational health, occupational safety, human factors, technological innovations, gender and diversity, policy, and regulatory framework. The analysis revealed that progress should be measured against the gaps identified to achieve zero harm. In addition, technological advancement must be tracked considering predictive approaches, artificial intelligence, and real-time risk tools. Training has increased since the Mining Qualification Authority has contributed to skills development, but behaviour change is lagging. The need for cultural change in the workplace has been identified but has not yet been achieved.

Key identified gaps include a lack of adoption and scalability of interventions, a lag in policy application, fast technology advancement compared to updates in regulation, and a more focused inclusion of diversity in system design. These findings suggest that the integrated systems approach that involves technology, policy, and human factors must evolve together. Improved metrics are required to track the results of funded research versus implemented safety changes. A visual road map with a matrix will be required for the stakeholder to identify areas of priority.

Keywords: mine safety, mine safety education, occupational health, occupational safety, systems safety

INTRODUCTION

Although efforts continue to eliminate or reduce the harm to mine workers in South African mines, there are still accidents and occupational diseases on the job. Understanding the factors that lead to hazards remains the most important part of addressing safety risks to achieve zero harm. However, there remains limited research that systemically explores these causal factors.

Mining in South Africa began in 1852 with the establishment of the first copper mining project, which led to the founding of the town of Springfontein in the Northern Cape Province. The large-scale coal production followed 12 years later (Casey, 2019). Since then, the mining industry has been characterised by a complex and long history marked by significant economic contributions and mining safety challenges. The severity of these safety challenges led to the promulgation of the Mine Health and Safety Act (MHSA) in 1996 as a mitigation strategy by the South African government, in addition to existing laws for this purpose. The MHSA eventually led to the establishment of the Mine Health and Safety Inspectorate and the Mine Health and Safety Council (MHSC), comprising representatives from government, organised business, and organised labour. (MHSA,1996)

The mandate of the MHSC encompasses a wide range of issues aimed at improving safety in the mining industry. These include providing expert advice to the Minister of Mineral Resources, promoting a safety culture in mines, formulating national policy, and finally funding and disseminating research to tackle the persistent and emerging occupational hazards associated with health and safety. The MHSC has been able to address these issues by organising its research into nine thrust areas. They are human factors and behavioural safety, explosions and fires, air pollutants, physical hazards, machinery and transportation, occupational diseases, rock bursts, rockfalls, and special projects. These foundational activities define the direction of the MHSC in addressing safety challenges in the mineral industry (MHSC, 1997).

The main goal the mining industry and the MHSC seek to achieve is zero harm. Understanding this paradigm shift hinges on inspiration, setting realistic cultural and strategic goals that emphasise the safety and health of the workforce, communities, and the environment (MHSC, 2015). These factors play an important role in the planning and implementation of relevant strategies to combat health and safety challenges. Khumbul'ekhaya strategy that was formulated by the industry CEOs in 2019 serves as an indicator for commitment to achieve zero harm (Seccombe, n.d.).

Despite recognition and concerted efforts to achieve zero harm, the reality is that mining workers in South Africa face a variety of hazards on the job, which pose a serious risk to their health and safety. The dangers persist, including exposure to various toxic substances, chemicals like cyanide and mercury (Frost-Killian, 2008). The impact of the mining industry extends beyond the operation to rural communities with inadequate health care resources due to migration, leading to increased rates of drug-resistant diseases. The suggested solution covers the following: improved housing, trafficking prevention, and standardised healthcare (Stuckler *et al.*, 2013).

Ngwenyama (2023) raised the need for effective emergency assistance and safety measures in the South African minerals industry, where explosions, underground fires, ground falls, and accidents involving mining machinery are encountered. Another study found that routine workplace violations caused by administrative barriers lacking self-enforcement capabilities lead to human error. The main contributing factors listed were the lack of strong leadership in safety and the proper analysis to understand systemic factors in mining safety (Bonsu, 2017). Eliminating these hazards (chemical or operational) requires an informed and rational understanding of new solutions available to remove or minimise them to lower levels. Traditional risk assessment methods cannot help in this case due to their limitations. The new approach that can help in this case is to look at the framework of systems thinking.

OVERVIEW OF THE SYSTEMS THINKING FRAMEWORK

It is important to discuss the origin and fundamental concepts in systems thinking because it has been applied in many fields to address complex problems. Secondly, it is the tool used in this paper to assess the MHSC's initiatives and to provide guidance. Systems thinking has a long history dating back to the 20th century, developed by scholars and practitioners from various disciplines like biology, social sciences, and engineering. The main reason for this interdisciplinary approach was to understand dynamic interactions and interdependencies of complex systems. Key contributors include Ludwig von Bertalanffy, Jay Forrester, Donella Meadows, and Peter Senge (Qudrat-Ullah, 2025).

Systems thinking is based on three fundamental principles which are holism, feedback loops, then stocks, and flows. Holism put emphasis on the interconnection of elements within a system while underestimating the impact of examining the system as a whole rather than individual parts (Sterman, 2000; Qudrat- Ullah, 2023). This implies that every component of a system is interdependent and changing one part can affect the entire system, leading to a domino effect throughout the whole system. Feedback loops shape the behaviour of the system. They are divided into two parts: reinforcing, which amplifies change with the system, and balancing loops, which aims to bring balance and equilibrium into the system (Sterman, 2000). Systems thinking acknowledges that systems involve the accumulation of resources (stocks) over time. Flows, on the other hand, indicate the rates at which resources move into, out of, or between stocks.

Holism assists stakeholders to observe the broader context and long-term implications of their decisions while understanding that the interplay between feedback loops is crucial for comprehending system behaviour to predict the consequences of interventions or changes. A clear understanding of the stocks and flows concept assists practitioners in developing systemic interventions which generate the desired outcomes and also mitigate against the undesirable system behaviour. Systems Thinking highlights the importance of embracing complexity and interconnectedness in addressing organisational and social challenges (Senge, 1990).

Another important question is how systems thinking differs from the traditional reductionist approaches that have always been used to solve real world problems. Systems thinking views a system as a whole, noting relationships and interaction between its parts or subsystems. This approach is based on the notion that systems cannot be fully understood by examining individual parts in isolation. In contrast, the reductionist approach aims to understand a complex phenomenon by analysing functional properties of individual parts (Koskinen, 2013). Systems thinking takes note of the dynamic and adaptive nature of complex systems characterised by feedback loops, non-linear causality, and emergent properties. The reductionist approach relies on linear cause and effect models which have limitations in capturing complexity and adaptability of real-world systems (Adam & de Savigny, 2012). Finally, systems thinking has been widely used, including health systems in low- and middle-income countries, to identify and address multifaceted and interconnected challenges (Adam & de Savigny, 2012). The reductionist approach has been used in many fields, including biological research, with an inability to provide sustainable solutions to complex, systemic issues like climate change and urban planning (Bosch *et al.*, 2014).

Although systems thinking has many advantages to assist in addressing complex problems in the real world, there is a place for the reductionist approach to contribute to problem-solving. The reductionist approach is more useful where a detailed analysis of individual components is required. As the complexity of global challenges increases in all areas of life, there is a need to move towards systems thinking that offers a more comprehensive and integrative framework to understand and address complex systems, of which mine safety is one. This shift requires the following: a change in mindset, and the development of new skills and methodologies to effectively address the complexities of the modern world (Green, 2024).

DATA AVAILABILITY AND METHODS

Data used

Data for this research were sourced from the MHSC. The MHSC uses a variety of documents to conduct its business. This includes research proposals, project reports (comprising final reports and summaries), bid documents, and guidance handbooks. All of these documents contain detailed information on research projects. In this research, I compiled the data using summaries of reports, although I also reviewed the full reports. The analysis period ranges from 2010 to 2025.

Seventy funded projects were evaluated, covering the following areas: occupational health, occupational safety, human factors, technological innovations, gender and diversity, and policy and

regulatory framework. The content of interest in all these documents was the nine thrust areas. Some documents were discarded on the basis of this choice.

Other documents used were the annual Mine Health and Safety Inspectorate (MHSI) reports covering the same period as those of the MHSC (2010-2023). The publication of MHSI for the years 2023 to 2025 was not yet available for review. The key issues covered in the MHSI programme are the programme performance, the state of safety in the mining industry, the state of health in the South African mining industry, and the activities of the Inspectorate. The data used for this research focused on the state of safety in the mining industry. The metrics considered were only fatalities; injury data were excluded from this analysis.

Methodological approach

The primary objective of this study was to assess progress toward zero harm by analysing research output funded by the MHSC. This was done to identify research areas that may need attention through the lens of system safety. This paper was intended to help the mining industry improve occupational safety and health outcomes. The continuous effort to achieve zero harm necessitates critical analysis to ensure that optimal resources are allocated for effective interventions.

The research problem for this task revolves around understanding how the MHSC initiatives, categorised according to the various thrust areas, function as a cohesive and interconnected system. The key basic questions that the paper attempts to answer are: (i) How do the MHSC's research thrust areas interconnect to achieve zero harm? (ii) What systematic research gaps exist for future funding based on the principles of system thinking?

To address these questions, this paper establishes a systems thinking framework for mine safety and then reviews the progress and performance of the MHSC's initiatives over the past 15 years, using statistics from the MHSI annual reports.

Finally, the interdependencies for this paper's thrust areas are analysed for effectiveness, and an alternative arrangement based on a systems thinking approach is suggested. This analysis will help identify critical research gaps and provide recommendations for an integrated approach to develop a comprehensive solution for safety in the mining industry.

RESULTS AND DISCUSSION

Mining Qualifications Authority

The Mining Qualifications Authority (MQA) serves as a cornerstone institution for developing skills in South Africa's mining industry. Its origin and function are related to the State's mandate to improve competence, productivity, and occupational health and safety. The uniqueness of MQA lies in its reporting to two government departments: the Department of Mineral Resources and Energy for health and safety standards, and the Department of Higher Education for skills policy and administration. This is because the MQA was established in terms of the Mine, Health and Safety Act of 1996 and the Skills Development Act of 1998 (MQA, n.d.).

The collaborative relationship between MHSC and MQA is intended to promote health and safety in the mining industry through research-informed education and training interventions. This was agreed upon at the Mining Health and Safety Summit in 2003, aiming to achieve zero harm in the mining sector by 2013. Platinum mines benefited from improved safety compared to their counterparts abroad as a result of this initiative (Genc *et al.*, 2019). However, the inherent challenge facing the MQA is the tension of satisfying two departments with different goals. Research adequately achieved given this limitation (MQA, 2019). Training has increased since MQA contributed to skills development, but accidents and fatalities persist. Rikhotso *et al.* (2024) note that, although there is extensive reporting of occupational health and safety performance indicators in the mining sector, a standardised approach for effective comparison is lacking, and these companies have not yet achieved zero harm.

Performance review of MHSC

The review of the MHSC council will be based on the research activities recorded from 2010 to 2025. The research articles in question cover the nine thrust areas as indicated in Table I.

Table I: Mine Health and Safety Council Thrust Activities 2010-20250

YEAR	Human Factors	Rock Falls	Rock bursts	Explosions	Machinery and Transport	Airborne Pollutants	Physical Hazards	Occupational Diseases	Special Projects	TOTAL
2010	0	0	0	0	0	0	0	0	0	0
2011	0	0	1	0	1	0	0	2	2	6
2012	0	0	0	1	1	0	0	0	1	3
2013	0	1	2	0	0	1	0	1	2	7
2014	1	0	0	1	3	0	1	0	1	7
2015	0	0	1	0	0	0	0	0	1	2
2016	0	4	3	0	0	0	0	3	0	10
2017	0	1	0	0	1	1	0	2	1	6
2018	0	0	0	0	0	1	0	1	1	3
2019	0	0	0	0	0	1	1	0	1	3
2020	0	0	0	0	0	0	0	0	0	0
2021	1	0	0	0	0	3	0	0	0	4
2022	4	0	0	0	0	1	0	0	1	6
2023	0	0	0	0	0	0	0	0	0	0
2024	0	0	0	0	0	0	0	0	0	0
2025	0	0	0	0	0	0	0	0	0	0
TOTAL	6	6	7	2	6	8	3	9	11	58

From Table I, project activity is uneven over the 16-year period from 2010 to 2025. It is concentrated in a few topic areas, while there are significant peaks and periods of no activity in research, indicating where research was focused mostly during this period.

Between 2010 and 2012, there was modest activity, which peaked around 2016 with 10 project reports. There were years of little or no recorded projects (2020, 2023-2025). This pattern suggests a disturbance rather than a steady annual pipeline.

Cumulative totals indicate that more activities are occurring in categories like machinery and transport (six projects), rockfalls/rock bursts (13 projects), related areas, and human factors (six projects). The research concentration effort focused on operational and physical hazard topics (machinery/transport, rockfall/rockbursts), with a priority on practical safety in mining operations.

In 2016, the highest number of projects was completed (10 projects), with related rockfall/rock bursts being the dominant area of focus. Occupational diseases, as a separate category, have the highest number of projects compared to the other thrust areas. The focus indicates a need for a response based on the potential to affect the workforce adversely.

Safety statistics

In 2024, the mineral industry had 42 fatalities (42% decrease from the previous year) and a 16% reduction in injuries, amounting to 1841 (Mining Review, 2025). This was achieved through the collaborative efforts of organised labour, industry and the government. Table II summarises the outcomes of interventions over the years from 2010 to 2024.

Table II: Evolution of fatalities in South African Mines (2010-2024)

YEAR	FALL OF GROUND	MACHINERY AND TRANSPORT	FIRES	GENERAL
2010	48	40	5	20
2011	40	43	0	25
2012	26	37	0	35
2013	32	34	0	16
2014	25	20	0	4
2015	22	20	0	0
2016	24	27	1	16
2017	33	36	0	18
2018	22	19	6	16
2019	20	19	0	5
2020	22	13	3	14
2021	22	24	0	14
2022	6	20	2	18
2023	15	18	1	8
2024	13	-	-	-

Trends and observations

2010-2014

The fall of ground decreased from 48 (2010) to 25 (2014), a reduction of 48%. The largest single-year drop was from 2011 to 2012 (from 40 to 26 fatalities).

Machinery and transport fatalities reached a peak in 2011 at 43, then decreased to 20 in 2014. This is a roughly 50% decrease.

Fire deaths dropped to 0 from 2011 onwards and remained at that level until 2015.

General deaths decreased from 20 (2010) to 4 (2014), with a spike to 35 in 2012, which is an outlier.

2015-2023

Fall of ground fatalities are the most variable, peaking at 33 (2017) and dropping to a lowest of 6 (2022).

Machinery and transport trends have reduced from a high of 36 fatalities (2017) to a low of 20 fatalities in 2022. In the years 2018, 2019, 2020, and 2023, the number of fatalities was below 20, except in 2021.

The deaths associated with fires are mostly low, with occasional spikes (6 deaths in 2018).

General fatalities declined from mid-high teens to a single digit in 2019 and later fluctuated to reach another single digit in 2023.

In general, the data indicate an improvement in safety statistics over the years, with a notable reduction in fatalities from fall of ground, machinery, and transport, as well as fires. There are fluctuations in numbers from year to year. A better picture of the trends is depicted in Figure 1.

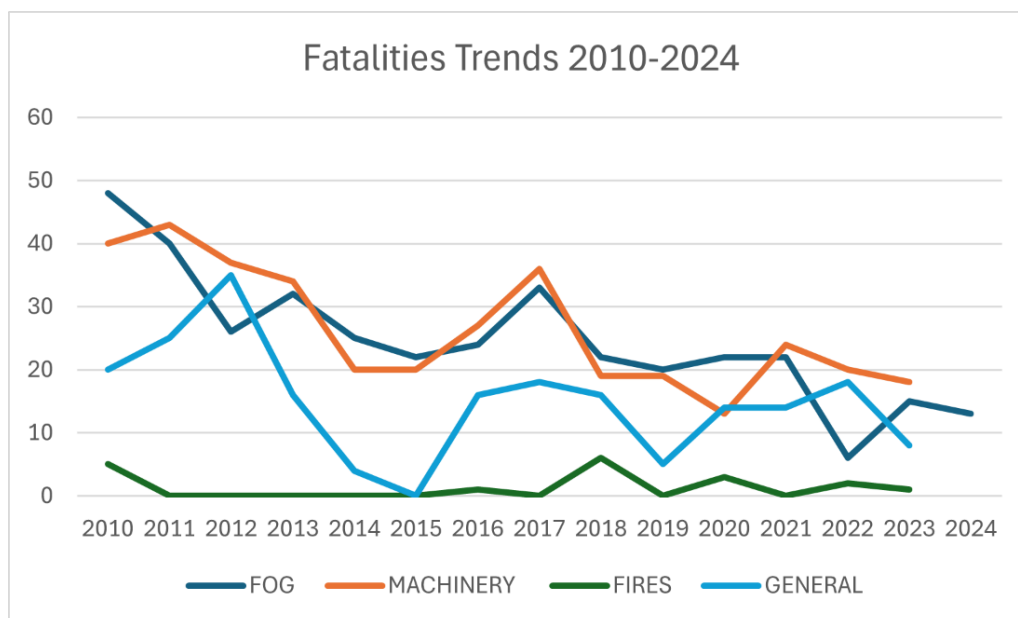


Figure 1. Fatalities trends from 2010 to 2024

All these improvements are related to the interventions that the MHSC has undertaken over the years in an attempt to achieve zero harm in the mining industry.

MHSC focus on thrust areas

The MHSC council has been focusing on nine thrust areas to achieve its objectives. These thrust areas are human factors and behavioural safety, explosions and fires, air pollutants, physical hazards, machinery and transportation, occupational diseases, rock bursts, rockfalls, and special projects. Not all of these thrust areas attracted the same resources based on their potential to cause fatalities.

Rockfalls and rock bursts: MHSC has invested more than R250 million in seismicity-related research, which has led to significant improvements in the following aspects: mine design, underground support methods incorporating pillar systems, multi-seam design, and early warning systems for seismicity (Sokutu, 2018). All of these contribute to improving safety initiatives.

Machinery and Transportation: While the hazards that have been identified over the years have been well controlled, new accidents have emerged in this area, resulting in additional fatalities. In response to this, the MHSC deployed resources by funding research into proximity detection systems and collision avoidance technologies. This also resulted in the promulgation of trackless mobile machinery (TMM), which became effective in 2022 to avert this risk (Shangoni, 2023).

Human factors and behaviour safety: MHSC acknowledges that technology alone cannot yield the desired results in terms of safety. As a result, research has been conducted on culture. This includes initiatives such as team mobilisation and Khumbul'ekhaya strategies with the main goal of changing the safety culture from dependence to interdependence. The Minerals Council of South Africa initiated the Khumbul'e ekhaya campaign.

Occupational diseases: Historically, the MHSC addressed the major health issues affecting the workforce, focusing on issues such as HIV/AIDS and tuberculosis, setting targets for mitigation purposes. In addition to that, MHSC research focused on long-term health risks associated with the following: diesel particulate matter, heavy metal exposure, crystalline silica, and mining methods.

This background clearly indicates the historical change in the profile of the accident pattern. The fall of ground was once a dominant factor, but it has been drastically reduced. This is an indicator of success due to the MHSC interventions mentioned above. However, as the depth of the mine increases, new technologies are introduced to enhance efficiency and mitigate traditional risks, but new hazards also emerge.

Interventions that result in an improvement in one area may give rise to vulnerabilities in other areas in ways that are difficult to predict due to feedbacks, delays, and incomplete understanding of interdependencies (Sterman, 2006; Holling, 1973; Carey et al., 2015). Based on this reality, there is a need to shift from a reactive, hazard-by-hazard approach to a more proactive, systems-level strategy. This approach anticipates and addresses these new and interconnected risks. The systems thinking framework has become the most appropriate tool for addressing such safety challenges.

Interdependencies and synergies-systems analysis

Interconnections

Although the MHSC's thrust areas are organised in silos, they are deeply interconnected. A systematic analysis reveals that any intervention in one area of focus has a profound effect and influences relationships in another area. Therefore, for a holistic understanding of mine safety, it is essential to map these relationships. Although this exercise can be carried out, the current MHSC research thrusts are not ideal to achieve zero harm.

Cultural and leadership integrations

The Culture Transformation Framework (CTF) was initiated under the MHSC and approved at the 2011 Tripartite Mine Health and Safety Summit. Its aim was to transform the health and safety culture across the mining industry by shifting the focus from only technical controls to organisational and leadership factors, learning systems, incentives, and collaborative tripartite action (MHSC, 2011).

The CTF aim to achieve its objectives by focusing on eleven pillars to drive culture change in the mining sector. These pillars include integrated mining activities, risk management, technology, leading practices, the elimination of discrimination, bonuses and performance incentives, tripartism, a regulatory framework, an inspectorate, data, and, finally, leadership. Some work has been done to ensure that CTF is effectively implemented in the mining industry, including breakaways, research and academic work (Magweregwede, 2021). The MHSC and the Minerals Council of South Africa describe intent, actions, monitoring and observed improvements regarding CTF. Despite these efforts, the CTF's direct contribution is not straightforwardly demonstrated in a single peer-reviewed study that directly assesses its causal impact. More needs to be done to quantify the exact contribution of this framework.

Another important initiative is the Khumbul'ekhaya campaign. The Khumbul'e khaya strategy and its focus on cultural transformation underpin all the other safety initiatives. Introducing a technical intervention like the collision avoidance system for TMM cannot succeed in a vacuum (CSIR, 2025). It

requires a complementary cultural shift where leaders demonstrate a clear personal commitment involving the mobilisation and training of teams to understand and trust the new technology. The shift from a dependent culture to an independent culture is the human element that enables seamless integration of technology. Without cultural transformation, even the most advanced technology or well-crafted legislation will fail to achieve its intended safety outcomes.

The role of technology in integration

Modern technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and digital twins, are not just tools; they form the infrastructure for a unified and integrated system. The CSIR's development of a digital twin for TMM collision is a prime example. This approach breaks down the traditional silos by allowing operators and decision-makers to visualise the interplay between driver behaviour, traffic management plans, and non-conformance events (CSIR, 2025). The move towards integrated systems is necessary to mitigate the risk of future technologies to achieve zero harm.

Systemic research gaps and future directions

Although the MHSC's historically siloed approach has been able to reduce fatalities from specific hazards, such as the fall of ground, the analysis suggests that this framework is less equipped to address the complex, interconnected, and evolving risks of the modern mining environment.

Based on the current reductionist approach, key identified gaps include a lack of adoption and scalability of interventions, lagging policy application, rapid technological advancement compared to regulatory updates, and a more focused inclusion of diversity in system design. These findings suggest that an integrated systems approach involving technology, policy, and human factors must evolve together.

Given these challenges, it is necessary to go beyond a traditional hazard-by-hazard review as currently done. A mine is a socio-technical system; therefore, hazards do not act in isolation. A systems approach suggests that safety domains should be organised around functions, flows, or control systems, capturing interactions, feedback loops, and emergent risks. Therefore, the new or reorganised thrusts that are suggested are as follows in Table III.

Table III: Description of the proposed thrust areas.

Thrust Area	Description
Risk governance, safety culture, leadership, and behavioural systems.	Covers human factors, behavioural safety, management systems, leadership, safety culture, policies, and regulations. Key issue: Behavioural and organisational drivers are central, not mitigations.
Operational systems, machinery, vehicle-equipment interactions	Combines transport and machinery, hazards (machine-related), and interactions between people and equipment. Key issues: focus on dynamic parts of operations
Geotechnical hazard systems	The fall of ground, rockfalls, and rock bursts/seismicity are interrelated through geology, mining depth, ground support, and stress redistribution.
Atmospheric and environmental exposure systems	Airborne pollutants, dust, gases, explosions, fires (environmental conditions), atmospheric monitoring, heat, and ventilation.
Health outcome and disease systems	Occupational diseases, cumulative exposure, long-term health surveillance, noise, vision, hearing loss, and tracking chronic and latent health outcomes.
Emergency, incident response and resilience systems	Explosions/fires, rescue, emergency preparedness, evacuation, post-incident recovery, redundancy system, failure prevention, monitoring, and early warning.
Special, emerging and enabled technologies	New technology, data and digital systems, AI/IoT, predictive systems, robotics, remote monitoring, automation, and special projects across all domains.

These thrusts are less hazard-by-risk but more about systems of risk, control, responses, feedback, and emergence. Each domain is large, but it is necessary to handle complexity based on the potential to produce more research topics for effective interventions in safety.

CONCLUSIONS

The analysis confirms that the historically hazard-based MHSC approach has contributed to reducing accidents in the mining industry, thereby resulting in a notable reduction in fatalities. However, fatalities have not been completely eliminated over a long period.

To achieve the aspiration of zero harm as a vision, a change in research direction is needed. The evidence indicates that the siloed and hazard-based approach is no longer sufficient to address the complex and interconnected challenges of the modern mining environment. A new paradigm is needed that takes into account systems thinking to investigate the interdependencies between technical, human, and social factors.

Future MHSC funding should shift towards a holistic, integrated research approach that identifies gaps in socio-technical systems, external threats, and employs proactive data analytics.

Improved metrics are needed to track the results of funded research versus the implementation of safety changes. A visual roadmap with a matrix will be required for stakeholders to identify areas of priority. Only by adopting this forward-looking approach can the mining industry maintain impressive safety records to achieve zero harm.

REFERENCES

- Adam, T. & de Savigny, D. (2012) 'Systems thinking for strengthening health systems in LMICs: need for a paradigm shift', *Health Policy and Planning*, 27, pp. 1–8. Available at: <https://doi.org/10.1093/heapol/czs084>
- Bonsu, J. (2017) 'A systemic study of mining accident causality: An analysis of 91 mining accidents from a platinum mine in South Africa', *Journal of the Southern African Institute of Mining and Metallurgy*, 117(1), pp. 59–66. Available at: <https://doi.org/10.17159/2411-9717/2017/v117n1a9>
- Bosch, O.J.H., Nguyen, N.C. & Buckle-Henning, P. (2014) 'Where is this so-called "Fifth Discipline" if project failures, blown-out budgets, decision disasters, and poor investments continue to plague our society?', *Systems Research and Behavioral Science*, 31(1), pp. 1–11.
- Carey, G., Malbon, E., Carey, N., Joyce, A., Crammond, B., & Carey, A. (2015). 'Systems science and systems thinking for public health: a systematic review of the field'. *BMJ open*, 5(12), e009002. <https://doi.org/10.1136/bmjopen-2015-009002>
- Casey, J.P. (2019) 'History of mining in South Africa'. Available at: <https://www.mining-technology.com/features/history-of-mining-in-south-africa/> (Accessed: 4 September 2025).
- Council for Scientific and Industrial Research (CSIR). (2025) 'CSIR-developed collision prevention digital twin to improve operational efficiencies in mining sector', 8 June. Available at: <https://www.csir.co.za/csir-developed-collision-prevention-digital-twin-improve-operational-efficiencies-mining-sector> (Accessed: 6 October 2025).
- Department of Mineral Resources (Mine Health and Safety Inspectorate). (2010) *Mine Health and Safety Inspectorate Annual Report 2009/2010*, October. Available at: <https://www.dmre.gov.za/Portals/0/Resource%20Center/Mine%20Health%20and%20Safety%20Inspectorate%20Annual%20Reports/2009-2010%20MHSI%20Annual%20Report.pdf> (Accessed: 6 October 2025).

- Frost-Killian, S. (2008) 'Geohazards: the risks beneath our feet', *Quest*, 4(2), pp. 28–31. Available at: https://journals.co.za/content/quest/4/2/aja1729830x_519
- Genc, B., Mlangena, T. & Onifade, M. (2019) 'Safety towards zero harm in the South African platinum sector', in *Advances in Human Factors, Business Management and Leadership*. Springer, Cham, pp. 535–544. Available at: https://doi.org/10.1007/978-3-319-99220-4_45
- Green, D. (2024) 'Systems thinking changes everything', in *Systems Thinking for a Changing World*, pp. 9–26. Available at: <https://doi.org/10.1093/oso/9780198899952.003.0002>
- Holling, C.S. (1973) 'Resilience and stability of ecological systems', *Annual Review of Ecology and Systematics*, 4(1), pp. 1–23
- Koskinen, K.U. (2013) 'Systemic view and systems thinking', in *Systemic Thinking in Project Management*. Springer, Heidelberg, pp. 13–30. Available at: https://doi.org/10.1007/978-3-319-00104-3_3
- Magweregwe, F. (2021) 'Refinement of the Culture Transformation Framework (CTF) for the South African Mining Industry (SAMI)'. University of the Witwatersrand, Johannesburg. Unpublished M Phil (thesis).
- Mine Health and Safety Council (n.d.) *Mine Health and Safety Council (MHSC) – official site*. Available at: <https://mhsc.org.za/> (Accessed: 4 September 2025).
- Mine Health and Safety Council (n.d.) *The pursuit of zero harm continues: MHSC history/booklet*. Available at: <https://mhsc.org.za/> (Accessed: 4 September 2025).
- Mine Health and Safety Inspectorate, Department of Mineral Resources. (2011–2024) *Mine Health and Safety Inspectorate Annual Reports (2010/2011–2023/2024)*. Pretoria: Department of Mineral Resources.
- Mining Qualifications Authority (MQA). (2019) *Sector Skills Plan for the Mining and Minerals Sector: Final Submission 2020–2025*, 1 August. Available at: <https://mqa.org.za/mqa-sector-skills-plan/> (Accessed: 6 October 2025).
- Mining Review. (2025) *Advancing Zero Harm: Minerals Council tackles fall-of-ground risks*. Available at: <https://www.miningreview.com/southern-africa/advancing-zero-harm-minerals-council-tackles-fall-of-ground-risks/> (Accessed: 4 September 2025).
- Ngwenyama, P.L. (2023) *An investigation and analysis of missing miner-related accidents and fatalities in the South African mining industry*. Available at: <https://doi.org/10.2139/ssrn.4510773>
- Qudrat-Ullah, H. (ed.) (2023) *Managing complex tasks with systems thinking*. Springer. Available at: <https://doi.org/10.1007/978-3-031-40635-5>
- Qudrat-Ullah, H. (2025) *Embracing systems thinking*. IGI Global Scientific Publishing. Available at: <https://doi.org/10.4018/979-8-3693-7190-9.ch004>
- Republic of South Africa. (1996) *Mine Health and Safety Act, No. 29 of 1996*. Pretoria: Government Gazette.
- Rikhotso, O., Shabangu, M.G. & Havenga, Y. (2024) 'The illusive pipedream of zero harm: A South African mining industry perspective', *Safety*, 10(3), 65. Available at: <https://doi.org/10.3390/safety10>
- Seccombe, A. (n.d.) *Khumbul'ekhaya – Minerals Council South Africa: safety and health in mining*. Available at: <https://www.safetyandhealthinmining.co.za/about> (Accessed: 4 September 2025).
- Senge, P.M. (1990) *The fifth discipline: The art and practice of the learning organization*. New York: Currency Doubleday.

- Shangoni. (2023) *Mine Health and Safety Act 29 of 1996: Commencement of the regulations relating to trackless mobile machinery*. Available at: <https://shangoni.co.za/mine-health-and-safety-act-29-of-1996-commencement-of-the-regulations-relating-to-trackless-mobile-machinery/> (Accessed: 4 September 2025).
- Sokutu, B. (2018) 'More than R250 m dedicated to deep-level mine research', *Knysna Plett Herald*, 20 August. Available at: <https://www.knysnaplett Herald.com/News/Article/National-News/more-than-r250m-dedicated-to-deep-level-mine-research-201808200900#:~:text=Share,Canada%20and%20the%20United%20States.%E2%80%9D> (Accessed: 4 September 2025).
- Sterman, J.D. (2000) *'Business dynamics: Systems thinking and modeling for a complex world'*. Boston: Irwin/McGraw-Hill.
- Sterman J. D. (2006). Learning from evidence in a complex world. *American Journal of Public Health*, 96(3), 505-514. <https://doi.org/10.2105/AJPH.2005.066043>
- Stuckler, D., Steele, S., Lurie, M.N. & Basu, S. (2013) 'Introduction: "Dying for gold": The effects of mineral mining on HIV, tuberculosis, silicosis, and occupational diseases in southern Africa', *International Journal of Health Services*, 43(4), pp. 639-649. Available at: <https://doi.org/10.2190/hs.43.4.c>



Lucky Albert Maseko

Senior Lecturer
University of South Africa

Worked at different mining companies as a mining engineering graduate at various positions. Companies worked for include Johannesburg Consolidated mines (JCI), South Deep Project, Anglo Coal (Greenside Colliery, New Vaal Colliery) and Mpumalanga Education Department. Before joining the University of South Africa in 2006 as a lecturer where he handled a variety of modules including curriculum design work. He is currently a Senior Lecturer.

Efficiency and sustainability: Evaluating the performance of lime-based expansive agents in hard rock mining – A field study

M. Mekgwe, T. Mmola, H. Grobler

University of Johannesburg, South Africa

Legal constraints are inherent to a mine operation and thereby require sustainable mining practices. Expansive agents are a sustainable alternative to conventional blasting in mining, offering reduced vibration, noise, and environmental impact. These are beneficial for Klipspruit Colliery, an opencast mine based in Mpumalanga. The proximity of neighbouring communities posed a legal constraint, and risked sterilising mineral resources. To provide a potential solution, quantitative research aimed to evaluate the efficacy of a lime-based expansive chemical agent was conducted, with varying spacing and burden in the removal of the overburden constituting hard rock. The rationale for the selected methodology was to evaluate the influence of hole spacing and burden to rock fracturing. The statistical analysis suggests a negative correlation for both holes spacing and burden_x respectively, but no causal relationship was established. In the field study, results suggested an optimum measure of 1.2m for hole spacing and 1m for the burden.

Keywords: NERB, expansive agents, sterilisation, crack width, correlation and regression.

INTRODUCTION

Study Background

The study was based in Mpumalanga, at Klipspruit Colliery – one of the operations owned by Seriti Resources Holdings (Pty) Ltd. Klipspruit Colliery planned to extend its mining operation to a particular site within its mining boundaries called Portion 10. A legal constraint was presented to the mine operation, as the two neighbouring host communities, i.e., Ogies and Phola are respectively 7 km and 2 km distance away from the planned extension (Seriti, 2025).

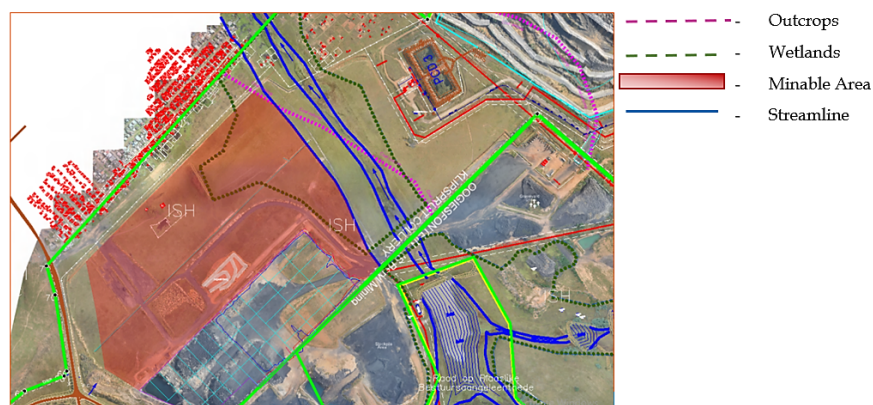


Figure 1.- Portion 10 extension relative to host communities and ecological systems (source: Klipspruit Colliery).

Not only is the operation constrained by host communities, but also by ecological systems shown in Figure 1, regulated by the National Environmental Management Act 107 of 1998 (Bray, 1999). Therefore, compliance to the two legal frameworks: Mine Health and Safety Act 29 of 1996, Chapter 4 relating to explosives law and the National Environmental Management Act 107 of 1998, challenged the mine operation. The MHSA (Act 29 of 1996), Chapter 4.16 paragraph 2 of the act states: “no blasting operations are carried out within a horizontal distance of 500 metres of any public building, public thoroughfare, railway line, power line; any place where people congregate or any other structure, which it may be necessary to protect in order to prevent any significant risk,” (MHSC, 2018). To address the legal constraints, research was conducted with permission of the mine management to evaluate alternative rock-breaking methods to comply with imposed regulations. Hence, the aim of this research was to evaluate the efficacy of expansive agents in hard rock-breaking for overburden removal composed of sandstone, siltstone and shale. The purpose of the research was to assess the hole spacing and burden_x optimal for efficiency. The burden_x is the minimum distance from the row of blastholes to the free breaking face and spacing is the distance between blastholes in the same row (Persson et al., 2018). The term ‘burden’ is commonly associated with dynamic explosives blasting; therefore, in this study the same distance is referred to as burden_x / B_x when applied to rock breaking using expansive agents, which are static in nature. The evaluation is to support sustainable mining practices using a lime-based expansive agent.

Mining Social Importance

The mining industry is transforming with time, and the complexity of mining demands research and development that can offer solutions to the challenges faced by the industry. Mining is concerned with the exploration and removal of rock or ores, or minerals from the earth (Elbeblawi et al., 2022). It contributes significantly to the gross domestic product, of this nation, hence the need for research and development to foster sustainability towards continuous improvement of best mining practice. According to Professor Griliche, research and development increase the growth of productivity in a company (Griliches, 1979). This research aims to address the efficacy of lime-based expansive agents’ performance applied in hard-rock mining to mitigate the risk of sterilisation.

Sterilisation of Mineral Resource

Mining is a dynamic industry with inherent complexities. These complexities emerge due to the increased scale of mining, production rates, the need for support infrastructure, and mines leverage on the availability of modern technology for a solution (Spitz and Trudinger, 2019). When no solution is found, mineral resources are sterilised. Mineral resources is defined as “a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible” (U. S. Bureau of Mines and U. S. Geological Survey, 1980, p. 1 cited in Taylor and Steven, 1983). The sterilisation of mineral resources refers to the loss of the possibility to extract mineral resources (Pendock, 1984). This occurs when modifying factors – mining considerations: metallurgical process, marketing, legal, environmental, social and governmental that assess the feasibility of profitable extraction, have low confidence in converting mineral sources to reserves ((Pendock, 1984; Stephenson, 2000). Hence, the importance of ore body assessment against modifying factors. An ore body may satisfy most of the modifying factors, however legal constraints may present a challenge if there is development overlying the mineral, which may render the mineral inaccessible (Wrighton et al., 2014). This is an instance of legal constraints due to proximity of the orebody to inhabited areas.

Sterilisation of mineral resources has a negative implication for a country. The effects of inaccessible minerals are reduced resource availability, potential economic losses, adverse social implications, and job losses (Lumadi and Nyasha, 2024; Sermet and Nieć, 2021; Wrighton et al., 2014). To mitigate sterilisation, there are technological advances and sustainable practices that can be implemented. Sustainability is defined as “the ability to meet present needs without compromising future generations’ ability to meet their own needs” (Brundtland and Mansour, 2010). Therefore, striking a balance between the economic, environmental and social considerations (Rajaram et al., 2005). In addition, it encourages mine operations to facilitate the mining process in a way that is protective to humans and the environment by minimising impact, thus ensuring continuation of usage in following generations. In

this paper we have evaluated lime-based expansive agents, which are environmentally friendly as a sustainable mining practice for efficient rock-breaking.

Literature Review

Rock Breaking

The rock-breaking mechanism is the in-situ liberation of minerals of interest and is explained in the field of fracture mechanics of materials. A rock not as a continuum, it is heterogeneous, containing discontinuities, which are planes of weakness in the material (Broberg, 1999; Malvern, 1969). A brittle rock means that the tensile strength is much smaller than its compressive one and therefore easier to fracture in tensile loading than in compressive loading (Zhang, 2016). Brittle materials fail abruptly with minimal deformation, whereas ductile materials exhibit substantial plastic deformation—such as elongation or bending—prior to fracture (Thompson and Clegg, 2018; Wu, 2018). The distinct difference between brittle and ductile fracture is the material's response to strain energy: brittle materials absorb only a small amount of strain energy before fracturing, whereas ductile materials can undergo significant plastic deformation and absorb larger amounts of energy prior to failure (Callister Jr and Rethwisch, 2020; Thompson and Clegg, 2018). Therefore, rock breaking occurs when the applied stress exceeds the fracture stress, inducing a 'break-up' process whereby there is a reduction in size to smaller fractions of the rock (Redner, 1990).

There are two types of brittle fractures: (1) shear fractures, which are oriented parallel to the fracture surface, or 30° to the compressive stress exerted, (2) extension fractures, which are displaced normal to the compressive axis (Handin, 1969; Logan, 1979). Both types of shear fractures are categorised according to the modes of failure - a theoretical framework developed by Irwin (1957), a continuation of Griffith's (1920) work on brittle failure (Mecholsky Jr, 1995). These modes of fracturing are Mode I, II and III (Irwin (1957) cited in Atkinson, 1987). Broberg, further develops the theoretical frameworks, by describing the fracture of brittle material in three phases. The work concluded by summarising the crack initiation to propagation, into three phases if no pre-existing cracks, the phase follows. The first phase, is the loading of the stress without crack growth, followed by the stable crack growth, and the third phase - unstable crack growth (Broberg, 1999a). Ultimately, deformation will occur in the third phase, which is the failure point, characterised by shearing or sliding of the material.

The extent of fracturing according to fracture mechanics principles is dependent the rock type and geological structures, which are directly associated with the rock strength, and fracture toughness (Zhang, 2016). The three geological classifications of rock types, namely, igneous, metamorphic and sedimentary, are directly related to the rock mechanical characteristics of various lithologies (Harris, 1977). The rock types are naturally arranged by geological structures, which refer to physical features that form within rock masses as a result of deformation processes and stresses generated in the Earth's crust (Price and Cosgrove, 1990). These features influence the distribution and concentration of stresses within a rock mass, thereby influencing the deformation response and rock strength (Zang and Stephansson, 2009). Therefore, for a fracture to occur, sufficient energy has to be exerted by a system onto a rock to overcome opposing stresses.

NERB Techniques

Rock breaking is an activity that can be achieved with or without the use of explosives. The term 'blasting' refers to the use of explosives, to reduce large in-situ rocks to manageable sizes, providing the quantity and quality required in production for comminution (Bhandari, 1997). However, the use of explosives is associated with unwanted negative impacts, especially when the blast operation is intended to be carried out near a large population (Al-Bakri and Hefni, 2021). These negative effects, include vibration, air blast, noise, and fly rock (Bhandari, 1997; Kramadibrata et al., 2015); which present hazards on surface mines during a blast, therefore may pose a risk to a development if in proximity to the operation. Therefore, to avoid litigation processes for non-compliance of mines near populations, non-explosive rock breaking (NERB) is an alternative to resolve any disputes (Hinze and Nelson, 1996).

There are three main groups shown in Table I, from the literature describing the various NERB methods and respective categories (Pickering, 2017; Santos et al., 2018; Al-Bakri and Hefni, 2021; Habib et al., 2022a; Yang et al., 2023).

Table I: Non-explosive Rock breaking Methods

Non-explosive Rock-Breaking Methods

Mechanical	Chemical	Electrical
Hydraulic splitting	Expansive Agents	Plasma Blasting
Hydraulic breaker	Carbon Dioxide Cracker	Heat Splitting Rocks
Boring Machine	Metal Burners	
Thermal Fragmentation	Supercritical Carbon Dioxide	
Thermal Spalling	Cardox	
Diamond Wire Cutting	Nonex	
Radial-Axial Splitter		
Pick – Cutting		
Penetrating Cone Fracture (PCF).		
High-Pressure Water Jet		

The tabulated methods are employed in various industries such as civil, mining, oil, and gas; when there is a need for environmentally-friendly rock breaking (De Silva et al., 2016, 2019; Habib et al., 2022). The methods have ensured continuity of mining, reduction in ore dilution and mineral losses, cutting down on the number of labourers required, increased safety, and eliminated the need for time blast-fumes to clear out (Dessouki and Mitri, 2011; Haase and Pickering, 2021). To obtain satisfactory outcomes, an operation must make an informed choice on the selection of NERB methods from the three broad categories – mechanical, chemical or electrical.

Lime-based Expansive Agents

Physical and Chemical Properties

Expansive agents are chemical NERB methods and have three common primary constituents that formulate the types of an expansive agent. The first is based on calcium sulphoaluminate ($\text{Ca}_4(\text{AlO}_2)_6\text{SO}_4$), secondly, on quick-lime (CaO), and thirdly, magnesium oxide (MgO) serving as primary ingredients (Gagné, 2016; Li et al., 2021). Variation of these primary constituents in different chemical proportions make the four types of expansive agents (ACI, 2010). The four types according to ACI (2010), are Type K – calcium sulphoaluminate and calcium sulfate, Type M – calcium aluminate and calcium sulfate, Type S – tricalcium aluminate and calcium sulfate and Type G – calcium dioxide and aluminate oxide.

Lime-based expansive agents are Type G expansive agent – a greyish, powdery lime-based chemical admixture added to cementitious material, that generates compressive stresses due to volumetric increase or swelling that induces tensile fracturing (Hinze and Brown, 1994; Gagné, 2016; Soeda et al., 2023). Expansive agents collectively are called soundless chemical demolition agents (SCDAs) traditionally used in the civil engineering industry (Hinze and Brown, 1994). Expansive agents are recognised with different names – soundless cracking demolition agent (SCDA), soundless cracking agents, non-explosive demolition agents, soundless stone cracking powder, static cracking agents (SCA), expansive demolition agents, non-explosive demolition agents, expansive mortar, etc., (Kesler, 1976; Kawano, 1982; Dowding and Labuz, 1982a; Hinze and Brown, 1994; De Silva et al., 2016; Zhai et al., 2018a). These names were coined owing to the various applications in industry, either civil or mining of the rock-breaking technique.

The composition of an SCDA constitutes anhydrite – CaSO_4 and calcium oxide – CaO , which are the main additives, and a mixture of Portland cement (Nagataki and Gomi, 1998; Konik et al., 2007). The agents are not flammable or explosive, safety adherence is relatively high, they have low breaking power, and the cracking time is longer (usually more than 10 hours), therefore are static in mechanism Zhou et al., 2018). A static mechanism is indicated when low pressure is exerted by slowly releasing the expansion pressure from the reaction, which could take 12-24 hours for maximum results in performance (Soeda et al., 2023). Consequently, the expansion pressure released induces fracturing in a restrained system, therefore leading to rock breakage.

All expansive agents are shrinkage compensating (ACI, 2010). Shrinkage is a process in which there is a reduction of the water's ability to evaporate, potentially causing the concrete that has not set to harden at the surface and develop cracks (Revilla-Cuesta et al., 2020). Therefore, a requirement of expansive agents is to control crack formation. The performance of expansive agents depends on the degree of restraint and the type of agent used (ACI, 2010; Gagné, 2016; Li et al., 2021; Nobre et al., 2020).

Expansive Materials

Expansive materials are a product of the combining of a type of expansive agent and a type of cementitious material (Gamage and De Silva, 2020). Cementitious material is one of the chemical admixtures in expansive material and may be in the form of cement, mortar, or grout in different applications (Gillot and Coutelas, 2018; Yuan et al., 2021). According to the American Cement Institute (ACI), expansive cements are defined as: “a cement that, when mixed with water, forms a paste that, after curing, tends to increase in volume to a significantly greater degree” (ACI, 1998). Curing is the enforcement of moisture and temperature conditions to allow for the hydration process in concrete (ACI, 2010 cite in Taylor, 2013 Taylor, 2013).

A mortar is a cementitious product that takes on the form of a paste after saturation, mixed with binding material as cement or lime, and fine aggregate ((ASTM, 2009a; Gillot and Coutelas, 2018; Gopi, 2025). Mortar used for SCDA is cement-based with several binders, however, Portland cement is the primary binder used (Gillot et al., 2018; Gamage et al., 2020; Revuelta, 2021). It has adhesive and cohesive properties, attributed to Portland cement a binder in the material and fine aggregate acting as a filler (Gillot and Coutelas, 2018). A fine aggregate added is sand, which is a non-reactive substance, assists with workability, shrinkage, and compressive strength in mortar (Revuelta, 2021). The presence of sand contributes to the bulk, strength, and stiffness of mortar (Gillot and Coutelas, 2018). In expansive mortar, the benefit of using Portland cement is its ability to facilitate the ‘hydration’ process in SCDA in application (Yuan et al., 2021).

Shrinkage compensating concrete or expansive materials exhibit a swelling action when saturated to compensate for cracking during shrinkage (Aitcin, 2016). Cracks are formed in concrete during drying shrinkage, due to volumetric changes caused by water loss during curing, particularly from environmental exposure, when the water-to-cement ratio results in evaporation and insufficient internal moisture (Bentz and Jensen, 2004). The cracks occur when filling-in empty pores formed and left unoccupied; therefore, less space is occupied, and deformation occurs to the hardened matter (La Chatelier, 1900; Nagataki and Gomi, 1998; Gagné, 2016). The swelled products of expansive agents, from the reaction, occupy the empty pores and thus prevent cracks (Nagataki and Gomi, 1998; ACI, 2010). This mechanism is maximised into engineering designs of various industries; expansive materials are used primarily in two applications – shrinkage compensation and self-stressing purposes. The efficacy of expansive agents for shrinkage compensating application, is primarily dependent on the forms of restraint. In shrinkage compensation is internal and in self-stressing applications used for rock breaking the restraint is external.

CaO-expansive Agents Hydrate Products

The resultant product of the chemical reaction of lime-based expansive mortar (Type G) combined with water is called *Portlandite*, which is an expansive hydrate or hydration product (Nagataki and Gomi, 1998; Yuan et al., 2021). The product is a result of the progressive conversion from a paste-state to a solid-state product, reacting over time by a process called hydration (Bye, 1999; Hammer, 2007; Yuan et al., 2021). Hydration is described in in two phases – setting (paste-state) and hardening (solid-state) (Vekilov, 2010; Yuan et al., 2021; Myerson and Ginde, 2002).

Portlandite is a crystal formed as a hydrate product of lime-based expansive agents (Gagné, 2016). The simplified chemical equation is $\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca}(\text{OH})_2$, illustrated in Figure 2, an adaptation from Xu et al., (2023), with added clarifying notes from authors (Liang et al., 2018; Xu et al., 2023). It is the production of Portlandite, that is responsible for the volumetric increase experienced by crystallisation (Nagataki and Gomi, 1998; Gagné, 2016; Walkley and Provis, 2019). The volumetric increase experienced is 2 – 3 times that of the original volume before hydration was initiated (Hinze and Brown,

1994; Tang *et al.*, 2012; Li *et al.*, 2021). The volumetric increase or swelling action induces expansive pressure.

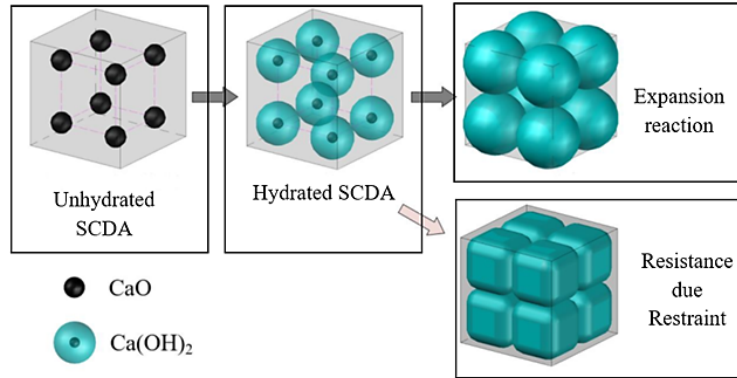


Figure 2: SCDA reaction under restraint (Xu *et al.*, 2018).

In the formation of hydrate products, heat is dissipated reaching around 150°C (Hinze and Nelson, 1996; Yuan *et al.*, 2021). In the dissipation, water is lost, strengthening the mechanical bonds between molecules, and therefore hardening takes place which is the last phase of hydration (Aïtcin, 2016; Gamage and De Silva, 2020; Yuan *et al.*, 2021). The completion of hydration occurs when all reactants are consumed, and Portlandite platelets and lumps of amorphous substance called calcium silicate hydrate (CSH) are formed (De Silva *et al.*, 2017). The presence of CSH lumps and Portlandite platelets in solid phase as powder are indicators that moisture in the products has evaporated and are therefore unhydrated, with a breakdown in cohesion (De Silva *et al.*, 2017).

During the process of hydration, fractures are formed in the brittle material induced by the mechanism of expansion when quicklime (CaO) and H₂O react to form calcium hydroxide (Ca (OH)₂). In the hydration process, internal expansion pressure is generated and if restrained, will cause fracturing (Gagné, 2016). The internal expansion pressure generates compressive stress in the radial direction and tensile stress in the tangential stresses within the surrounding material, shown in Figure 13 (Gagné, 2016; Zhong *et al.*, 2023). The volumetric expansive pressure acts on the restraint in the radial direction symmetrically around the borehole (Sakhno and Sakhno, 2024). The build-up of stresses will encounter the surface area of restraint – borehole. The compressive stresses normal to the confinement area are induced, and pressure is exerted in the radial and tangential direction (Habib *et al.*, 2022). At the point when the tensile stress exceeds the tensile strength of the rocks, deformation of the rock will occur as crack fractures (Sakhno and Sakhno, 2024). Therefore, tangential tensile stress is the primary cause of cracking and will diminish away from the confinement (Zhong *et al.*, 2023). The generated expansive pressure exerted against the walls of the confinement is estimated to be about 50 – 80 MPa (Sakhno and Sakhno, 2024).

Lime-based Expansive Agent Application

The application of expansive mortar is user-friendly. It does have legal requirements in terms of transportation and handling as it is not an explosive (Huynh and Laefer, 2009; Hinze and Brown, 1994). Not only legal constraints, but safety constraints are mitigated as well. The NERB method is ideal for use near inhabited areas, natural gas lines, roadways, or other areas (Hinze and Brown, 1994). Both mitigation strategies are beneficial to a mine operation incorporating expansive mortar for rock breaking.

To administer hydrated expansive mortar expansive mortar mixed in the correct prescribed dosage as powdery materials at the factory and made available in packages onsite (Revuelta, 2021). Expansive mortar as powder is added to water at a recommended ratio and thereafter loaded into drilled boreholes (Huynh and Laefer, 2009; Natanzi and Laefer, 2014). This procedure is simple, requiring little training for users. Therefore, these advantages made expansive agents a viable option as a solution for extraction purposes in any mining environment.

Methodology

The field study adopted a quantitative research design, using a deductive approach. The location of the field study site (Figure 3) was determined by a non-probability purposeful sampling method. This ensured reliability of the results from the study and was located in the geological area of interest – the proposed extension of mining. Figure 4 illustrates the view from the study site looking towards the R545, with the residential road that separates Klipspruit Colliery – Portion 10 and Ogies.

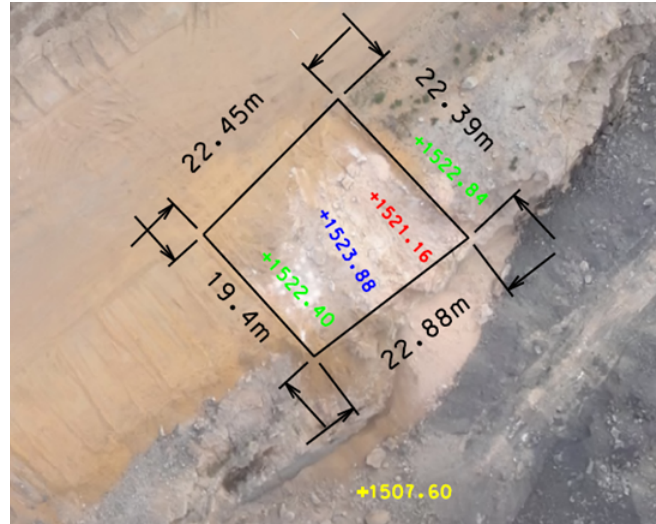


Figure 3 - Study site dimensions in Portion 10.



Figure 4 - View of the R545 from the study site.

Within the area of the study, four areas were designated (Area 1,2,3, and 4), with different measurements of hole spacing and burden_x as detailed in Table II. In the initial phase of the study, we were guided by two theoretical frameworks developed by Gómez and Mura from 1984, and Habib, Vennes and Mitri from 2022. The two theoretical frameworks guided the hole spacing distance used in the geometric design pattern. Gómez and Mura developed an equation:

$K = \frac{L}{D}$, where L is the hole spacing, D - hole diameter and K - material-dependent proportionality factor, corresponding rock type.

A k-constant of 10 for hard rock, was used corresponding to the rock strength in uniaxial compressive strength of the overburden composed of sandstone and siltstone. Sandstone and siltstone were assessed to have a UCS of 66.3 and 137.6 MPa respectively. The equation returned a value of 1m, for hole spacing. Habib, Vennes and Mitri developed an equation:

$Hole\ Spacing = 12.8 - 14.6\Phi$, where Φ – bore hole diameter.

The 12.8 -14.6 is the ratio of spacing to hole diameter. The median ratio of spacing-to-diameter constant of 13.7 was used for the case study. Inputting 102 mm, the borehole diameter which was a constant in the field study. The equation returned a value of 1.4 m hole spacing. These values guided the range from which the hole spacing of the four areas was determined.

Table II. Four areas designated into the field site geometric configurations

Areas		Row number	Number of Holes	Spacing (m)	Burden _x (m)	Angle of Drill Production Hole (°)
1		1	19	B=1	B=1	10
		2	20	B=1	B=1	5
		3	20	B=1	B=1	5
2		4	9	L=1.2	L=1	~ 0
3		5	17	B=1.2	R=1.5	~ 0
2		6	16	B=1.2	1	~ 0
4		7	13	B=1.5	1.2	~0
Total Holes			114			

The hole spacing and burden_x are the dependent variables, and crack width and fragmentation were independent variables. The fragmentation assessment was conducted using an image analysis software – WipFrag 4, developed by WipWare Inc. based in Canada. The software is used to process field images, to derive the quantitative fragmentation parameters and provide a particle distribution curve (PSD) (Wipware, 2025). The fragmentation data, crack width, crack types and spacing-to-burden ratio was used to draw correlation and infer a causal relationship. The collection of different types of data was synthesised through statistical (descriptive, correlation, linear and multi-linear regression), on which hypothesis testing was performed. In additions, thematic analysis was done by triangulation. The continuous (crack width) and discrete data (fragmentation) was corroborated with categorical data (crack types) by triangulation to enhance validity and increase accuracy in results interpretation.

The field study was five days for the actual drilling and loading of the expansive material. On arrival we received an induction to the mine for external personnel. After time was spent on administrative activities, drilling was only started on day 2 of arrival. After five days the entire field site was drilled and loaded with lime-based expansive material. An assessment of the fragmentation was conducted after maximum expansion time had lapsed. This occurred at a late stage due to operational constraints. The area was ‘pulled-apart’ by an excavator, as expansive agents are not dynamic, therefore there was no displacement of the rock mass in the field study site. The excavator was only able to operate on Area 1, which had a hole spacing and burden_x design of 1m × 1m.

Results and Discussion

Fracture Response over time

Expansive agents are static in operation, therefore required daily observation on the boreholes that were loaded with the expansive chemical. The rate of fracturing that occurred appeared as hair-line cracks and widened with time. This is the period between loading the expansive material into the boreholes and the appearance of the first visible cracks on the rock surface. The first set of 19 boreholes drilled and loaded were observed on day 4 indicating cracks formed between the boreholes shown in Figure 5.



Figure 5 – Fracture observation of row two on day four.

On day 4, boreholes that were loaded on day 3 with expansive material were still reacting and had not yet shown signs of fracturing. After the maximum expansion time of 35 days, there was visible fracturing observed from the site, shown in Figure 6. The site area was blocky due to the formation of the fractures that radiated from individual boreholes. The highly fractured study site was created by longitudinal and diagonal cracks.



Figure 1 – Field fractures after maximum expansion time allowance.

An estimated number of six diagonal cracks were observed in the field site. The highest frequency of diagonal crack occurred between row 3 and row 4 in Area 3 with three diagonal cracks shown in Figure 7. The second highest number of diagonal cracks was between row 2 and row 3 with two of the crack types. One diagonal crack was observed between rows 5 and 6. Area 3 with the highest frequency of diagonal cracks, has a geometric design hole spacing of 1.2 m and burden_x of 1 m, and a spacing-to-burden_x ratio of 1.2.

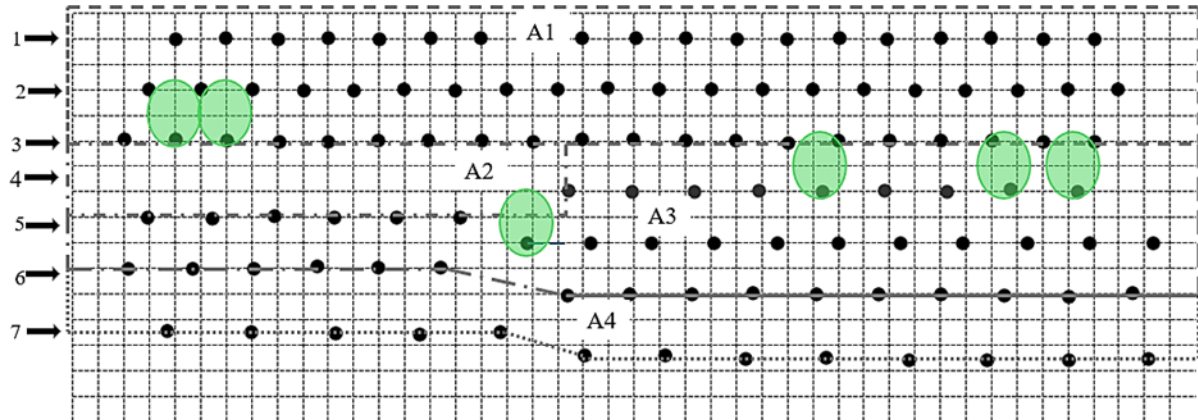


Figure 7 - Location of diagonal cracks on the field area.

Correlation Analysis

Spacing-to- burden_x ratio and diagonal cracks

To investigate the correlation and causal relationship between the spacing-to- burden_x (S/B_x) ratio and diagonal cracks created from the pattern, we analysed the numerical data with the statistical techniques. A correlation analysis was performed on results indicated in the schematic drawing of the field site in Figure 7. The computed results of correlation are summarised in Table III.

Table III - Correlation results for diagonal cracks observations

Variable	Spacing	Burden _x	S/B_x	No. cracks
Spacing	1			
Burden _x	0,290821	1		
S/B_x	0,540542	-0,6431	1	
No. cracks	-0,46442	-0,77354	0,359753	1

The results from the correlation analysis suggest a positive relationship between S/B_x and the number of diagonal cracks formed with a correlation coefficient of $r = 0.3598$. Indicating a higher S/B_x ratios are slightly associated with more diagonal cracks, but the relationship isn't strong. It suggests that while ratio matters, burden_x and spacing individually have stronger effects on crack development. Spacing and number of diagonal cracks returned a correlation coefficient of $r = -0.4644$. There is a moderate negative correlation. As hole spacing increases, the number of cracks decreases. This suggests that closer spacing promotes more crack development, which supports the idea that tighter spacing enhances rock fracturing. Lastly, discussing the burden_x and number of diagonal cracks has a correlation coefficient of $r = -0.7735$. This negative correlation suggests that as the burden_x increases, the number of cracks decreases sharply. This implies that larger the burden_x, the lesser the propagation of cracks, likely because the expansive energy is distributed across more rock volume.

Spacing-to-burden_x ratio and crack widths

The analysis of the entire field study crack widths returned a positive correlation coefficient of $r = 0.4018$, which indicates a moderate positive correlation. Showing that as the S/B_x ratio increase, the crack width widens. The probability value is 0.057362077, therefore there is no statistical significance indicating that the observed association could be due to chance. Therefore, no definitive conclusion about a causal relationship can be inferred to the variables.

S/B_x and cracks multi-linear regression analysis

Multiple regression analysis was performed on the hole spacing, burden_x and S/B_x . This inferential statistical technique allowed us to observe independent effects of the spacing, burden_x, S/B_x onto the

number of diagonal cracks formed. In performing this analysis, the causation relationship was inferred in comparison to the null hypothesis.

Table IV - Multiple regression for the independent variables

Variables	Coefficients	Standard Error	t Stat	P-value
Intercept	-16	26.77205	-0.59764	0.58227
Spacing (m)	-16.6667	23.47619	-0.70994	0.516938
Burden _x (m)	13.33333	21.90515	0.608685	0.575606
S/B _x	20	27.65901	0.723092	0.509644

From Table IV, all the p-value (probability) was above the p-value of 0.05 alpha constant at 95% confidence level; indicating that there is no statistical significance to establish causation between S/B_x and the number of diagonal cracks formed. Therefore, the data fails to reject null hypothesis. The coefficients of the variables support the findings from the correlation analysis, which suggest that as the hole space increase, the number of diagonal cracks decrease. Conversely, as the burden_x increases the number of diagonal cracks decrease.

Fragmentation Analysis

Fragmentation analysis was conducted to evaluate the size distribution of rock fragments produced following the application lime-based expansive chemical agent. The assessed fragmentation was collected from the left-side of the field site and had an S/B_x of 1. For calibration purposes, a boulder of known dimensions was used a reference point to work-out the fragment size for the image analysis software and generated a PSD-curve shown in Figure 8, with a histogram which organised the numerical fragment size into discrete data as bins.

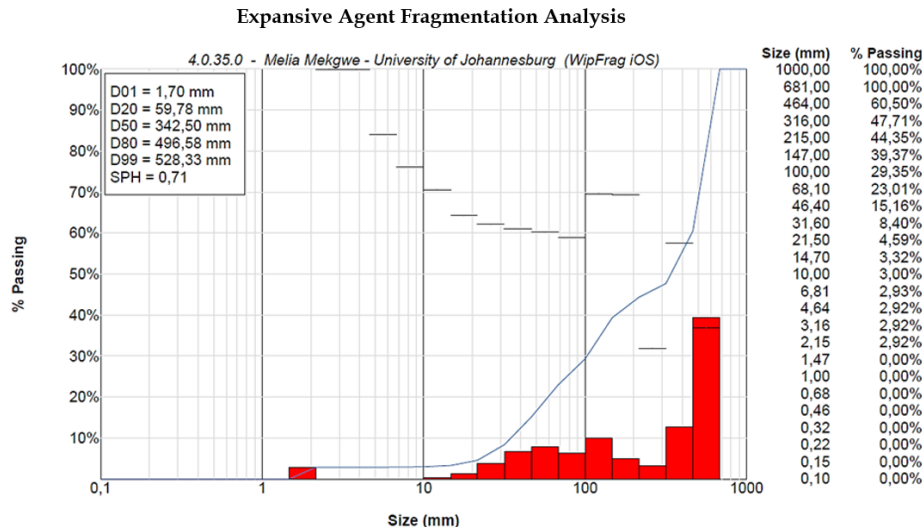


Figure 8 - Particle size distribution curve.

According to Figure 8, D₅₀ (mean particle size of rocks) and D₈₀ (80% of the fragmentation size) are 342.50 and 496.58 mm respectively. From the specified mean particle size, an informed decision can be determined regarding the crusher mesh size for comminution processes (Taiwo, 2024). Since 100% of fragments are below 681–1000 mm, the material is within the acceptable range for feed at a typical primary crusher (jaw crusher), usually or within a maximum feed width of 1600 x 2514 mm depending on make of the crusher (Gupta and Yan, 2016; Metso, 2011). This implies the expansive agent achieved adequate breakage and minimised secondary breaking requirements.

The distribution of the curve is positively skewed, therefore indicating large amounts of fine particle size. The shape of the distribution is steep, indicating a near-symmetrical, narrow distribution which means that there is uniformity in the particle sizes, therefore consistent cracking. The majority of the particle sizes are centred around the range of 20 mm to 160 mm. The sphericity (SPH) of the case study is 0.71; being above 0.5, the general shape of the fragment is angular, elongated and irregular. The fragmentation analysis using WipFrag provided a quantitative assessment from the application of the expansive chemical agent, and from the results the fragmentation analysis indicate compatibility. From the truck fleet complement at Klipspruit Colliery; the fragmentation is suitable to be handled by the CAT 785, and 793 models, according to D_{50} and D_{80} . Therefore, the case study site was well-fragmented, and demonstrated that the expansive agent was effective in producing controlled rock- breakage.

Statistical limitations

Limitations encountered in the field study was firstly, the field conditions. They could not be fully controlled, such as the planes of weakness in the rock mass, as it may have influenced the crack initiation and propagation, and thereby, the fragmentation assessment. Secondly, the sample area was too small to accommodate the four designated geometric pattern. Reducing the number of hole spacing and burden configuration, would have increased the empirical data of a dataset, therefore strengthen the statistical analysis.

Recommendation for future work

To promote the adoption of expansive agents in the mining industry, in addition to quarry mining, there needs to be clear and concise regulations for practical application in the field. One suggestion to achieve this intention, is to invest more research into investigation into the impact and influence of the perpendicular distance to the free breaking face, also called the burden_x in the context of using explosives. The consideration of this parameter recognises the need for creating diagonal cracks, not just longitudinal.

Conclusion

The summary of the findings indicates that there is a direct influence of the hole spacing and burden_x. A correlation between S/B_x and diagonal crack is established, but no cause-and-effect relation can be statistically proven. From the results, conclusions can be determined that lime-based expansive agents are effective in breaking hard rock, at an optimal geometric pattern design of hole space and burden_x of 1.2 m and 1 m respectively. The fragmentation of hole spacing to burden of 1 m × 1 m, is compatible with trucks operating at the surface mine. The research indicated the importance of a burden_x to generate diagonal cracks, which stimulates the growth of multi-directional fracturing and efficient fragmentation. Expansive agents are effective in hard rock, an environmentally-friendly alternative to mitigate the risk of sterilisation, and satisfy legal constraints.

Acknowledgments

- Klipspruit Colliery for the opportunity to conduct the research at their site, and financial support.
- Harlen Supplies (Pty) Ltd – distributors of the expansive agents, are thanked for sharing their expertise on the NERB method.

REFERENCES

- ACI, 2010. ACI 223R-10 Guide for the use of shrinkage compensating concrete. Farmington Hills: American Concrete Institute.
- ACI, 1998. Standard Practice for the Use of Shrinkage-Compensating Concrete.
- Al-Bakri, A., Hefni, M., 2021. A review of some nonexplosive alternative methods to conventional rock blasting. Open Geosciences 13, 431–442. <https://doi.org/10.1515/geo-2020-0245>
- Atkinson, B.K., 1987. Fracture mechanics of rocks.

- Bentz, D.P., Jensen, O.M., 2004. Mitigation strategies for autogenous shrinkage cracking. *Cem Concr Compos* 26, 677–685. [https://doi.org/10.1016/S0958-9465\(03\)00045-3](https://doi.org/10.1016/S0958-9465(03)00045-3)
- Bhandari, S., 1997. Engineering rock blasting operations.
- Bray, E., 1999. Co-operative governance in the context of the National Environmental Management Act 107 of 1998. *South African Journal of Environmental Law and Policy* 6, 1–12.
- Broberg, K., 1999. CRACKS AND FRACTURE, in: Broberg, K.B. (Ed.), *Cracks and Fracture*. Academic Press, San Diego, pp. 753–754. <https://doi.org/10.1016/B978-0-12-134130-5.50026-X>
- Broberg, K.B., 1999. 9 - Dynamic Processes in Fracture Mechanics, in: Broberg, K.B. (Ed.), *Cracks and Fracture*. Academic Press, San Diego, pp. 624–659. <https://doi.org/10.1016/B978-012134130-5/50010-6>
- Brundtland, G.H., Mansour, K., 2010. World commission on environment and development (wced). 1987. Our common future 2010.
- Callister Jr, W.D., Rethwisch, D.G., 2020. *Materials science and engineering: an introduction*. John Wiley & sons.
- De Silva, R.V., Pathegama Gamage, R., Anne Perera, M.S., 2016. An alternative to conventional rock fragmentation methods using SCDA: a review. *Energies (Basel)* 9, 958.
- De Silva, V.R.S., Ranjith, P.G., Perera, M.S.A., Wu, B., 2019. The effect of saturation conditions on fracture performance of different soundless cracking demolition agents (SCDAs) in geological reservoir rock formations. *J Nat Gas Sci Eng* 62, 157–170.
- Dessouki, A. El, Mitri, H., 2011. Rock Breakage Using Expansive Cement. *Engineering* 03, 168–173. <https://doi.org/10.4236/eng.2011.32020>
- Dowding, C.H., Labuz, J.F., 1982. Fracturing of rock with expansive cement. *Journal of the Geotechnical Engineering Division* 108, 1288–1299.
- Elbeblawi, M.M.A., Elsaghier, H.A.A., Amin, M.T.M., Abdellah, W.R.E., 2022. *Surface mining technology*. Springer.
- Gagné, R., 2016. Expansive agents, in: *Science and Technology of Concrete Admixtures*. Elsevier, pp. 441–456. <https://doi.org/10.1016/B978-0-08-100693-1.00022-9>
- Gamage, R.P., De Silva, R.S.V., 2020. United States Patent. US 10,836,955 B2.
- Gillot, C., Coutelas, A., 2018. Cements, mortars, binders. *The Encyclopedia of Archaeological Sciences* 1–5.
- Gopi, S., 2025. Basic Civil Engineering , in: *Basics to Civil Engineering - Chapter 14 (Mortar)*. O'Reilly .
- Griliches, Z., 1979. Issues in Assessing the Contribution of Research and Development to Productivity Growth. *The Bell Journal of Economics* 10, 92. <https://doi.org/10.2307/3003321>
- Gupta, A., Yan, D., 2016. Jaw Crusher, in: Gupta, A., Yan, D. (Eds.), *Mineral Processing Design and Operations*. Elsevier, pp. 123–152. <https://doi.org/10.1016/B978-0-444-63589-1.00004-6>
- Habib, K.-M., Shnorhokian, S., Mitri, H., 2022. Evaluating the Application of Rock Breakage without Explosives in Underground Construction—A Critical Review of Chemical Demolition Agents. *Minerals* 12, 220. <https://doi.org/10.3390/min12020220>
- Hammer, T.A., 2007. Deformations, strain capacity and cracking of concrete in plastic and early hardening phases. *Fakultet for ingeniørvitenskap og teknologi*.

- Harris, P.M., 1977. Igneous & metamorphic rock [WWW Document]. NERC Open Research Archive . URL <https://nora.nerc.ac.uk/id/eprint/540026/> (accessed 8.23.25).
- Hinze, J., Brown, J., 1994. Properties of soundless chemical demolition agents. *J Constr Eng Manag* 120, 816–827.
- Hinze, J., Nelson, A., 1996. Enhancing Performance of Soundless Chemical Demolition Agents. *J Constr Eng Manag* 122, 193–195. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1996\)122:2\(193\)](https://doi.org/10.1061/(ASCE)0733-9364(1996)122:2(193))
- Kawano, T., 1982. Non-explosive demolition agent. *Gypsum and lime* 176, 41–48.
- Kesler, C.E., 1976. Control of expansive concretes during construction. *Journal of the Construction Division* 102, 41–49.
- Konik, Z., Małolepszy, J., Roszczynialski, W., Stok, A., 2007. Production of expansive additive to portland cement. *J Eur Ceram Soc* 27, 605–609.
- La Chatelier, H., 1900. Sur les changements de volume qui accompagnent le durcissement des ciments. *Le Ciment: son emploi et ses applications nouvelles en France et à l'étranger* 5, 38.
- Li, S., Feng, Y., Yang, J., 2021. Expansion Mechanism and Properties of Magnesium Oxide Expansive Hydraulic Cement for Engineering Applications. *Advances in Materials Science and Engineering* 2021, 5542072. <https://doi.org/10.1155/2021/5542072>
- Liang, Y., ZHANG, N., Jiaguang, K.A.N., 2018. The concept, model and reserve forecast of green coal resources in China. *Journal of China University of Mining & Technology* 47, 1–8.
- Logan, J.M., 1979. Brittle phenomena. *Reviews of Geophysics* 17, 1121–1132. <https://doi.org/10.1029/RG017i006p01121>
- Lumadi, V.W., Nyasha, S., 2024. Technology and growth in the South African mining industry: An assessment of critical success factors and challenges. *SAIMM* 124, 163–171.
- Malvern, L.E., 1969. *Introduction to the Mechanics of a Continuous Medium*.
- Mecholsky Jr, J.J., 1995. Fracture mechanics principles. *Dental Materials* 11, 111–112.
- Metso, 2011. *Crushing and screening handbook* . Metso Expect Results .
- MHSC, 2018. Mine Health and Safety Act 29 of 1996 and Regulations. *Mine Heal Saf Counc* 588, 588.
- minejxsc, 2023. Primary Crushing: What You Need to Know [WWW Document]. JXSC. URL https://www.minejxsc.com/blog/what-is-primary-crushing/?utm_source=chatgpt.com (accessed 10.20.25).
- Nagataki, S., Gomi, H., 1998. Expansive admixtures (mainly ettringite). *Cem Concr Compos* 20, 163–170. [https://doi.org/10.1016/S0958-9465\(97\)00064-4](https://doi.org/10.1016/S0958-9465(97)00064-4)
- Natanzi, A.S., Laefer, D.F., 2014. Using chemicals as demolition agents near historic structures.
- Nobre, J., Ahmed, H., Bravo, M., Evangelista, L., de Brito, J., 2020. Magnesia (MgO) Production and Characterization, and Its Influence on the Performance of Cementitious Materials: A Review. *Materials* 13, 4752. <https://doi.org/10.3390/ma13214752>
- Pendock, M.J., 1984. Sterilisation and safeguarding of mineral deposits in Britain. *Minerals and the Environment* 6, 23–41. <https://doi.org/10.1007/BF02072662>
- Persson, P.-A., Holmberg, R., Lee, J., 2018. *Rock blasting and explosives engineering*. CRC press.
- Pickering, R.G.B., 2017. Controlled foam injection: a new and innovative non-explosive rockbreaking technology. *J South Afr Inst Min Metall* 117, 237–243. <https://doi.org/10.17159/2411-9717/2017/v117n3a5>

- Price, N.J., Cosgrove, J.W., 1990. Analysis of geological structures. Cambridge University Press.
- Rajaram, V., Dutta, S., Parameswaran, K., 2005. Sustainable mining practices: a global perspective. CRC Press.
- Redner, S., 1990. Fragmentation, in: Statistical Models for the Fracture of Disordered Media. Elsevier, pp. 321–348. <https://doi.org/10.1016/B978-0-444-88551-7.50021-5>
- Revilla-Cuesta, V., Skaf, M., Faleschini, F., Manso, J.M., Ortega-López, V., 2020. Self-compacting concrete manufactured with recycled concrete aggregate: An overview. *J Clean Prod* 262, 121362. <https://doi.org/10.1016/j.jclepro.2020.121362>
- Revuelta, M.B., 2021. Mortars, in: Bustillo Revuelta, M. (Ed.), Construction Materials: Geology, Production and Applications. Springer International Publishing, Cham, pp. 307–337. https://doi.org/10.1007/978-3-030-65207-4_11
- Sakhno, I., Sakhno, S., 2024. Directional fracturing of rock by soundless chemical demolition agents. *Heliyon* 10, e26068. <https://doi.org/10.1016/j.heliyon.2024.e26068>
- Santos, R.P. dos, Pierri, L.C., Faria, P., Noronha, M.A.M., 2018. New concept of tunnel boring machine: high performance using water jet and diamond wire as rock cutting technology. *REM - International Engineering Journal* 71, 9–17. <https://doi.org/10.1590/0370-44672017710027>
- Seriti, 2025. Klipspruit [WWW Document]. Seriti Resources . URL <https://seritiza.com/business/seriti-power/klipspruit/#:~:text=Klipspruit%20is%20an%20opencast%20mine,life%20of%20mine%20until%202048> (accessed 10.29.25).
- Sermet, E., Nieć, M., 2021. Not Mining Sterilization of Explored Mineral Resources. The Example of Native Sulfur Deposits in Poland Case History. *Resources* 10, 30. <https://doi.org/10.3390/resources10040030>
- Soeda, K., Yamada, S., Nakashima, Y., Nakaya, S., Haneda, H., Izawa, N., 2023. Non-explosive demolition agent, in: Demolition Methods and Practice V1. CRC Press, pp. 116–125.
- Spitz, K., Trudinger, J., 2019. Mining and the Environment. CRC Press LLC.
- Stephenson, P.R., 2000. The JORC Code—Its operation and application, in: Proceedings of the Codes Forum. pp. 81–89.
- Taylor, P.C., 2013. Curing concrete. CRC press.
- Taylor, R.B., Steven, T.A., 1983. Definition of mineral resource potential. *Economic Geology* 78, 1268–1270.
- Thompson, R.P., Clegg, W.J., 2018. Predicting whether a material is ductile or brittle. *Curr Opin Solid State Mater Sci* 22, 100–108. <https://doi.org/10.1016/J.COSSMS.2018.04.001>
- Walkley, B., Provis, J.L., 2019. Solid-state nuclear magnetic resonance spectroscopy of cements. *Mater Today Adv* 1, 100007. <https://doi.org/10.1016/j.mtadv.2019.100007>
- Wipware, 2025. WipFraf Image Analysis Software [WWW Document].
- Wrighton, C.E., Bee, E.J., Mankelow, J.M., 2014. The development and implementation of mineral safeguarding policies at national and local levels in the United Kingdom. *Resources Policy* 41, 160–170. <https://doi.org/https://doi.org/10.1016/j.resourpol.2014.05.006>
- Wu, J., 2018. Material Interface of Pantograph and Contact Line. *Pantograph and Contact Line System* 165–191. <https://doi.org/10.1016/B978-0-12-812886-2.00005-7>
- Xu, Z., Cao, Y., Li, C., Tai, L., He, S., 2023. Mechanism of Hard Rock Static Blasting-induced Crack Expansion.

- Yang, F., Liu, W., Zhu, X., Xiang, C., 2023. The Rock-Breaking Mechanism of Thermal Spalling-Assisted Rock Cutting by PDC Cutter. *Rock Mech Rock Eng* 1–20.
- Yuan, Q., Liu, Z., Zheng, K., Ma, C., 2021. Inorganic cementing materials, in: *Civil Engineering Materials*. Elsevier, pp. 17–57. <https://doi.org/10.1016/B978-0-12-822865-4.00002-7>
- Zhang, Z.-X., 2016. *Rock fracture and blasting: theory and applications*. Butterworth-Heinemann.
- Zhong, Z., Tao, P., Zhang, H., Jin, H., Lou, R., Cui, Y., Huang, Q., Liu, J., 2023. Research progress and future prospective of soundless chemical demolition agents (SCDAs) and associated applications. *Constr Build Mater* 409, 134209. <https://doi.org/10.1016/j.conbuildmat.2023.134209>
- Zhou, H., Xie, X., Feng, Y., 2018. Rock breaking methods to replace blasting. *IOP Conf Ser Mater Sci Eng* 322, 022014. <https://doi.org/10.1088/1757-899X/322/2/022014>



Melia Mekgwe

Lecturer
University of Johannesburg

Melia Mekgwe is a mining engineer with over a decade of experience in both industry and academia. She graduated from the University of the Witwatersrand in 2014 with a Bachelor of Science Honours in Mining Engineering. Thereafter, she went to work in the production department at a renowned hard-rock underground mine trading in gold. Critical field experience was gained, a deep understanding of operational safety was developed, and production efficiency. The learning transitioned to an engineering department in 2018, where she joined a massive mine in the province of Northern Cape. In the mine, she worked directly with automated systems, enforcing safety and efficiency. Currently, she works in academia and has spent over three years in the sector. In this position, she delivers quality teaching experience to the next generation of mining professionals, bridging theoretical knowledge with real-world application, drawing extensively from industry experience to enrich the learning environment.

Being in the academia sector has opened opportunities to further contribute to the industry through research and development. Areas of interest for research are: rock breaking efficiency in mining, retention of female mining engineers, and the management of dispersion of mining graduates through the mining value chain to the professional level. She is an active member and contributor to the *Strategic Mineral Resource Group*, one of the research centres at the institution of higher learning, dedicated to encouraging sustainability in mining through research and offering practical solutions to the complex inherent nature of the industry.

Committing to lifelong learning, Melia Mekgwe is currently finishing her master's qualification in sustainable mining with the University of Johannesburg. The research aims to support sustainability in mining through green mining. It focuses on the application and effectiveness of non-explosive rock-breaking agents in opencast mining environments, particularly within South African coalfields. This contribution extends to the professional responsibility to ensure sustainability for generations to come, operational safety, and technological advancement within the mining sector.

The versatility in her mining engineering portfolio has enabled her to acquire a comprehensive knowledge of the mining value chain. This has developed a strong professional profile that blends field experience, engineering acumen, and academic excellence. My current professional mandate is to advance mining practices through education, research, industry collaboration mentoring graduates through their transition to the industry. A reflection of her aspirations to offer a meaningful contribution to the industry.

Eliminating fall of ground incidents in underground mines: Lessons from Australia for the Southern African mining industry

A. Mapuranga

Northern Star Resources, Australia

Fall of ground (FoG) incidents continue to be one of the leading causes of injury and fatalities in underground mining operations around the world. While technology and regulation have improved significantly over the years, FoG events remain a persistent challenge, especially in regions where mechanisation and technology are still evolving. In Australia, a combination of proactive ground control measures, robust regulatory oversight, and widespread adoption of areal support systems has contributed to a noticeable decline in FoG-related incidents. This paper examines how lessons from the Australian mining industry can be adapted to help eliminate FoG incidents in the Southern African context, and how reciprocal learnings between the two regions can drive safer mining practices. Drawing on proven approaches from Australian sites, such as the standardised use of mesh in development headings and consistent classification of unsupported ground, this paper shows how such measures can enhance FoG control and management in Southern African mines. Rock engineering and geotechnical practices from both Australian and Southern African operations reveal a mix of successes, challenges, and opportunities where collaboration can drive mutual improvement and elevate global ground-control standards.

INTRODUCTION

Fall of ground (FoG) incidents remain one of the most persistent safety challenges in underground mining worldwide. Despite decades of technological advances in rock support, monitoring, and regulatory oversight, FoG continues to be a leading cause of injuries and fatalities. According to the International Council on Mining & Metals (ICMM, 2024), FoG was the second-highest cause of fatalities in 2024 ; in South Africa FoG accounted for ~30% of mining fatalities as of Oct 2024 (MHSC, 2024); and in Zimbabwe FoG comprised ~37% of sector fatalities in Q2 2025 (Mapuranga, 2025). The continuing risk reflects the complexity of mining, rockmass behaviour and the adequacy of controls.

In highly mechanised jurisdictions such as Australia, the combination of proactive ground control strategies and regulatory driven use of areal support systems has led to a measurable decline in FoG-related incidents over the past two decades. Practices such as the systematic installation of mesh in development headings, coupled with strong oversight from regulatory authorities, have contributed significantly to reducing exposure to unsupported ground. By contrast, in Southern Africa, where mining operations range from highly mechanised to labour-intensive operations, FoG incidents remain a critical hazard. While progress has been made in formalising ground control regulations and improving support practices, challenges persist due to resource constraints, legacy mining methods, mining environment, depth and gaps in technology adoption. This contrast provides an opportunity to draw lessons from both the Australian and Southern African mining industry and consider cross-pollination of ideas to strengthen FoG management in Southern Africa.

BACKGROUND AND LITERATURE REVIEW

Global trends in fall of ground incidents

FoG incidents remain one of the most significant hazards in underground mining and have historically accounted for a large proportion of injuries and fatalities (Netshilaphala & Zvarivadza, 2022). Despite sustained improvements in mining technology, ground-support systems and risk-management practices, the inherently complex and variable nature of rock masses means that complete elimination of FoG remains a persistent challenge (Fuławka *et al.*, 2022). Across jurisdictions, there is convergence on several key mitigation strategies such as improving support designs, adopting systematic ground-support, enforcing rigorous regulatory oversight, and cultivating a resilient safety culture, all aimed to reducing FoG risk.

Australian experience in ground control

Australia has robust mechanisms in FoG management due to proactive adoption of areal support systems, i.e., mesh and in some cases, fibrecrete as standard inclusions in ground-support standards. In addition, the implementation of clear unsupported ground such as ‘no entry in unsupported ground’ is strongly reinforced by the regulatory framework embedded in the Work Health and Safety (Mines) Regulations 2022 (DMIRS, 2025).

Western Australia’s mining safety performance has remained consistently strong, driven by legislation and mature safety management systems. The 2022–23 Safety Performance Report recorded three fatalities across the entire mineral industry, one of which was classified as a FoG-type incident where a worker was struck by falling rock underground (WorkSafe WA, 2025). Although FoG-specific data are not published as a continuous time series, available evidence shows FoG incidents are not as frequent compared with mobile equipment or fall from height accidents. Mechanisation and systematic areal support have been effective in maintaining a low and stable FoG risk profile. The regulatory framework enforced by the Department of Mines, Industry Regulation and Safety (DMIRS) ensures high compliance and transparent incident reporting where learnings are shared and accessible to all mines (WorkSafe WA, 2025).

Southern African context

Southern Africa presents a different risk profile, particularly in gold, platinum and chrome mines as well as small-scale artisanal mining. Conventional methods and labour-intensive operations increase exposure to unsupported ground. While mechanisation is expanding, adoption of universal areal support remains uneven due to cost and logistical constraints. In Southern Africa, FoG is still one of the leading causes of underground fatalities in hard-rock mining.

South Africa and Zimbabwe experience

South Africa’s mining industry has historically reported high FoG-related fatality rates due to its labour intensiveness, deep-level tabular reef mining and high-stress environments. In 2024, the country recorded 42 mining fatalities, marking a 24% reduction from 2023 and the lowest on record (Ajayi, 2025). According to the Mine Health and Safety Council (MHSC) and the Mining Occupational Safety and Health (MOSH) Learning Hub, FoG incidents accounted for approximately 30% of these fatalities as of October 2024 (MOSH, 2024). Targeted industry programmes including the Falls of Ground Action Plan (FOGAP), seismic management protocols, and improvements in ground support have been instrumental in improving outcomes. Notably, FoG fatalities fell from 22 in 2021 to six in 2022, a 73% reduction (MOSH, 2024). The long-term trend in South Africa therefore shows a steady decline in FoG incidents, attributed to coordinated regulatory enforcement, improvement in systems, and structured behavioural safety initiatives. However, despite this encouraging progress, the industry has yet to reach its ultimate goal of zero harm.

In Zimbabwe, FoG remains the leading cause of mining fatalities in Zimbabwe. In the first two months of 2024, 17 of the 33 recorded mining deaths (52%) were attributed to FoG (Zvinonzwa, 2024). The previous year saw at least 237 mine fatalities nationally, many within small-scale or artisanal operations that lack engineered ground control systems (Business & Human Rights Resource Centre, 2024). The volatility and persistence of FoG incidents in Zimbabwe reflect limited industry mechanisation,

inadequate enforcement of safety standards, and widespread informal mining. It is important to note that Zimbabwe's FoG incident statistics are disproportionately affected by events in the informal and small-scale mining sector. These operations typically lack engineered support systems, qualified supervision, and compliance monitoring (Matambo, 2024). By contrast, tier-one operators such as Zimplats, Mimosa, and Unki have established formal ground-control programs aligned with international best practice. As a result, FoG events within these companies occur at a considerably lower frequency and are often contained before escalation. National FoG rates should therefore be interpreted with caution, as aggregated data over-represents the risk relative to the regulated, mechanised segment of the industry.

While the Chamber of Mines has introduced campaigns aimed at improved ground-control awareness, FoG continues to dominate Zimbabwe's mining fatality statistics over the last decade, particularly in gold, platinum and chromite operations due to inadequately supported work areas and at-risk practices (Nyikadzino, 2024).

Research and knowledge transfer

In both regions, there is a shared understanding that FoG is a critical risk that must be eliminated. Evidence shows that structured ground-control practices, particularly the standardisation of areal support systems reinforced through regulation, significantly improve safety outcomes in Australia (DMIRS, 2019).

This section examines the opportunities for transferring effective FoG management practices between mining jurisdictions. The intent is to cross-pollinate proven technical, organisational, and regulatory measures across the entire mining spectrum, from tier-one operations to artisanal and small-scale mines. Knowledge transfer is considered both as a technical process (sharing design standards, ground-support technologies, and monitoring tools) and as a cultural process (embedding learning, reporting, and behavioural reinforcement) (Duryan *et al.*, 2018).

KEY TECHNICAL AND PRACTICAL LESSONS FOR ADOPTION

Formalising Support in the Informal Sector

FoG statistics in Southern Africa, particularly Zimbabwe, are heavily skewed by incidents in the artisanal and small-scale mining sector (Business & Human Rights Resource Centre, 2024). Structured support to this sector is essential. Governments, mining chambers, and academic institutions should develop portable ground-support standards, basic training programmes, and low-cost areal support solutions that can be deployed in small workings. Introducing the compulsory use of basic support elements would immediately reduce exposure to unsupported ground. These measures should be complemented by community-level safety education, subsidised access to engineering advice, and extension services similar to agricultural outreach programmes but focused on mine safety and FoG control.

Strengthening collaboration between tier-one and small-scale operations

Large mining companies worldwide have advanced ground-control systems and access to professional geotechnical oversight. Establishing structured mentorship and technical-exchange programmes between these tier-one companies and surrounding small-scale miners could accelerate knowledge diffusion and raise baseline safety performance. Shared services could include geotechnical inspections, provision of government support, and participation in FoG awareness sessions. Such collaboration mirrors sustainable mining frameworks that promote inclusive development and safer regional ecosystems (MOSH, 2024).

Government and institutional support

Governments and regional mining authorities should institutionalise technical support for small scale mining operations through geological surveys, safety audits, and dedicated training programmes. National skills authorities could also fund scholarships and bursaries in rock mechanics, strata control, and geotechnical engineering to mitigate the ongoing brain drain from the region. Hebblewhite (2010) highlights how Australia's Mining Education Australia programme demonstrates the value of sustained

university–industry collaboration in building advanced mining capability. Adapting similar collaborative frameworks through partnerships between institutions and Southern African universities could foster regional centres of excellence in ground-control research and education for the wider benefit of the industry.

Cross-regional collaboration and incident information sharing

Australia’s safety model demonstrates the value of transparent reporting and rapid dissemination of lessons learned. When a FoG incident occurs, the Department of Mines, Industry Regulation and Safety (DMIRS) issues safety flashes and incident bulletins accessible to all operators (WorkSafe WA, 2025). This practice enables continuous learning and early adoption of preventive measures. In contrast, Southern African regulators seldom or selectively circulate incident information beyond the affected mine, limiting institutional learning. Establishing a Southern African Ground Control Forum could enable cross-mine information sharing, common data repositories, and annual workshops (MOSH, 2024). Harmonising regulatory definitions of ‘unsupported ground,’ minimum support standards, and incident reporting obligations across the Southern African Development Community would enhance consistency and transparency.

CROSS-POLLINATION OF PRACTICES BETWEEN AUSTRALIA AND SOUTHERN AFRICA

Australia’s underground mines have established areal support as the baseline standard, with universal installation of mesh, fibrecrete, and cable bolts in all development drives (WorkSafe WA, 2025). Systematic quality assurance/quality control (QAQC) processes and integration of regulatory requirements in the mining workflow has created a closed feedback loop where support design, verification, and performance continually inform one another (DMIRS, 2019).

In contrast, Southern African operations demonstrate uneven implementation of similar systems, with selective mesh installation and reactive practices (MOSH, 2024). A practical pathway forward involves cross-pollinating Australia’s engineering discipline with Africa’s contextual adaptability. Australian standardisation can be blended with local empirical practice to accommodate narrower reef workings. Research-driven collaboration between Australian institutions such as the Australian Centre for Geomechanics and Southern African universities could accelerate the localisation of support technologies.

Harmonising management of unsupported ground

Australia’s ‘no person in unsupported ground’ principle is a cornerstone of its ground-control culture. The policy is driven by regulation and operationalised through clearly-defined procedures and physical demarcations. For context, unsupported ground in Western Australia mining operations means no mesh and bolts. Southern Africa already recognises this principle conceptually but suffers from variable interpretation between operations (MOSH, 2024).

A harmonised approach should formalise an industry-wide definition of ‘unsupported ground’ reinforced through training, procedural audits, and industry coordination. Aerial support as shown in Figure 1 and Figure 2 remains a critical engineering control, significantly reducing personnel exposure in the intervals between installed bolts or timber supports.

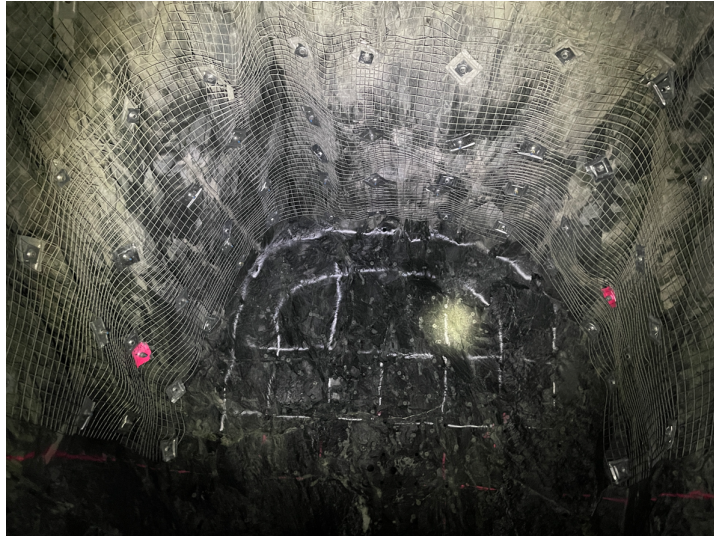


Figure 1: Supported ground with mesh and bolts in Western Australia.



Figure 2: Supported ground with shotcrete, mesh, straps and bolts in Western Australia.

STRENGTHENING THE REGULATORY AND INSTITUTIONAL FRAMEWORK

Australia's Work Health and Safety (Mines) Regulations 2022 and DMIRS enforcement model demonstrate how clear, enforceable rules combined with transparent data reporting reduce FoG exposure (DMIRS, 2019). DMIRS conducts random audits, publishes improvement notices, and disseminates open 'safety-flash' bulletins, allowing lessons learned to circulate industry-wide (WorkSafe WA, 2025).

In Southern Africa, while the Mine Health and Safety Act 1996 provides the legal basis, regulatory capacity remains stretched (MOSH, 2024). A cross-pollination strategy would involve joint DMIRS-DMRE-MHSC taskforces and exchange programmes focused on inspection methodology, investigation techniques, and database management. Embedding knowledge-sharing forums within mine health and safety frameworks could institutionalise transparency and collective learning.

Leveraging education and knowledge transfer

Knowledge transfer must operate at both the technical and cultural levels. It requires not only sharing design standards and monitoring tools but also reinforcing learning and behavioural discipline across all job roles (Duryan et al., 2018). South Africa's structured competency framework for rock engineering stands as one of the most mature and measurable systems in Africa – even globally. The Rock Engineering Certificate, administered under the Minerals Council and including the Mine Health and Safety Act, provides formal recognition of technical proficiency in ground control design, stability analysis, and strata control supervision. The certification process includes rigorous theoretical examinations, practical assessments, and mandatory experiential training; resulting in professionals with demonstrable and auditable competencies (Minerals Council South Africa, 2022). This qualification system has proven instrumental in professionalising the discipline and driving measurable reductions in FoG incidents by ensuring that all ground control designs and decisions are overseen by certified practitioners.

On the other hand, Australia's framework for geotechnical and ground control competency remains largely experience-based and institution-driven, with professional accreditation typically governed by Engineers Australia and site-specific training processes. While effective, it lacks the formal national certification and measurable competency assurance seen in South Africa's model. Adopting a similar structured qualification or 'Rock Mechanics Certificate' pathway in Australia would enhance uniformity, benchmarking, and accountability across operations. However, a persistent challenge is the brain drain of certified South African rock engineers and strata control officers migrating to Australia, Canada, and other mining jurisdictions. This trend underscores the international demand for structured, competency-based certification and the need for collaborative training pipelines between both regions to build and retain technical capacity.

ELIMINATING FALL OF GROUND INCIDENTS

Achieving zero FoG harm requires a harmonised approach that draws from both Southern African and Australian mining practices. Each jurisdiction offers valuable lessons: Zimbabwe bridging the information gap between tier 1 mining companies and small-scale miners; South Africa's strong behavioural and verification culture through the FOGAP programme, and Australia's robust regulatory and engineering design frameworks via Ground Control Management Plans (GCMPs) and Critical Control Management systems (Emery *et al.*, 2020 & DMIRS, 2025).

Leadership and critical control management form the foundation for FoG elimination. The International Council on Mining and Metals (ICMM, 2015) advocates for critical control frameworks that define material unwanted events, critical controls, verification standards, and accountability at senior levels. Australia has embedded this practice through GCMPs mandated by state regulators (DMIRS, 2025), while South Africa's Minerals Council implemented a similar structure under the FOGAP, which includes mandatory leadership verification and 'no work under unsupported ground' protocols.

Engineering design and support systems remain the technical backbone of ground stability. Chikande and Zvarivadza (2016) suggest improvement is needed in local support, spacing, design and mining practices. Site experience has demonstrated that permanent mesh and bolts significantly reduce FoG in underground operations.

Work execution discipline and human factors are equally critical. FOGAP (Minerals Council South Africa, 2022) emphasises supervisor-led verification of ground conditions, illumination improvements, and behavioural coaching. Australia's ground control literature, (Emery *et al.*, 2020) discuss how Australian underground coal mines use formal critical-control verification processes within a proactive ground-control management system. Zimbabwe can merge these approaches to enhance FoG management strategies.

Finally, the uplift of small-scale and contract mining sectors, particularly in Southern Africa, is essential to achieve sustainable FoG elimination. While not explicitly addressed in Chikande & Zvarivadza (2016), the evidence they present suggests that complementing their technical recommendations with

standardised GCMPs, shared geotechnical services and periodic audits could help reduce FoG burdens in operations with ground control challenges. These initiatives should be jointly supported by government, universities, and major operators, echoing South Africa's FOGAP training collaborations and Australia's mine safety regulator–university partnerships.

In summary, a cross-jurisdiction FoG elimination framework must merge Zimbabwe's structural redesign emphasis, South Africa's behavioural control culture, and Australia's systemic governance and technology integration. Together, these elements form a verifiable, auditable pathway to eliminating FoG across the mining industry.

DISCUSSION AND CONCLUSIONS

This paper has demonstrated that eliminating FoG incidents requires a cross-jurisdictional approach that transcends traditional regional boundaries and leverages the strengths of different mining systems. The comparative review between Australian, South African, and Zimbabwean operations shows that while each jurisdiction faces unique geological, operational, and socio-economic conditions, the fundamental mechanisms driving FoG risk remain consistent, that is, inadequate ground support, seismicity, poor QAQC and deficiencies in supervision and compliance.

Australia's experience illustrates the value of systematic engineering discipline, underpinned by rigorous regulatory oversight, continuous QAQC, and a proactive safety culture. Mandatory areal support installation, critical control verification, and robust enforcement by the DMIRS have proven highly effective in maintaining low FoG frequencies (DMIRS, 2025). South Africa, through the FOGAP, has demonstrated the effectiveness of structured behavioural and leadership interventions, complemented by rigorous data tracking and information sharing across the sector (Minerals Council South Africa, 2022). Zimbabwe, though at a different developmental stage, presents significant potential for improvement through structured capacity building, adoption of technology, and progressive regulatory strengthening.

Cross-pollination between these jurisdictions presents tangible opportunities for progress. The combination of Australian engineering rigour, South African behavioural discipline, and Zimbabwean contextual innovation could form the basis of a robust, regionally-adaptable FoG elimination framework. For instance, Australian GCMP and Critical Control Management methodologies could be localised in Southern Africa to include economic and logistical constraints, while maintaining auditability and verification integrity. Similarly, South Africa's illumination and supervision-led verification standards could reinforce Australia's existing QC systems and provide a more holistic FoG control culture across all regions.

In conclusion, eliminating FoG incidents across Southern Africa will depend on strong regulatory harmonisation, leadership accountability, and the adoption of auditable technical standards. The integration of real-time monitoring, predictive analytics, and cross-sector collaboration can transition FoG control from a reactive to a proactive discipline. The evidence from this paper suggests that success lies in engineering discipline, behavioural compliance and institutional integration and technology partnerships. Together, these form a sustainable pathway toward zero harm. By aligning institutional frameworks, technological innovation, and cultural leadership, the mining industry can move decisively toward the complete elimination of FoG incidents.

REFERENCES

- Ajayi, O. (2025), South Africa's mine safety performance improves in 2024, *Mining Weekly*, 15 January. Available at: <https://www.miningweekly.com> (Accessed 14 October 2025).
- Business & Human Rights Resource Centre (2024), Zimbabwe: At least 237 killed in mine accidents, 26 January. Available at: <https://www.business-humanrights.org/en/latest-news/zimbabwe-at-least-237-killed-in-mine-accidents-govt-says-most-are-unregistered-mines-which-it-cannot-control-due-to-shortage-of-resources/> (Accessed 20 September 2025).
- Chikande, B. & Zvarivadza, T. (2016), Ground control practices and lessons from Zimbabwean mines, *Journal of the Southern African Institute of Mining and Metallurgy*, 116(3), pp. 233–240.
- Department of Mines, Industry Regulation and Safety (DMIRS) (2019), *Ground Control for Western Australian Mining Operations: Code of Practice*. Perth: Government of Western Australia. Available at: https://www.worksafe.wa.gov.au/system/files/documents/2025-02/MSH_CoP_GroundControl.pdf (Accessed 19 October 2025).
- Department of Mines, Industry Regulation and Safety (DMIRS) (2025), *Work Health and Safety (Mines) Regulations 2022: Ground Control Management Guideline*. Perth: Government of Western Australia.
- Duryan, M., Smyth, H., Roberts, A. & Rowlinson, S. (2018), Knowledge transfer and organisational learning in mining safety, *Safety Science*, 110, pp. 47–58. doi: 10.1016/j.ssci.2018.07.023.
- Emery, J., Mikula, P. & Kaiser, P.K. (2020), *Critical Control Management for Ground Control in Underground Mines*. Perth: Australian Centre for Geomechanics.
- Fuławka, K., Stolecki, L., Szumny, M., Pytel, W., Jaśkiewicz-Proć, I., Jakić, M. & Nöger, M. (2022), 'Roof fall hazard monitoring and evaluation—state-of-the-art review', *Energies*, 15(21), p. 8312. doi: 10.3390/en15218312.
- Hebblewhite, B.K. (2010), University–industry collaboration in mining education: The Australian model, *Mining Technology*, 119(1), pp. 46–52. doi: 10.1179/037178409X12507063284450.
- ICMM (2024), *2024 Safety Performance of Members*. International Council on Mining & Metals. Available at: <https://www.icmm.com/en-gb/news/2025/2024-safety-performance> (Accessed 10 October 2025).
- Matambo, F. (2024), 'Occupational safety and health in small-scale mining: A case of informal artisanal miners in Mount Darwin, Zimbabwe', *Occupational Medicine*, 74 (Suppl 1). doi: 10.1093/occmed/kqae023.0869.
- MHSC (2024), *Breakaway feedback: Falls of Ground Safety* (18 October 2024). Johannesburg: Mine Health and Safety Council. Available at: <https://mhsc.org.za> (Accessed 20 October 2025).
- Minerals Council South Africa (2022), *Falls of Ground Action Plan (FOGAP): Industry Progress Report 2022*. Johannesburg: Minerals Council SA.
- Mapuranga, R. (2025), 'Fall of Ground incidents remain leading cause of mining fatalities', *Mining Zimbabwe*, 15 August. Available at: <https://www.miningzimbabwe.com/fall-of-ground-incidents-remain-leading-cause-of-mining-fatalities/> (Accessed 4 October 2025).
- MOSH Learning Hub (2024), *Falls of Ground Action Plan (FOGAP) Progress Update*. Johannesburg: Mine Occupational Safety and Health Learning Hub.
- Netshilaphala, V. & Zvarivadza, T. (2022), 'Fall of Ground management through underground joint mapping: Shallow chrome mining case study', *Geotechnical and Geological Engineering*, 40, pp. 2231–2254. doi: 10.1007/s10706-021-02023-3.

Nyikadzino, G. (2024), 'The nightmare of mining disasters', The Zimbabwe Independent, 12 January. Available at: <https://www.newsday.co.zw/theindependent/opinion/article/200021964/the-nightmare-of-mining-disasters> (Accessed 26 September 2025).

WorkSafe WA (2022), Safety Performance in the Western Australian Mineral Industry 2021–22. Perth: Government of Western Australia.

WorkSafe WA (2025), Safety Performance in the Western Australian Mineral Industry 2024–25. Perth: Government of Western Australia.

Zimbabwe Now (Zvinonzwa, E.) (2024), 'Mining sector records 33 fatalities in 37 accidents', Zimbabwe Now, 5 April. Available at: <https://zimbabwenow.co.zw/articles/9097/mining-sector-records-33-fatalities-in-37-accidents> (Accessed 14 October 2025).



Amos Mapuranga

Senior Engineer: Geotechnical
Northern Star Resources

Amos Mapuranga Pr. Eng (ECSA), CPEng (EA) is a Chartered Professional Engineer with over 11 years of experience in the mining industry, specialising in mining, geotechnical/ rock engineering. He currently serves as a Senior Geotechnical Engineer at Northern Star Resources in Australia. Amos holds an MSc and BSc in Mining Engineering from the University of the Witwatersrand and is registered with both ECSA and Engineers Australia. He also holds the Rock Mechanics Certificate and Strata Control Certificate, demonstrating advanced competency in underground support systems and stability design.

His previous roles include Head of Rock Engineering at Zimplats, where he led a team across five underground mines, and Mine Planning Engineer at SRK Consulting. His experience spans sublevel stoping, bord and pillar, Avoca mining methods, seismic risk management, and backfill systems.

With a strong focus on safety, innovation, and cross-functional collaboration, Amos brings a practical, results-driven approach to mining and geotechnical engineering. He is committed to driving improvements in mine safety, performance, and sustainability through technical leadership and continuous professional development.

Beyond compliance: Addressing psychosocial risks in Southern African mining – integrating ubuntu, systems thinking, and innovative practices for a sustainable workforce

A.K.B. Chigwada

ABE Risk Solutions, Australia

Mining operations across Southern Africa are entering a critical transition. While physical safety performance has improved through mechanisation, regulatory pressure, and structured safety management systems, psychosocial risks remain under-recognised and under-managed. Fatigue, mental distress, harassment, job insecurity, community pressure, and intergenerational trauma increasingly shape workforce wellbeing, stability, and productivity. These risks are no longer a 'soft' HR issue; they are a material business risk with direct implications for production discipline, ESG performance, and social licence to operate.

This paper proposes an integrated psychosocial risk governance model for the Southern African mining sector that combines (1) Ubuntu as a culturally grounded philosophy of collective care and accountability; (2) systems thinking, treating psychosocial harm as a product of organisational design rather than individual weakness; and (3) technology-enabled early detection and escalation. Drawing on case insights from platinum, coal, gold and diamond operations across Zimbabwe, South Africa, and Botswana, the paper demonstrates how culturally-aligned wellbeing programs and data-informed controls can reduce absenteeism, improve safety climate, and build sustainable workforce resilience. The work also situates Southern Africa in a global context by comparing emerging approaches in Australia, Canada, and Chile, where psychosocial harm is now explicitly regulated.

The argument is simple and urgent: psychosocial risk management must move from reactive wellness initiatives to a strategic, auditable, leadership-owned control framework. A mine that protects the mind secures its legacy.

Keywords: Psychosocial Risks, Ubuntu, Systems Thinking, ISO 45003, Mining, Southern Africa, Mental Health, Human Factors, ESG, Workforce Resilience

INTRODUCTION

The Southern African mining sector remains a socio-economic engine for the region, providing formal employment, foreign currency, and community infrastructure. At the same time, the sector carries an inherited burden of complex human impacts: migrant labour systems, historical inequality, displacement of land-based livelihoods, high-risk production targets, and deeply gendered, male-dominated work cultures.

Over the last two decades, physical injury rates have improved significantly in many high-exposure operations. Mechanisation, remote operation, behavioural safety programs, and leading practice adoption systems such as MOSH (Mining Industry Occupational Safety and Health) have driven down lost-time injury frequency rates across major South African sites (South African Chamber of Mines, 2017). Despite this progress, an equally material threat has accelerated: psychosocial harm.

Psychosocial risks include chronic fatigue from extended rosters; traumatic exposure to fatalities and near misses; bullying and harassment; perceived unfairness in work allocation; job insecurity under contracting models; isolation in remote camps and hostels; and financial anxiety linked to debt and remittances. These risks manifest in burnout, substance dependency, presenteeism, self-harm ideation, escalation of interpersonal conflict, and ultimately, instability in production crews. Absenteeism linked to mental ill health in mining workforces in Southern Africa has been reported to have increased by more than 30% in recent years, while worker surveys across platinum and coal operations identify fatigue, stress, and job security as leading perceived threats to personal wellbeing.

Yet, psychosocial risk is still often managed informally: an employee assistance programme (EAP) helpline here, a poster campaign there, a supervisor told to 'check in' on the crew. It is rarely embedded in critical control verification, risk registers, or executive assurance reporting. This is the frontier. This paper argues that psychosocial risk must be governed with the same discipline as physical hazards. It must be designed into work, resourced at leadership level, benchmarked, assured, and disclosed as part of environmental, social and governance (ESG) performance and social licence to operate.

To that end, this paper advances an integrated framework drawing on three pillars:

- Ubuntu, as the cultural logic of collective accountability: 'I am because we are.'
- Systems thinking, treating psychosocial harm as an emergent property of work design, production pressure, and culture.
- Digital intelligence, enabling ethical, near-real-time visibility of emerging psychosocial hotspots.

The paper also outlines how these principles can be mainstreamed into governance using ISO 45003:2021 Psychological Health and Safety at Work, ESG reporting expectations, and Board-level oversight.

Literature Review and Theoretical Framework

Psychosocial risk is not new in occupational health science, but its explicit treatment as a controllable, leading indicator of operational performance in mining is relatively recent. Three theoretical lenses are most useful for the mining context:

Job Demand–Control–Support Model

Karasek's Job Demand–Control–Support model proposes that psychological strain emerges when workers experience high demand (workload, time pressure, exposure to trauma) combined with low control (little autonomy, rigid supervisory command) and low social support (weak team cohesion, unsympathetic leadership) (Karasek, 1979). In deep-level or high-intensity operations, workers often face extreme production pressure with minimal say in how work is sequenced or paced. That structural imbalance is a psychosocial hazard.

Effort–Reward Imbalance Theory

Siegrist's Effort–Reward Imbalance theory argues that sustained high effort that is not matched by fair reward (material, social, or reputational) produces chronic stress with physical and psychological consequences (Siegrist, 1996). This is acutely relevant in Southern Africa, where some mineworkers carry multigenerational family expectations and community pressure while dealing with insecure contract arrangements.

Socio-Technical Systems Thinking

Mining operations are complex socio-technical systems. Accidents and breakdowns are rarely caused by one worker making one mistake, but rather by multiple latent conditions aligning (Reason, 1997).

Similarly, psychosocial harm is rarely the consequence of individual 'weakness'. It is produced by roster design, camp living conditions, labour models, supervisory style, production targets, and community tensions. A systems view therefore reframes psychological harm not as a wellness deficit but as an organisational design failure.

Ubuntu as Operational Philosophy

Ubuntu, often expressed as 'I am because we are,' is more than an ethical slogan. It encodes a duty of care that is collective, relational, and identity-forming. In the mining context, Ubuntu suggests that psychological safety is not an individual entitlement but a shared obligation among workers, leaders, unions, and community structures. This stands in contrast to many Western-origin safety models that privilege individual resilience training. Embedding Ubuntu operationally therefore means building peer-support norms, leadership empathy, and shared recovery mechanisms into the way work is organised, supervised, and assured.

Taken together, these lenses position psychosocial harm as foreseeable, measurable and governable—not accidental, unpredictable, or private. They provide the theoretical foundation for the framework advanced in this paper (ISO, 2021; International Council on Mining and Metals [ICMM], 2023; Safe Work Australia, 2023).

Methodology

This paper synthesises:

- Internal program evaluations and workforce sentiment tracking conducted between 2018 and 2024 in large-scale platinum and base metal operations in Zimbabwe and South Africa (ABE Risk Solutions, 2019; Zimplats, 2019).
- Reported wellbeing and safety climate metrics from a diamond mining operation in Botswana where psychosocial factors were integrated into the site-wide operational risk register and governance routines (Debswana, 2022).
- Publicly available program summaries and wellbeing disclosures from multinational mining houses, including Anglo American's WeCare initiative, which has combined on-site counselling, telehealth, and post-incident support mechanisms across Southern Africa.
- Global guidance material and regulatory trends including ISO 45003:2021, ICMM's Mental Health and Wellbeing Framework for Mining (ICMM, 2023), and psychosocial risk codes emerging in jurisdictions such as Australia (Safe Work Australia, 2023).

The analysis is interpretive and translational. It does not claim to be a statistically representative workforce study. Instead, it aims to extract implementation lessons that can inform governance models for psychosocial risk in high-risk, high-pressure mining environments.

Ubuntu Philosophy: Cultural Foundations for Psychosocial Safety

Ubuntu frames identity as relational. The wellbeing of the individual is inseparable from the wellbeing of the team, the family, and the community. In mining, this counters the myth of the isolated, self-reliant worker and replaces it with an ethic of mutual obligation.

In practice, embedding Ubuntu into psychosocial safety has taken several forms:

- Peer-support structures and buddy systems, where workers are explicitly encouraged and trained to check on one another's fatigue levels, stress load, and emotional state—particularly after high-energy production cycles or serious incidents.
- Inclusion of respected community figures (social workers, elders, chaplains, union health reps) in workforce welfare committees, normalising help-seeking behaviour and reducing stigma around mental distress.
- Leadership accountability for empathy. Instead of treating empathy as 'soft', some operations now include measures of psychological safety, fairness of task allocation, and quality of supervisor check-ins in frontline leader performance reviews.

Case experience from Zimplats shows that a culturally-resonant program using storytelling and shared

responsibility language ('Don't Drop the Clay Pot') reduced incident-related absenteeism by approximately 25% and improved self-reported cohesion in production crews (ABE Risk Solutions, 2019; Zimplats, 2019). The metaphor of the clay pot – once dropped, it cannot simply be reassembled – communicated the idea that safeguarding one another's wellbeing is both urgent and irreversible.

Systems Thinking: Psychosocial Risk as a Complex Adaptive Challenge

Mining workforces exist inside complex adaptive systems where production pressure, supervision quality, living conditions, and personal financial stress interact. Psychosocial harm is therefore multicausal. Fatigue may be linked to mandatory overtime to meet quarterly targets; isolation may be linked to rotational rosters that pull parents away from children for 3–6 week blocks; anxiety may be linked to rumours of contractor renewal or retrenchments.

In this sense, psychosocial harm is a latent condition in the same way that poor maintenance is a latent condition. James Reason's Swiss Cheese Model (Reason, 1997) is directly transferable: catastrophic events emerge when latent weaknesses align without barriers. If we accept that cognitive overload, anger, exhaustion and moral injury can erode hazard awareness and decision-making discipline, then psychosocial risk must be managed as an antecedent control for physical safety.

This is consistent with prior research on human error in platinum operations, which found that roughly 70% of recorded operational deviations were linked to cognitive overload, distraction, or stress-related lapses rather than technical incompetence (Chigwada, 2016). Psychosocial stability, therefore, is not only a wellbeing outcome. It is a production control.

The Five-Pillar Framework for Psychosocial Risk Management

To operationalise psychosocial governance, this paper proposes a five-pillar framework that integrates cultural intelligence (Ubuntu), systems thinking, and formal Workplace Health & Safety (WHS)/ESG governance expectations. This framework is designed to sit alongside existing ISO 45001 safety management systems and align directly with ISO 45003:2021.

Pillar	Description / Application in Mining Operations
1. Leadership & Culture	Embed psychologically safe leadership behaviours. Measure supervisor empathy, listening, fairness, and follow-through as part of performance assessment. Treat psychological safety as a critical control, not a wellness gesture.
2. Work Design & Flexibility	Redesign rosters, task rotation, break structures, and accommodation policies to reduce chronic fatigue, role overload, and perceived unfairness. Link roster design to cognitive performance and error risk.
3. Worker Participation (Ubuntu in Action)	Co-create controls with workers, unions, and community representatives. Use storytelling, dialogue, and lived-experience panels to surface psychosocial hazards early and remove stigma.
4. Digital Intelligence & Early Detection	Use ethical, privacy-conscious data sources (absenteeism spikes, near-miss trends, overtime patterns, EAP access, anonymous surveys) to identify hotspots. Deploy mobile and chatbot-based confidential reporting and triage.
5. Governance & Assurance	Integrate psychosocial KPIs into WHS dashboards, critical control verifications, Board risk reporting, and ESG disclosure. Treat psychosocial risk as auditable, with accountable owners.

Technology-Enabled Monitoring and Analytics

Historically, psychosocial harm has been difficult to quantify because it sits in the space between ‘feelings’ and ‘performance’. Emerging approaches are closing that gap.

Leading practices now include:

- Wearables and fatigue monitoring: Biometric indicators (alertness, micro-sleep events, heart-rate variability) are being trialled to detect high fatigue exposure in haul truck and drill rig operators.
- Integrated dashboards: Some operators now fuse absenteeism data, overtime exposure, crew conflict reports, and safety climate survey scores to flag at-risk departments in near real time.
- Anonymous digital counselling access: AI-enabled chat interfaces and telehealth escalation pathways (piloted in Southern African and West African gold operations) are widening access to psychosocial support while bypassing stigma.

These tools are promising, but they also raise ethical and industrial-relations questions. Data governance must be grounded in informed consent, confidentiality, and non-retaliation. Psychosocial surveillance cannot become a productivity weapon. Without trust, workers will not disclose early signals, and leading indicators will be lost.

Figure 1 (conceptual placeholder below) illustrates how a proactive psychosocial dashboard can operate as an early-warning system for both production leadership and health, safety and environment (HSE) governance.

Figure 1. Psychosocial Risk Early Warning Dashboard (conceptual placeholder):

Inputs: overtime hours ↑, unplanned absenteeism ↑, counselling requests ↑, peer conflict reports ↑ →

Alert to: Superintendent / HSE Lead / HRBP →

Response: roster review, crew dialogue, supervisor coaching, escalation to wellbeing clinician.

Socio-Economic Context: Mining, Inequality, and Mental Health

Psychosocial strain in the Southern African mining workforce does not emerge in a vacuum. It sits inside a regional socio-economic story shaped by legacy and present-day realities: apartheid systems of migrant labour, persistent wage disparities, informal settlements and substandard housing around mine leases, debt cycles, and the emotional load of being a primary economic provider for extended family structures.

The Marikana tragedy in 2012 remains a stark demonstration that unresolved psychosocial drivers—anger, financial distress, hostility toward management—can escalate into instability with irreversible human and reputational cost. Beyond immediate trauma, these crises damage long-term trust between companies, workers, unions, and communities.

For this reason, psychosocial risk is inseparable from ESG. Leading mining companies in Southern Africa now report mental health and wellbeing within the ‘social’ dimension of ESG, framing psychological safety and dignity at work as core to their social licence to operate and stakeholder legitimacy (Debswana, 2022; ICMM, 2023).

Empirical Insights from Southern Africa

Three implementation stories from the region illustrate how psychosocial risk can be operationalised:

Zimplats – ‘Don’t Drop the Clay Pot’

This cultural safety and accountability program used storytelling rooted in shared responsibility. Workers were taught that wellbeing is a fragile collective asset, not a private struggle. Outcomes included a ~25% reduction in incident-related absenteeism and measurable improvement in perceived team cohesion (ABE Risk Solutions, 2019; Zimplats, 2019).

Anglo American – WeCare Program (South Africa)

WeCare combined on-site counselling, trauma support following serious incidents, and telehealth access for workers and their families. By 2023 it had reached more than 10,000 individuals and began to

normalise mental health check-ins as an accepted part of safety culture. Anglo also positioned psychosocial wellbeing as essential to production stability and long-term employability (Anglo American, 2023).

Debswana (Botswana)

Debswana integrated psychosocial indicators (fatigue risk, morale, conflict exposure) directly into its Operational Risk Register and HSE dashboards. Over approximately two years, safety climate scores reportedly improved by around 20%, and supervisors began to escalate psychosocial hotspots in the same forums where they escalated physical hazards and equipment defects (Debswana, 2022).

These examples demonstrate feasibility: psychosocial risk can be structured, measured, and governed – not just campaigned about.

Comparative Global Perspectives

While this paper is rooted in Southern Africa, similar psychosocial dynamics exist globally.

Australia: Remote and FIFO (fly-in fly-out) operations face isolation, extreme roster compression (e.g., 2/1, 3/1), fatigue, and mental health stigma among predominantly male crews. In response, Australian regulators have moved toward explicitly regulating psychosocial hazards as workplace health and safety risks. The national Model Code of Practice for Managing Psychosocial Hazards (Safe Work Australia, 2023) treats psychosocial risk as enforceable, not optional, and requires employers to apply controls, not just awareness campaigns.

Canada: Arctic and sub-Arctic mining communities report similar isolation stressors and community disruption effects, especially where workers are flown in from distant provinces. Companies have begun embedding mental health and cultural support services into camp design and collective bargaining arrangements.

Chile: High-altitude copper operations report significant fatigue and cognitive strain because of hypoxia, long shifts, and remote camp life. Psychosocial regulation has increasingly been framed as part of occupational hygiene rather than HR policy, aligning mental health with exposure control thinking.

Global convergence is becoming visible. ISO 45003:2021 is being embedded as a companion to ISO 45001 in multiple jurisdictions. The ICMM's 2023 Mental Health and Wellbeing Framework has moved mental health from 'nice to have' to Board accountability. The opportunity for Southern Africa is to contribute Ubuntu-driven, relational models of care to global practice, rather than importing only Western individual-resilience models.

This is reverse innovation: Southern Africa is not 'catching up'; it is offering leadership.

DISCUSSION

The evidence and practice insights in this paper point to four core conclusions.

First, psychosocial harm is structurally produced. It is not a matter of individual weakness or personal coping deficits. It emerges from roster design, production intensity, job precarity, and unresolved socio-economic pressures. This means it can be designed out, just like fall-from-height risk or energy isolation failures.

Second, psychosocial stability is a production control. When fatigue, anger, despair, or moral injury rise, hazard awareness falls, conflict escalates, and attention to critical controls erodes. Treating psychosocial risk as a first-order control is both morally responsible and operationally rational.

Third, culture matters. Ubuntu is not sentimental branding; it is an operational logic for collective

resilience, peer accountability, and social healing inside high-pressure production systems. Where workers co-own wellbeing, uptake of support mechanisms is dramatically higher.

Fourth, assurance must evolve. Boards and executive teams are comfortable with Total Recordable Injury Frequency Rate (TRIFR), exposure hours, and critical control verification. Psychosocial governance requires similarly visible metrics and escalation pathways. This is starting to happen in Botswana, South Africa, and Australia. It should become standard.

The implication is that psychosocial risk governance is not an HR program. It is a line accountability and executive assurance function. It belongs in the enterprise risk register, the sustainability report, and the Board pack.

Recommendations for the Southern African Mining Industry

Based on the analysis above, seven immediate recommendations are proposed:

1. Adopt ISO 45003:2021 alongside ISO 45001 to create dual systems for physical and psychological safety.
2. Mandate psychosocial risk reporting in ESG disclosures and sustainability reporting, including Board visibility.
3. Train supervisors and superintendents as 'psychological safety leaders,' with accountability for fairness, listening, and early escalation.
4. Embed psychosocial indicators into critical control verifications and site risk registers—treating fatigue, job insecurity, and harassment as operational risks.
5. Deploy digital wellbeing analytics (with explicit privacy and consent) to proactively identify hotspots, not to punish individuals but to fix work design.
6. Leverage Ubuntu-led co-design between management, unions, and communities to normalise mental health dialogue and collective recovery.
7. Establish regional benchmarking and knowledge-sharing forums across the Southern African Development Community on psychosocial risk performance, rather than competing site by site in isolation.

Future Research and Industry Collaboration

Three areas for further collaborative research and industry practice emerge from this paper:

- Predictive analytics for psychosocial precursors: How can we responsibly build leading indicators that warn leaders of cumulative fatigue, psychosocial load, and crew instability—before an incident, walkout, or escalation?
- Economic case modelling: What is the quantified business case linking psychosocial stability to production continuity, talent retention, legal risk, and ESG investment attractiveness? Demonstrating this in CFO language will accelerate adoption.
- Cross-cultural transferability: How can Ubuntu-informed relational safety models be responsibly adapted to other mining regions such as Australia's FIFO operations or Chile's high-altitude workforce without cultural appropriation or dilution? Conversely, what elements of Australian regulatory enforcement and Canadian remote-camp mental health practice can strengthen Southern African operations?

Future research should explicitly bridge psychosocial risk governance, ESG performance, and social licence to operate. The psychosocial conversation must move from compassion to strategy.

CONCLUSION

Psychosocial risk management is the next defining capability of mining leadership in Southern Africa. It is no longer credible to separate safety from mental health, or performance from dignity. The evidence from Zimplats, Anglo American, and Debswana shows that culturally aligned, data-enabled, leadership-owned psychosocial governance is both feasible and impactful.

The integration of Ubuntu, systems thinking, and digital intelligence creates a pathway out of reactive, compliance-driven wellness campaigns and into a strategic, preventative model of organisational resilience. This approach positions psychosocial wellbeing not as a cost centre, but as a core enabler of safe production, social licence, and ESG credibility.

In simple terms: a mine that protects the mind secures its legacy.

Appendix A. Example Psychosocial Performance Indicators

Table A1 illustrates a sample set of lead and lag indicators that can be included in site-level dashboards, critical control verifications, and Board WHS reporting. These are indicative and should be co-designed with the workforce, unions, and community representatives to ensure trust and legitimacy.

Indicator	Type (Lead / Lag)	Why it matters
Unplanned absenteeism (by crew / function)	Lead	Early signal of fatigue, burnout, or conflict before formal incident reports.
Overtime hours above rostered baseline	Lead	Flags production pressure and cumulative fatigue risk exposure.
Reported harassment / bullying cases closed with action	Lag (with governance overlay)	Measures psychological safety and fairness of treatment under supervision.
Voluntary counselling / peer support uptake	Lead	Tests trust in systems. Uptake going up can indicate cultural safety, not just distress.
Safety climate / cohesion score (crew self-rating)	Lead	Strong predictor of incident proneness, conflict, and production instability.

REFERENCES

- ABE Risk Solutions. (2019). Don't Drop the Clay Pot: Psychosocial Safety and Collective Accountability in High-Risk Operations. Internal Evaluation Report.
- Anglo American. (2023). WeCare Annual Report: Mental Health, Resilience, and Family Wellbeing in Mining Workforces.
- Chigwada, A.K.B. (2016). The Role of Human Error in Organisational Performance: A Case of the Zimbabwe Platinum Mine. The Da Vinci Institute.
- Debswana. (2022). Sustainability and Wellbeing Report.
- International Council on Mining and Metals. (2023). Mental Health and Wellbeing in Mining: A Framework for Action.
- International Labour Organization. (2016). Workplace Stress: A Collective Challenge.
- ISO. (2021). ISO 45003: Occupational Health and Safety Management — Psychological Health and Safety at Work — Guidelines for Managing Psychosocial Risks.

- Karasek, R. (1979). Job Demands, Job Decision Latitude, and Mental Strain: Implications for Job Redesign. *Administrative Science Quarterly*, 24(2), 285–308.
- Nielsen, K., & Noblet, A. (2020). Organizational Interventions for Health and Well-being in High-Risk Industries. *Safety Science*, 130, 104–118.
- Reason, J. (1997). *Managing the Risks of Organizational Accidents*. Ashgate.
- Safe Work Australia. (2023). *Managing Psychosocial Hazards at Work: Model Code of Practice*.
- Siegrist, J. (1996). Adverse Health Effects of High-Effort/Low-Reward Conditions. *Journal of Occupational Health Psychology*, 1(1), 27–41.
- South African Chamber of Mines. (2017). *Mining Industry Occupational Safety and Health (MOSH) Leading Practice Adoption System*.
- World Health Organization. (2024). *Global Strategy on Workers' Health 2025–2030: Advancing Psychosocial Risk Prevention in High-Risk Sectors*.
- Zimplats. (2019). *Don't Drop the Clay Pot Program Evaluation*. Internal Report.



Abednego Kholwani Bayne Chigwada

Executive Director
Abe Risk Solutions

Dr Abednego KB Chigwada is an accomplished Environmental, Health, Safety, and Risk Executive with over 25 years' experience spanning mining, manufacturing, government, and essential services across Southern Africa and Australia. He holds a PhD in the Management of Technology and Innovation, with research focused on human factors and operational performance in high-risk environments. Dr Chigwada has led transformative WHSE programs in mining giants such as Zimplats and Rio Tinto Zimbabwe, embedding critical risk management frameworks and psychological safety practices. As a Fellow of the Australasian Institute of Mining and Metallurgy and a Certified Risk Management Professional, he is passionate about integrating systems thinking and indigenous philosophies like Ubuntu to advance sustainable safety cultures. Dr Chigwada is currently a senior advisor and trainer, supporting organisations to build resilient, high-performing workforces grounded in wellbeing and shared purpose.

Understanding battery chemistries, safety considerations, and suppression challenges in the mining industry

A.K. Townsend¹, J. van Rensburg², H. Olivier²

¹North West University, South Africa

²Sibanye-Stillwater, South Africa

Social media often generalises lithium-ion batteries (LIBs) as a single, inherently dangerous category, not distinguishing between the various chemistries and their safety indices. There are several widely used and emerging lithium-ion cell chemistries; each with a preferred application, based on its individual characteristics and different thermal reactivity. As the application of batteries in the mining industry broadens, it is imperative to understand how these chemistries differ, specifically in terms of the hazard associated with each. With the growing public concern vs the potential benefits each lithium-ion chemistry offers, it was deemed necessary to conduct in-depth research into all major chemistries. This included a focused evaluation of a preferred type, aimed at understanding the safety characteristics and how they compare to the batteries currently used in mining operations. To support this research, a full-scale test was conducted at the CSIR Kloppersbos Explosion Research Facility. During the tests both lead-acid and lithium-ion phosphate batteries – along with their locomotive systems – were subjected to extreme heat conditions via exposure to open flames. The objective was to rigorously assess the behaviour of the batteries (and their control systems) under thermal runaway scenarios. It was also necessary to evaluate the effectiveness of any existing mitigation systems as well as potentially suitable chemical fire suppression products. It was found that with correct construction and chemistry selection the lithium-ion phosphate batteries performed significantly better than existing lead acid systems – showing less reactivity, exhibiting self-extinguishing behaviour and a safer environment for emergency response control.

Keywords: Lithium-ion, thermal runaway, crystal lattice structure, battery-electric locomotive, underground mining, lithium-ion batteries

INTRODUCTION

The mining industry, especially in underground operations, is adopting increasing numbers of electrically-powered, battery-operated, and hybrid machines. This change is largely driven by the global shift toward reducing greenhouse gas emission through decarbonisation, improving safety for personnel and increasing efficiency (Tabelin *et al.*, 2021; Ye *et al.*, 2022). At the forefront of these improvements are lithium-ion batteries (LIBs) (Yu and Manthiram, 2021). Furthermore, these batteries are seen as the replacement for lead acid batteries in a wide variety of applications, increasing their prevalence. With higher numbers of LIBs in use, potentially significant safety risks associated with thermal runaway may increase as well (Khade, 2021).

LIBs are under increasing scrutiny due to their thermal instability. When subjected to abusive conditions they may enter thermal runaway, leading to rapid temperature escalation, heat and fire propagation, the release of toxic and flammable gases, asphyxiation and explosion risks. These risks are significantly increased with increase in size, especially in an enclosed space with limited ventilation (Jhu *et al.*, 2011, 2012; Koronaki, Prentza and Papaefthimiou, 2017; Larsson *et al.*, 2017; Lei *et al.*, 2017; Feng *et al.*, 2018; Porzucek, Loj and d'Obyrn, 2022; Wang and Huang, 2023).

There are several widely used and emerging lithium-ion cell chemistries. The former referring to lithium-cobalt-oxide (LCO), lithium-iron-phosphate (LFP), lithium-titanate (LTO), lithium-nickel-cobalt-manganese-oxide (NCM), lithium-nickel-cobalt-aluminium-oxide (NCA) and lithium polymer (LiPo) (Wang *et al.*, 2017; Chen *et al.*, 2021; Robinson *et al.*, 2021; Shahid and Agelin-Chaab, 2022; Mei *et al.*, 2023; Talele *et al.*, 2023). These different types of LIB chemistries behave differently and have unique properties in relation to capacity, energy density, but most importantly – safety.

As mines adjust their battery use towards better performance it is imperative to understand how these chemistries differ (Lamb *et al.*, 2021) and, in the case of an emergency, if different hazard controls need to be implemented to suppress a LIB fire (Feng *et al.*, 2020). LIB fires differ from typical combustion events (Ghiji *et al.*, 2020) as they are self-sustaining (Mao, Chen and Chen, 2024; Huhn *et al.*, 2025) once thermal runaway occurs. This makes suppression more complex and emphasises the importance of chemistry-specific risk assessments (Hsieh *et al.*, 2021).

This paper presents the findings from tests conducted to assess the current large scale LIB selection compared to existing LA systems, along with a detailed comparison of major lithium-ion chemistries, their relative risks, and the implications for equipment selection, construction, emergency response, and safety standard development in the mining industry.

Background

Thermal runaway is a phenomenon seen in various systems, not just batteries, and can result in severe or even fatal outcomes (Wang *et al.*, 2017; Shahid and Agelin-Chaab, 2022). Although the hazard of thermal runaway is acknowledged, what remains less widely recognised is the range of LIB chemistries and their respective differences in safety and suppression requirements (Lamb *et al.*, 2021). Given the importance of employee and emergency response team safety, especially underground, these specific characteristics require thorough scrutiny (Ghiji *et al.*, 2020).

Lithium-ion chemistries

As mentioned, there are various LIB chemistries with various characteristics (Liu *et al.*, 2019; Ghiji *et al.*, 2020; J. Li *et al.*, 2022; Huhn *et al.*, 2025). Each of these chemistries have a preferred application due to the respective energy densities, capacities, and thermal behaviours (Xu *et al.*, 2023).

Due to their high energy density NCM, NCA, LiPo and LCO batteries are fast emerging as a crowd favourite – mainly due to their quick response and fast charge characteristics (Placke *et al.*, 2017). The former allows for quick acceleration and fast alterations in the load, whilst the latter allows for faster charging of the cells and more efficient regenerative braking (as compared to the other chemistries) (Pasupuleti, Tummuru and Misra, 2023).

However, this increase in energy density is accompanied by a decrease in safety, specifically related to thermal runaway (Wang *et al.*, 2021), which has become synonymous with LIBs (Feng *et al.*, 2020). It is important to note that all these batteries are LIBs, but not all LIBs are the same, especially when it comes to their thermal characteristics.

Thermal runaway

Each chemistry is distinguished by the difference in the electrode composition, the crystal lattice structure (CLS) and their intramolecular bonds. LCO, NMC and NCA have a layered CLSs; LMO and LTO are spinel; LFP is olivine; and LiPo (an LIB with electrodes of either NCM or LCO and polymer electrolyte) is generally also layered (S. Li *et al.*, 2022).

Additionally, LCO, LMO, NCM, NCA and LiPo all have a pure metal oxide cathode which oxidise during charge. LFP has a metal phosphate cathode, which has a more solid intramolecular oxide bond and therefore does not readily release oxygen, thus resisting thermal runaway. In LTO the anode is a titanium oxide, and the cathode is generally NCM, LFP or LTO – making these chemistries very stable but with low energy density (Manthiram, 2020;) (Wei *et al.*, 2023).

During charge lithium-ions move from the cathode to anode, causing the cathode to oxidise, weakening the intramolecular bonds and in certain cases (higher temperatures) causes the release of oxygen gas – destabilising the cathode. This oxidation can occur at any point when the battery is operated under strain or high temperatures – leading to thermal runaway (Dose *et al.*, 2022; Zhuang and Bazant, 2022; Zhang *et al.*, 2023; Peiris *et al.*, 2024; Prempluem *et al.*, 2024; Dai and Panahi, 2025).

These variations are what determine the volatility and tendency of the cell to enter a hazardous condition of thermal runaway (Lamb *et al.*, 2021; Nahidi *et al.*, 2023).

Hazard control

Due to the volatility of metal oxide LIBs and the high temperature at which these batteries burn (>500°C, (Liu *et al.*, 2019; Ghiji *et al.*, 2020; J. Li *et al.*, 2022; Huhn *et al.*, 2025)) it is important to understand which type of LIBs should be permitted, how they react under thermal incidents and how to control a possibly very hazardous situation.

As explained, a clear distinction can be made between the safety of phosphate metal LIBs and metal oxide LIBs. The metal oxide LIBs have a greater tendency to enter thermal runaway due to the oxidation during charge and discharge, generating extreme heat and free radicals (Manthiram, 2020; Dose *et al.*, 2022; Zhuang and Bazant, 2022; Zhang *et al.*, 2023; Peiris *et al.*, 2024; Prempluem *et al.*, 2024; Dai and Panahi, 2025). This breakdown also causes a self-propagating exothermic reaction – leading to the creation of a fire tetrahedron (Mao, Chen and Chen, 2024; Huhn *et al.*, 2025) – herein lies the hazard of thermal runaway in LIBs. Metal-oxide LIBs have all four of these components during thermal breakdown leading to thermal runaway which is exceedingly difficult to suppress or extinguish.

LFPs, on the other hand, having a solid oxide bond, do not produce enough of any of these components internally, thus tending to remain stable or self-extinguish in the case of a thermal event. They do produce flammable gases, in the presence of sufficient external heat, which can be ignited externally in the presence of sufficient oxygen (Manthiram, 2020). LFP fires are mainly external and are sustained if the electrolyte breakdown generates enough flammable gases and the external oxygen concentration is sufficient for the flame (Shi, 2023).

This last point is the key aspect in the construction design of larger systems – if they are of such that the level of oxygen to the batteries is limited, then a flame will not be sustained (Ghiji *et al.*, 2020; Huhn *et al.*, 2025).

Experimentation

Due to the uncertainty of these various batteries, it was considered necessary to assess the batteries presently used in the underground environment (LA and LIB) at Sibanye Stillwater. Multiple variations of LIBs are used in general day to day life, however, when kept to a capacity smaller than 150 Wh, the hazard of these batteries, regardless of chemistry, is easily manageable. Due to its thermal stability LFP was chosen for the large-scale systems (>150 Wh); however under strict limitations and requirements with regards to the construction and safety measures installed. For this, the battery-electric underground rail bound locomotives supplied by Trident S.A. (90 kWh system with 120 cells (3.25V, 230Ah)) will be used.

Purpose

The purpose of these tests is to determine the hazard of the batteries at large scale >150 Wh. The midscale LFP modules and full-scale LFP locomotive (all inclusive) were provided by Trident S.A; the LA modules and locomotive obtained from an operational shaft.

These systems will be tested on mid-scale (single module) to assess the initial hazard, thereafter they will be tested at full-scale (multiple modules inside of locomotive enclosure) to assess the full hazard. These tests will place the systems in a worst-case environment similar to one that has occurred previously underground where a transformer burned in excess of 800°C. A mock-up emulating the underground environment with ventilation (1.5m/s) at Kloppersbos Explosion Test Facility was used to conduct these tests under the same harsh underground conditions in which these machines typically operate.

Setup

A heat source was applied to the side of a locomotive, such as shown in Figure 1; this is based on the typical operating environment underground in which these locomotives operate.

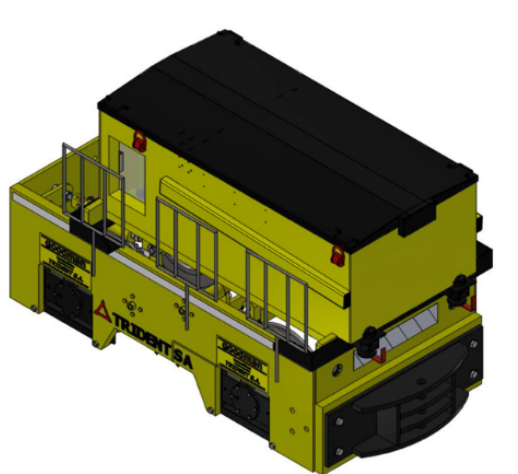


Figure 1. Underground locomotive supplied by Trident S.A.

Small scale (single cell) testing was omitted as these have been conducted extensively by the different suppliers. Each test was conducted on both the LA and LFP systems. For the midscale tests the module was placed in the same position as would be placed inside the locomotive battery enclosure with the same orientation to the flame, as shown in Figure 2(a) and (b).

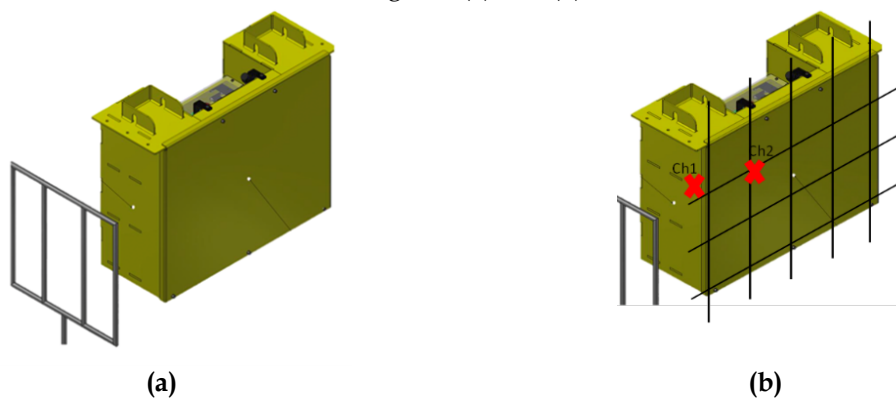


Figure 1. Single module (Trident S.A.) test orientation, with (a)burner and (b)thermocouple location.

For this test there are five thermocouples placed around the module – refer to

Figure 1(b) – two on the module (one inside, one outside) and the remainder placed at 1 m, 2 m and 5 m distances from the module in the direction of the flow of ventilation; the gases will also be monitored for each test.

The midscale tests were performed in two segments – (1) half of the cells to enter thermal breakdown; monitor the flame front and propagation of the flame; apply water as the suppressant; (2) same as test

(1), but apply the F500 encapsulator agent (EA) instead of water, to assess the effectivity thereof. This agent plus water were identified as viable solutions for the emergency response team to control the hazard of all battery fires underground or on surface, hence the requirement for the tests.

For the full-scale test, the burners were placed directly above the locomotive lid to assimilate worst case scenario of flame propagation over the top of the machine. The temperature sensors were placed in similar locations as with the midscale tests – one inside the locomotive, one directly outside in direct contact with the flame and the remainder positioned 2 m, 5 m and 10 m away from the machine. The gases were also sampled for this test to determine the extent of the hazard.

The temperature of the burner administered a consistent 900°C for the duration of all the tests. For the full-scale tests the flame was applied until the accumulative flame front started to decrease, was allowed to self-extinguish, whereafter the suppressant was applied.

Results

For the various tests shown in Figure 3, Figure 5, Figure 7, Figure 9 and Figure 11 – *Ch1* refers to the thermocouple in direct contact with the propane burner flame, *Ch2* is above the venting port of the cell/module, *Ch3*, *Ch4* and *Ch5* are the thermocouples placed at various distances from the test, as explained above.

Midscale test 1: LFP thermal breakdown with water as suppressant.

The sequence of events for the midscale test of the LFP battery is shown in Figure 3.

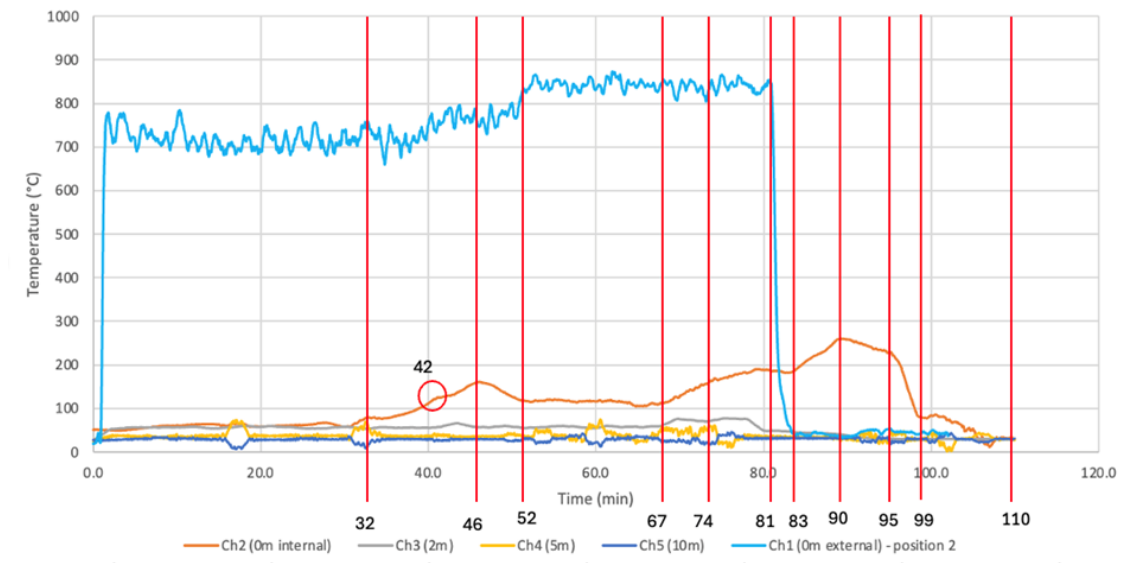


Figure 3. Temperature results of LFP midscale test 1.

The significant events are described using Figure 4(a)-(b) as visual aids.



Figure 4. Visual representation of sequence of events of LFP midscale test.

After ~42 minutes (125°C) the first venting event occurred (Figure 4(a)). After this the module was left to burn until the fire was ignited and sustained. At ~82 minutes the propane was shut off (Figure 4(b)) and a further venting event was seen at ~83 minutes (Figure 4(d)). At ~91 minutes the flame self-extinguished and the system cooled. The temperature visibly dropped without the flame (260°C to 240°C) and the battery was flooded at 95 minutes with water to observe the cooling effects.

The water is seen as a sufficient suppressant to reduce the temperature of the batteries (from 240°C to 80°C) in the four minutes of application, without visible adverse effects. The application of water was removed, and the system left to cool.

Midscale test 2: LFP thermal breakdown with F500 EA as suppressant.

Figure 5 presents the sequence of events for the midscale test of the LFP system.

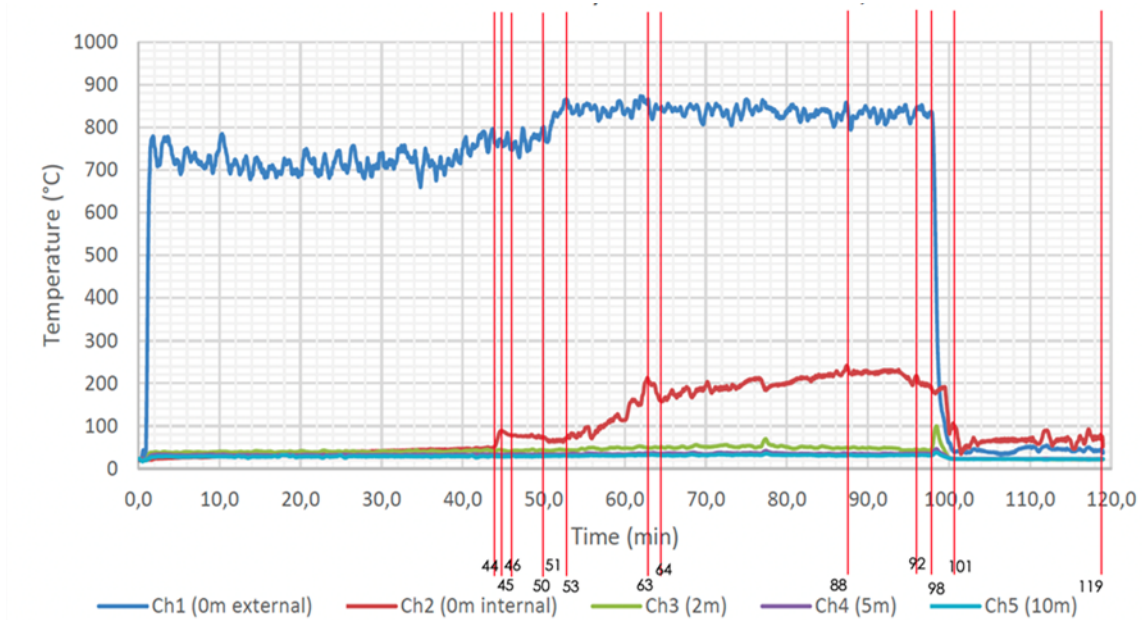


Figure 5. Temperature results of LFP midscale test 2.

Figure 6(a)-(f) is used as a visual representation of the significant events for this midscale test.



Figure 6. Visual representation of sequence of events of LFP midscale test 2.

After ~44 minutes the first venting event occurred (Figure 6(a)), heard as an audible popping of the aluminium vent and the gas ignited (Figure 6(b)). The oxygen concentration in the nearby vicinity was not sufficient for the flame to be sustained, causing a self-extinguishment shown in Figure 6(c), where the gas was released but not ignited. The maximum flame front is seen in Figure 6(d), sustained for 2-3 seconds, at which point the propane supply was switched off and the F500 EA was applied (Figure 6(e)) to assess the performance under these circumstances. The flame was extinguished within 6s, shown in Figure 6(f).

Midscale test 3: LA thermal breakdown with F500 EA as suppressant.

Figure 7 shows the sequence of events for the midscale test of the LA system??

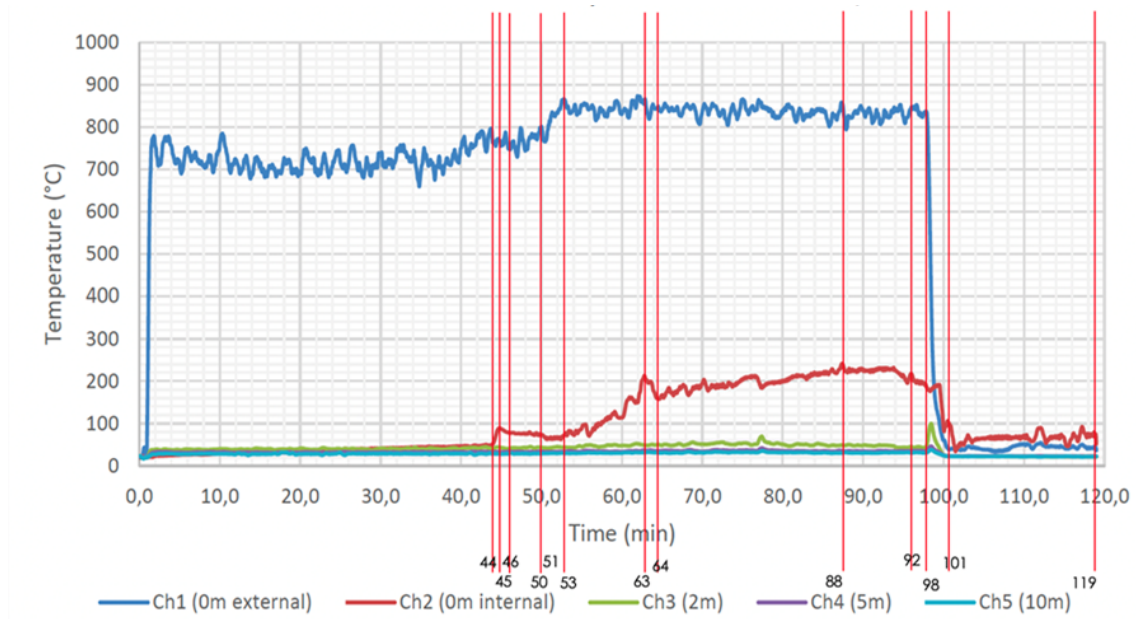


Figure 7. Temperature results of LA midscale test 3.

Figure 8(a)-(d) will be used to visually present the significant events.



(a)



(b)



(c)



(d)

Figure 8. Visual representation of sequence of events of LA midscale test 3.

After ~four minutes the cells start to burn and leak sulfuric acid (Figure 8(a)). No audible popping is heard, or explosion observed. The propane flame was administered until the flame front started to decrease (Figure 8(b)). At the height of the flame, the temperature was 1:1 with the propane burner. At this point, the burner was shut off. The flame was reduced but did not extinguish after which the F500 EA was applied. The results of this test are seen in Figure 8(c) and (d) – showing the extent of the damage to the cell and leakage of the acid.

Full-scale test 1: LFP thermal breakdown with F500 EA as suppressant.

Figure 9 presents the sequence of events of the LFP system's full-scale test.

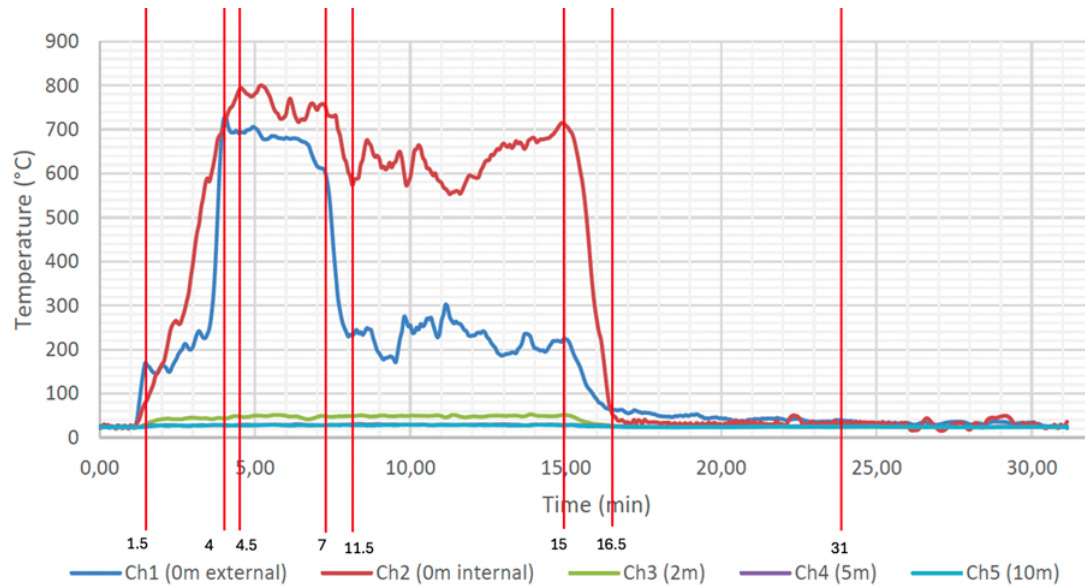


Figure 9. Temperature results of LFP full-scale test 1.

Figure 10(a) –(d) will be used to visualise the significant events of this test.

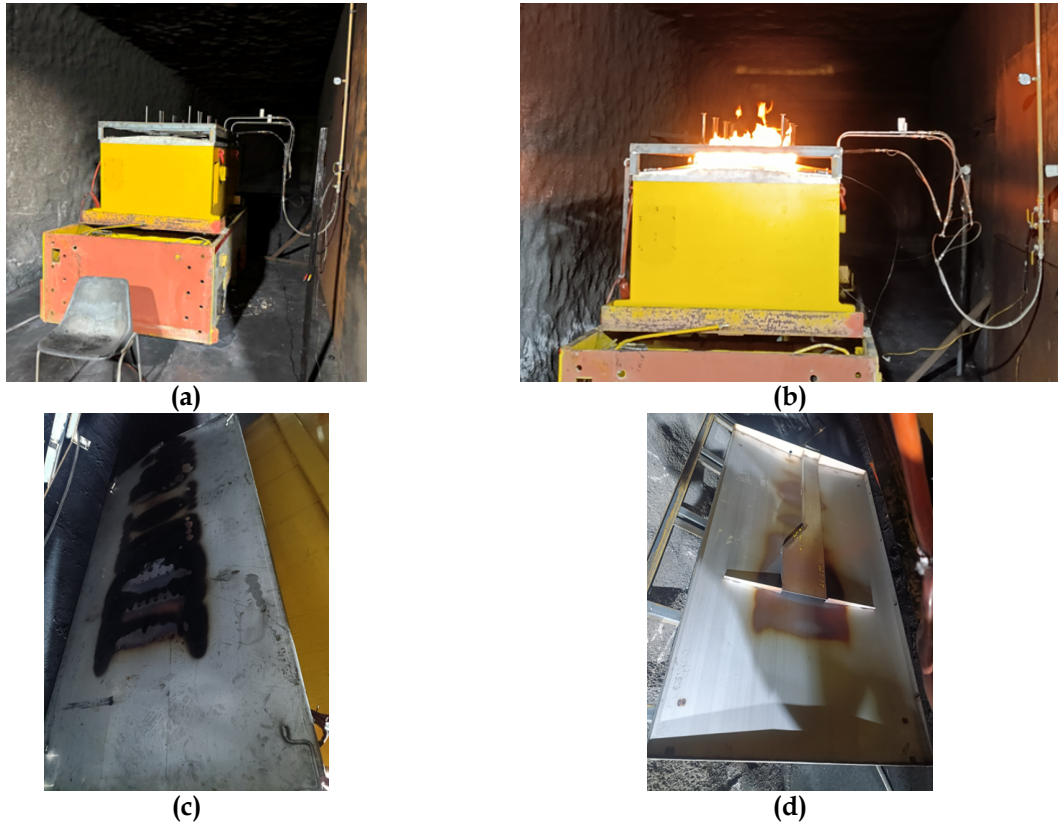


Figure 10. Visual representation of sequence of events of LFP full-scale test.

The flame was administered to the top of the locomotive for four hours (Figure 10(a) and (b)). Using handheld thermal cameras, the temperature on the lid was actively monitored. No significant event was seen. The inner suppressant canisters were set to release suppressant at 105°C – this was not reached. The temperature increased by 15°C during the first hour, by 5°C in the second, by 3.9°C in the third and the fourth hour saw a 2.4°C increase. The BMS PCBs per module indicated an elevated temperature, however they did not reach a temperature that required a shut-down of the system.

Figure 10(c) and (d) show the burn pattern of the burner's application to the lid of the locomotive – thus presenting the extreme heat of the lid.

Full-scale test 2: LA thermal breakdown with F500 EA as suppressant.

Figure 11 is used to describe the sequence of events of the LA full scale test.

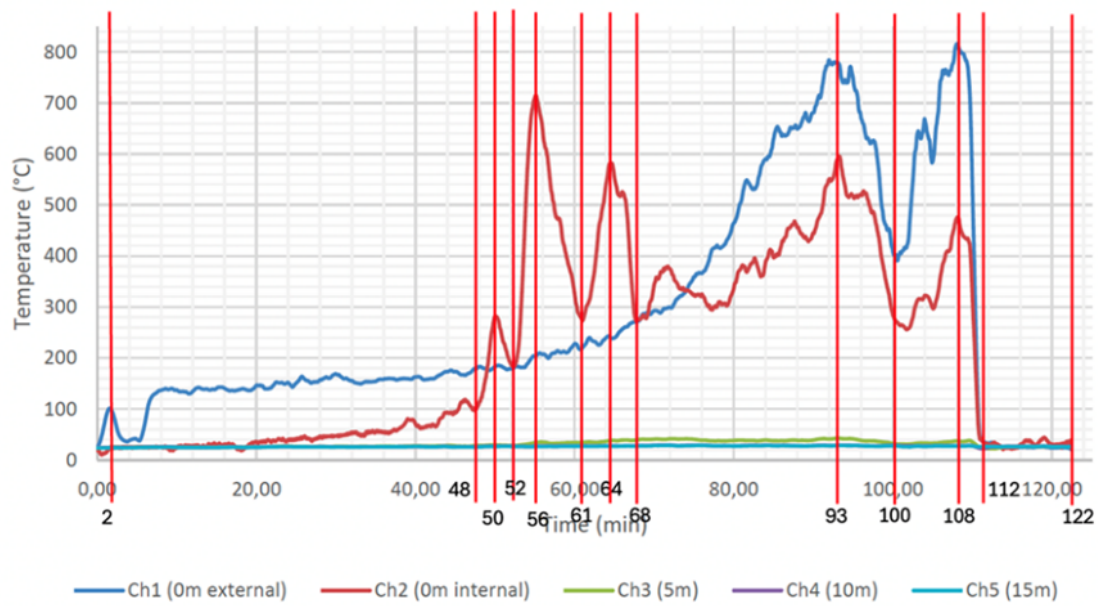


Figure 11. Temperature results of LA full-scale test 2.

Figure 12(a)-(d) will be used to visualise the explanation of the significant events for this test.

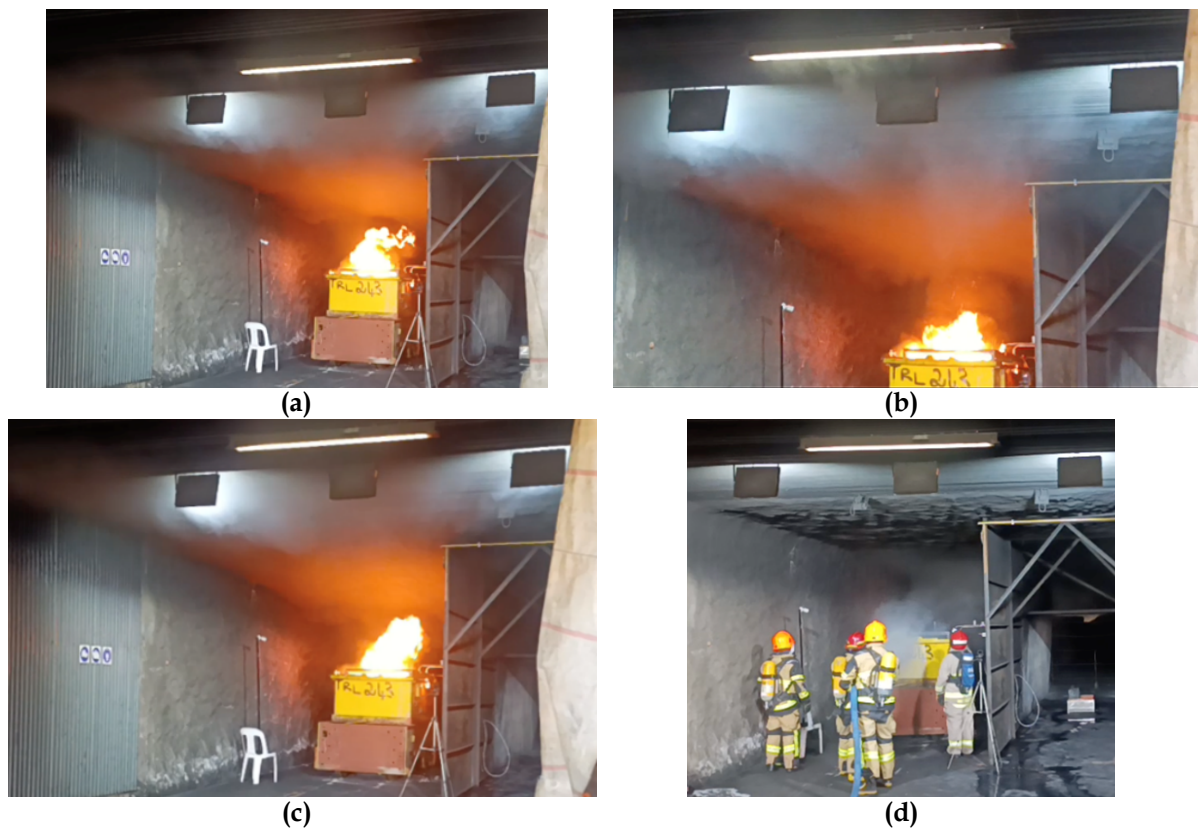


Figure 12. Visual representation of sequence of events of LA full-scale test 2.

The plastic lid of the battery started to melt within 20 minutes after commencement of the test. Within 40 minutes the LA cells were on fire (Figure 12(a)). Audible popping was heard from some cells as they

entered thermal runaway. Propagation occurred between the cells as the fire front increased when more cells started to burn. The gases released by the burning cells increased significantly to a point where the gas pushed back against the ventilation (Figure 12(b) and (c)) leading to the evacuation of the observers from the building to fresh air. When the propane was removed the cells continued to burn, vent, pop; the flames increased when the F500 EA was applied to the flame and doused it within minutes – it can also be seen (Figure 12(d)) that the gases released are significantly reduced.

Discussion of results

The learnings from each of the midscale and full-scale LFP and LA tests are discussed and respective results compared in Table I.

Table I. Comparison of midscale tests.

	Lead acid battery	LFP battery
Size	5 kWh, 836 Ah	22.4 kWh, 690Ah
Time to first reaction	4 minutes	41 minutes
Description of first reaction	Rupture of the cell, leakage of electrolyte, continuous burn of casing and electrolyte	Popping sound of aluminium vent opening. Venting and ignition of gases
Summarised sequence of events	Continued burning until there is no substance to burn.	Additional venting increases flame front momentarily. Self-extinguishes due to low concentration of the flammable gases.
Gases released (possible)	CO ₂ – 0.07 vol%, peak – 0.16 CH ₄ – 0 %SEL, peak – N/A NO – 1.1 ppm, peak – 1.1 NO ₂ – 0 ppm, peak – 0.0 CO – 8 ppm, peak – 12	Low concentrations of burning electrolyte (LiPF ₆ in EC/DMC/EMC/DEC) leads to release of aldehydes, HF, CO, CO ₂ , H ₂ .
	The lower molecular mass gas results returned values in the ng range, safe operating limits are in the µg-mg range. Gas-analyst at the CSIR agreed that these values are within safe regions.	
Flame front	Max 0.5 m Continuous 0.2-0.3 m flame front Flame does not self-extinguish	Max between 0.5- 1 m Continuous ~0.1 m Flame self-extinguishes
Max temperature of cell (at externally applied 800°C)	800°C within 4.5 minutes	240°C within 88 minutes
Reaction with removal of burner	Continuous burning; Flame front decrease to roughly 0.2 m;	Continues to burn for max 10 minutes; Self-extinguishes

The results from the large-scale tests are compared in the Table II.

Table II. Comparison of full-scale tests.

	Lead acid battery	LFP battery
Size	100 kWh, 836 Ah	89.7 kWh, 690 Ah
First reaction time	Batteries started to burn within 40 minutes of 900°C flame application	None
Summary of sequence of events	Rupture of the cell, leakage of electrolyte, continuous burn of casing and electrolyte. Audible pop of LA heard Gas volume noticeably increases, temperature increases consistently.	No venting occurred, lid temperature increases causing deformation of the plate, internal temperature gradient decreases during test.
Gasses measured	CO - 14 ppm O ₂ - 20.8 %vol H ₂ S - 1ppm	None
	Same as mid-scale test	
Volume of gas per kWh battery capacity (litres)	The flame front is significantly larger and continuous at 2 m – due to the concentration of gases as well as the accumulation that can occur as all the cells will be exposed at higher temperatures due to melting of the lid.	None
Flame front from top of box	Close to 2 m continuously	None
Max temperature	700°C within 56 minutes	90°C
Reaction with removal of source	Continuous burning; Flame front decrease; Burning continuously.	No venting or burning occurred

CONCLUSION

The learnings from these tests will be shared with the mining industry to inform their emergency response teams, and generate the protocols and procurement standards for LFP batteries capable of self-extinguishing. Venting ports on cells are imperative to eliminate pressure build up. The design of battery systems and enclosures are of the utmost importance to allow passive air circulation; no air-tight conditions should be allowed (this can lead to oven-like situations).

Thermal runaway for the LFP battery means that the battery releases gas due to the breakdown of the electrolyte (diethyl carbonate $\text{OC}(\text{OCH}_2\text{CH}_3)_2$) – this gas needs an external source to ignite, and ignition increases overall temperature, but up to a point. This temperature decreases as the electrolyte fuel reduces. Rupture of the cells leads to leakage of the electrolyte (non-toxic) – this burns if ignited but does not sustain a fire – design will allow the electrolyte to escape, removing the gaseous fuel created when the electrolyte breaks down, thus preventing further reaction from the specific cell.

If the electrolyte does not leak out it can sustain the fire for longer as it will continue to release diethyl carbonate. The heat from each cell did not propagate to the neighbouring cells, instead the heat from the source combined with the heat from the burning electrolyte caused the thermal event to propagate through the module. This is seen where the flame reaches a maximum flame front during the application of the burner but decreases and reduces continuously leading to self-extinguishment, only reigniting once the concentration of the flammable substance in the gas can sustain a fire.

Segregation of the cells reduces the flammable concentration of the gas thus reducing the possibility of a fire and duration of such fire.

The enclosures of the battery system increase the thermal properties of the system requiring a significant temperature ($>1000^{\circ}\text{C}$, continuously) for an extended period of time (>20 hours) for a possible venting event. This temperature will need to be sustained for the venting to continue. The LA battery has a visibly worse reaction to the application of the flame, generating hazardous fumes and significant heat that create a hazardous environment for all in the vicinity.

Overall, the selection of the correct chemistry of the battery will ensure that the cells have the desirable venting and self-extinguishing qualities. The design of the enclosure of the batteries will further ensure that they behave desirably and with controllable hazard under extreme heat or thermal runaway conditions.

We cannot ban the use of specific LIB chemistries within mining operations as these are very common in everyday devices, such as laptops, cell phones, portable handheld tools, gas detection instruments and cap lamps (these all make use of metal oxide LIBs); we can however restrict the size of these systems and implement safety measures such that the hazard would still be controllable.

REFERENCES

- Dai, Y. and Panahi, A. (2025) "Thermal runaway process in lithium-ion batteries: A review," *Next Energy*, 6, p. 100186. Available at: <https://doi.org/10.1016/j.nxener.2024.100186>.
- Dose, W.M., Li, W., Temprano, I., O'Keefe, C.A., Mehdi, B.L., De Volder, M.F.L. and Grey, C.P. (2022) "Onset Potential for Electrolyte Oxidation and Ni-Rich Cathode Degradation in Lithium-Ion Batteries," *ACS Energy Letters*, 7(10), pp. 3524–3530. Available at: <https://doi.org/10.1021/acsenergylett.2c01722>.
- Feng, X., Ouyang, M., Liu, X., Lu, L., Xia, Y. and He, X. (2018) "Thermal runaway mechanism of lithium ion battery for electric vehicles: A review," *Energy Storage Materials*, 10, pp. 246–267. Available at: <https://doi.org/10.1016/j.ensm.2017.05.013>.
- Feng, X., Ren, D., He, X. and Ouyang, M. (2020) "Mitigating Thermal Runaway of Lithium-Ion Batteries," *Joule*, 4(4), pp. 743–770. Available at: <https://doi.org/10.1016/j.joule.2020.02.010>.
- Ghiji, M., Novozhilov, V., Moinuddin, K., Joseph, P., Burch, I., Suendermann, B. and Gamble, G. (2020) "A Review of Lithium-Ion Battery Fire Suppression," *Energies*, 13(19), p. 5117. Available at: <https://doi.org/10.3390/en13195117>.
- Hsieh, M.K.H., Lai, M.C., Sim, H.S.N., Lim, X., Fok, S.F.D., Joethy, J., Kong, T.Y. and Lim, G.J.S. (2021) "Electric Scooter Battery Detonation: A Case Series And Review Of Literature.," *Annals of burns and fire disasters*, 34(3), pp. 264–276.
- Huhn, E., Braxtan, N., Chen, S.-E., Bombik, A., Zhao, T., Ma, L., Sherman, J. and Roghani, S. (2025) "Lithium-Ion Battery Thermal Runaway Suppression Using Water Spray Cooling," *Energies*, 18(11), p. 2709. Available at: <https://doi.org/10.3390/en18112709>.
- Jhu, C.-Y., Wang, Y.-W., Shu, C.-M., Chang, J.-C. and Wu, H.-C. (2011) "Thermal explosion hazards on 18650 lithium ion batteries with a VSP2 adiabatic calorimeter," *Journal of Hazardous Materials* [Preprint]. Available at: <https://doi.org/10.1016/j.jhazmat.2011.04.097>.
- Jhu, C.-Y., Wang, Y.-W., Wen, C.-Y. and Shu, C.-M. (2012) "Thermal runaway potential of LiCoO_2 and $\text{Li}(\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3})\text{O}_2$ batteries determined with adiabatic calorimetry methodology," *Applied Energy*, 100, pp. 127–131. Available at: <https://doi.org/10.1016/j.apenergy.2012.05.064>.

- Khade, J.K. (2021) "Design and Fabrication of Electric Motorcycle," *International Journal of Advanced Research in Science, Communication and Technology*, pp. 124–131. Available at: <https://doi.org/10.48175/IJAR SCT-1824>.
- Koronaki, I.P., Prentza, L. and Papaefthimiou, V.D. (2017) "Parametric analysis using AMP and MEA as aqueous solvents for CO₂ absorption," *Applied Thermal Engineering*, 110, pp. 126–135. Available at: <https://doi.org/10.1016/j.applthermaleng.2016.07.140>.
- Lamb, J., Torres-Castro, L., Hewson, J.C., Shurtz, R.C. and Preger, Y. (2021) "Investigating the Role of Energy Density in Thermal Runaway of Lithium-Ion Batteries with Accelerating Rate Calorimetry," *Journal of The Electrochemical Society*, 168(6), p. 060516. Available at: <https://doi.org/10.1149/1945-7111/ac0699>.
- Larsson, F., Andersson, P., Blomqvist, P. and Mellander, B.-E. (2017) "Toxic fluoride gas emissions from lithium-ion battery fires," *Scientific Reports*, 7(1), p. 10018. Available at: <https://doi.org/10.1038/s41598-017-09784-z>.
- Lei, B., Zhao, W., Ziebert, C., Uhlmann, N., Rohde, M. and Seifert, H. (2017) "Experimental Analysis of Thermal Runaway in 18650 Cylindrical Li-Ion Cells Using an Accelerating Rate Calorimeter," *Batteries*, 3(2), p. 14. Available at: <https://doi.org/10.3390/batteries3020014>.
- Li, J., Dai, L., Wang, Z., Wang, Hao, Xie, L., Chen, J., Yan, C., Yuan, H., Wang, Hongliang and Chen, C. (2022) "Cellulose nanofiber separator for suppressing shuttle effect and Li dendrite formation in lithium-sulfur batteries," *Journal of Energy Chemistry*, 67, pp. 736–744. Available at: <https://doi.org/10.1016/j.jechem.2021.11.017>.
- Li, S., Qian, G., He, X., Huang, X., Lee, S.-J., Jiang, Z., Yang, Y., Wang, W.-N., Meng, D., Yu, C., Lee, J.-S., Chu, Y.S., Ma, Z.-F., Pianetta, P., Qiu, J., Li, L., Zhao, K. and Liu, Y. (2022) "Thermal-healing of lattice defects for high-energy single-crystalline battery cathodes," *Nature Communications*, 13(1), p. 704. Available at: <https://doi.org/10.1038/s41467-022-28325-5>.
- Liu, Y., Huang, Z., Liao, H., Lyu, C., Zhou, Y., Jiao, Y., Li, H., Hu, C. and Peng, J. (2019) "A Temperature-Suppression Charging Strategy for Supercapacitor Stack With Lifetime Maximization," *IEEE Transactions on Industry Applications*, 55(6), pp. 6173–6183. Available at: <https://doi.org/10.1109/TIA.2019.2930221>.
- Manthiram, A. (2020) "A reflection on lithium-ion battery cathode chemistry," *Nature Communications*, 11(1), p. 1550. Available at: <https://doi.org/10.1038/s41467-020-15355-0>.
- Mao, Y., Chen, Y. and Chen, M. (2024) "Review of Flame Behavior and Its Suppression during Thermal Runaway in Lithium-Ion Batteries," *Batteries*, 10(9), p. 307. Available at: <https://doi.org/10.3390/batteries10090307>.
- Nahidi, S., Jafari Gavzan, I., Saedodin, S. and Salari, M. (2023) "Temperature rise and thermal runaway phenomena in Flooded Lead-Acid Batteries based on experimental studies," *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 45(1), p. 8. Available at: <https://doi.org/10.1007/s40430-022-03923-y>.
- Pasupuleti, S.S., Tummuru, N.R. and Misra, H. (2023) "Power Management of Hybrid Energy Storage System Based Wireless Charging System With Regenerative Braking Capability," *IEEE Transactions on Industry Applications*, 59(3), pp. 3785–3794. Available at: <https://doi.org/10.1109/TIA.2023.3234231>.
- Peiris, M.D.H.C., Liepinya, D., Liu, H. and Smeu, M. (2024) "Electrolyte reactivity, oxygen states, and degradation mechanisms of nickel-rich cathodes," *Cell Reports Physical Science*, 5(6), p. 102039. Available at: <https://doi.org/10.1016/j.xcrp.2024.102039>.
- Placke, T., Kloepsch, R., Dühnen, S. and Winter, M. (2017) "Lithium ion, lithium metal, and alternative rechargeable battery technologies: the odyssey for high energy density," *Journal of Solid State Electrochemistry*, 21(7), pp. 1939–1964. Available at: <https://doi.org/10.1007/s10008-017-3610-7>.

- Porzucek, S., Loj, M. and d'Obyrn, K. (2022) "Surface Microgravity Monitoring of Underground Water Migration: A Case Study in Wieliczka, Poland," *Energies*, 15(11), p. 4012. Available at: <https://doi.org/10.3390/en15114012>.
- Prempluem, S., Sangsanit, T., Santiyuk, K., Homlamai, K., Tejangkura, W., Songthan, R., Anansuksawat, N. and Sawangphruk, M. (2024) "Complex reaction mechanisms of electrolyte decomposition at large-scale Ni-rich Li-ion battery cells including electrode crosstalk effect," *Journal of Power Sources*, 606, p. 234538. Available at: <https://doi.org/10.1016/j.jpowsour.2024.234538>.
- Shahid, S. and Agelin-Chaab, M. (2022) "A review of thermal runaway prevention and mitigation strategies for lithium-ion batteries," *Energy Conversion and Management: X*, 16, p. 100310. Available at: <https://doi.org/10.1016/j.ecmx.2022.100310>.
- Shi, Y. (2023) "Feasibility of BYD blade batteries in electric vehicles," *Highlights in Science, Engineering and Technology*, 32, pp. 193–198. Available at: <https://doi.org/10.54097/hset.v32i.5087>.
- Tabelin, C.B., Dallas, J., Casanova, S., Pelech, T., Bournival, G., Saydam, S. and Canbulat, I. (2021) "Towards a low-carbon society: A review of lithium resource availability, challenges and innovations in mining, extraction and recycling, and future perspectives," *Minerals Engineering*, 163, p. 106743. Available at: <https://doi.org/10.1016/j.mineng.2020.106743>.
- Wang, Q., Huang, P., Ping, P., Du, Y., Li, K. and Sun, J. (2017) "Combustion behavior of lithium iron phosphate battery induced by external heat radiation," *Journal of Loss Prevention in the Process Industries*, 49, pp. 961–969. Available at: <https://doi.org/10.1016/j.jlp.2016.12.002>.
- Wang, Q., Liu, B., Shen, Y., Wu, J., Zhao, Z., Zhong, C. and Hu, W. (2021) "Confronting the Challenges in Lithium Anodes for Lithium Metal Batteries," *Advanced Science*, 8(17). Available at: <https://doi.org/10.1002/advs.202101111>.
- Wang, Y.-W. and Huang, H.-L. (2023) "Thermal explosion energy evaluation on LCO and NCM Li-ion polymer batteries using thermal analysis methodology," *Process Safety and Environmental Protection*, 177, pp. 82–94. Available at: <https://doi.org/10.1016/j.psep.2023.06.093>.
- Wei, Z., Liang, C., Jiang, L., Sun, M., Cheng, S., Wang, L., Chen, S., Fang, Z., Li, Y., Zhang, N., Peng, Q., Meng, X., Zhang, W., Sun, J. and Wang, Q. (2023) "Probing the thermal degradation mechanism of polycrystalline and single-crystal Li(Ni_{0.8}Co_{0.1}Mn_{0.1})O₂ cathodes from the perspective of oxygen vacancy diffusion," *Energy Storage Materials*, 56, pp. 495–505. Available at: <https://doi.org/10.1016/j.ensm.2023.01.029>.
- Xu, J., Cai, X., Cai, S., Shao, Y., Hu, C., Lu, S. and Ding, S. (2023) "<scp>High-Energy</scp> Lithium-Ion Batteries: Recent Progress and a Promising Future in Applications," *ENERGY & ENVIRONMENTAL MATERIALS*, 6(5). Available at: <https://doi.org/10.1002/eem2.12450>.
- Ye, W., Shen, W., Qian, Z. and Zheng, J. (2022) "Robust longitudinal motion control of underground mining electric vehicles based on fuzzy parameter tuning sliding mode controller," *Computers & Electrical Engineering*, 98, p. 107683. Available at: <https://doi.org/10.1016/j.compeleceng.2022.107683>.
- Yu, X. and Manthiram, A. (2021) "Sustainable Battery Materials for Next-Generation Electrical Energy Storage," *Advanced Energy and Sustainability Research*, 2(5). Available at: <https://doi.org/10.1002/aesr.202000102>.
- Zhang, X., Chen, S., Zhu, J. and Gao, Y. (2023) "A Critical Review of Thermal Runaway Prediction and Early-Warning Methods for Lithium-Ion Batteries," *Energy Material Advances*, 4. Available at: <https://doi.org/10.34133/energymatadv.0008>.
- Zhuang, D. and Bazant, M.Z. (2022) "Theory of Layered-Oxide Cathode Degradation in Li-ion Batteries by Oxidation-Induced Cation Disorder," *Journal of The Electrochemical Society*, 169(10), p. 100536. Available at: <https://doi.org/10.1149/1945-7111/ac9a09>.



Ashleigh Townsend

Lecturer
North-West University; Sibanye Stillwater

Ashleigh is currently a Lecturer in the Faculty of Engineering at North-West University. She began her career at Anglo American Platinum before transitioning to Sibanye Stillwater during her undergraduate studies. Upon completing her degree, she joined Sibanye Stillwater full-time as a Junior Engineer and was later promoted to Superintendent: Projects. In this role, she led multiple initiatives focused on battery and hydrogen substitution technologies in the mining sector.

She continues to consult part-time for Sibanye Stillwater, where she contributes to ongoing battery-related projects, including co-authoring the company's internal standard for lithium-ion battery procurement and implementation. Her most recent work involved the comparative safety testing of lithium iron phosphate and lead-acid batteries in underground locomotive applications.

Currently pursuing her PhD, her research focuses on enhancing the performance of lithium-ion batteries.

Bridging gaps in mining safety understanding: Leveraging visual animations to overcome language and literacy barriers

A.K.B. Chigwada

ABE Risk Solutions, Australia

The mining industry continues to experience persistent safety and communication challenges, particularly across multilingual and low-literacy workforces where conventional, text-based safety communication often fails to achieve understanding and behavioural compliance. Workers frequently misinterpret safety procedures not because of negligence, but due to barriers in language, literacy, and cultural relevance. This gap in comprehension has contributed to recurring incidents, inconsistent hazard awareness, and limited engagement with formal safety systems.

This paper explores how visual animation-based safety communication can bridge these understanding gaps by translating complex technical information into intuitive, accessible, and cultural resonant visual formats. Drawing comparative insights from Southern African mines and leading global operations such as BHP (Australia) and Vale (Brazil), the paper introduces the *Visual Safety Systems Framework (VSSF)*. This framework integrates human-factors theory, indigenous philosophy, and technological innovation to enable inclusive, high-impact safety learning.

Empirical evidence from case studies across Zimbabwe, South Africa, Botswana, and Australia demonstrates measurable improvements in hazard recognition, compliance, and safety culture following the adoption of visual training tools. The findings confirm that visual communication not only enhances learning outcomes but also fosters a shared safety culture grounded in inclusivity and psychological safety. The paper concludes with strategic recommendations for institutionalising visual safety systems within corporate training policies, regulatory frameworks, and international mining standards.

INTRODUCTION

Communication failure remains a key contributor to industrial accidents in mining, where workforces are often multilingual, transient, and exposed to high-risk environments. Studies by the International Labour Organization (2022) and the Minerals Council South Africa (2023) reveal that misunderstandings of procedures, rather than deliberate non-compliance, drive most incidents. Despite English being the official training medium, only about 60% of mine employees in Southern Africa possess functional workplace literacy (UNESCO, 2023). Traditional, text-heavy training materials are often ineffective for workers with limited literacy or language proficiency.

Globally, mining leaders such as BHP and Rio Tinto have adopted animation-based safety learning, achieving shorter induction times and reduced incident rates. However, Southern African operations lag behind in scaling such innovations. This paper investigates how visual communication and animation can bridge the safety comprehension gap and improve outcomes in culturally-diverse mining environments.

LITERATURE REVIEW

Global Context

Research in cognitive psychology affirms that visual learning enhances comprehension and long-term retention (Sweller, 1998). Studies by Hallowell and Gambatese (2009) and Wu *et al.*, (2019) show that workers trained through animated simulations recall up to 60% more procedural content. BHP and Rio Tinto's implementation of standardised animation modules have correlated with measurable declines in incident frequency rates.

Southern African Studies

In Southern Africa, van Wyk and de Jager (2021) demonstrated that visual content improved hazard-identification accuracy by 35%. Case studies from Zimplats (2020) and Anglo American (2023) reveal that multilingual animations increase engagement in toolbox sessions and strengthen supervisor-worker communication.

Theoretical Foundation

The research draws from three theoretical streams:

1. **Human Factors and Ergonomics (HFE)** – reducing cognitive load through intuitive communication.
2. **Social Constructivism** – learning as a shared process reinforced by visual reference points.
3. **Ubuntu Philosophy** – collective responsibility and inclusion as foundations for team-based safety culture.

Conceptual Framework and Methodology

This study synthesises insights from five Southern African mines (Zimbabwe, South Africa, Botswana, Namibia, Zambia) and three international comparators (Australia, Brazil, Canada). The proposed *Visual Safety Systems Framework (VSSF)* incorporates four integrated elements:

1. **Visual Content Design** – translating procedures into universally interpretable animated content.
2. **Cultural Encoding** – embedding local idioms and symbols to reinforce relevance and meaning.
3. **Technology Integration** – delivering content via tablets, learning management systems, and digital screens.
4. **Feedback Loops** – continuous evaluation through comprehension checks and observed behavioural outcomes.

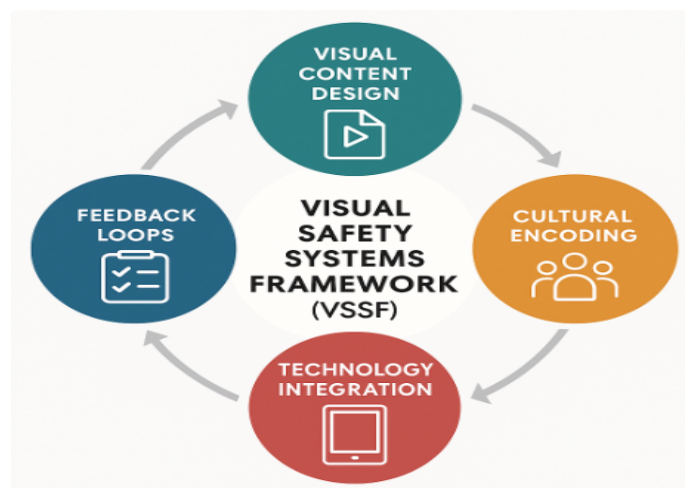


Figure 1: Visual Safety Systems Framework (VSSF)

(Diagram Description: A circular model showing the four interconnected pillars – Visual Content Design, Cultural Encoding, Technology Integration, and Feedback Loops – surrounding a central core labelled "Inclusive Safety Learning".)

FINDINGS AND CASE STUDIES

Zimplats (Zimbabwe) – Animated haul-truck increased comprehension test scores from 62% to 89%, with near-miss reporting improving by 40%.

Anglo American Platinum (South Africa) – A trilingual visual induction (isiZulu, Setswana, English) improved clarity by 70% and reduced repeated safety violations.

Debswana (Botswana) – Animated critical-control narratives enhanced hazard-spotting performance and cross-shift communication.

BHP Olympic Dam (Australia) – Behavioural-animation modules reduced onboarding time by 30%, achieving consistent induction standards across contractors.

DISCUSSION

Visual safety systems transcend literacy barriers and promote inclusivity in safety communication. Animated content provides a dynamic, culturally grounded method for embedding procedural understanding and behavioural reinforcement. Challenges to adoption include limited digital infrastructure, budget constraints, and managerial perceptions that animation trivialises safety. However, when aligned with ISO 45001 principles and co-designed with employees, animation-based modules can serve as auditable training evidence and promote psychological safety by normalising uncertainty and learning dialogue.

CONCLUSION AND RECOMMENDATIONS

Visual animation training is a scalable, evidence-based intervention for closing the safety comprehension gap. To institutionalise adoption:

1. **Regulators** should recognise digital visual modules as approved safety-training media.
2. **Mining companies** should co-create scalable animation libraries with employees and local artists.
3. **Unions and training institutes** should integrate visual literacy within skills frameworks.
4. **Researchers** should link visual learning metrics to safety indicators such as LTIFR and near-miss frequency.

FUTURE RESEARCH AND POLICY IMPLICATIONS

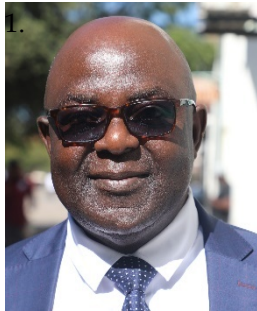
Future research should explore long-term behavioural retention and integration with emerging technologies such as virtual reality (VR) and augmented reality (AR). Policymakers and academic institutions could collaborate through an *African Visual Safety Consortium* to develop shared, multilingual training resources, aligning with SDG 8 (Decent Work) and SDG 9 (Innovation and Infrastructure).

ACKNOWLEDGEMENTS

The author acknowledges ABE Risk Solutions, Zimplats Holdings Ltd, Anglo-American Platinum, and the broader Southern African mining community for contributing data and experiential insights that informed this research. Appreciation is also extended to international collaborators from BHP Australia and Vale Brazil whose comparative experiences enriched the global perspective of this paper. By integrating animated safety resources into training programmes, mining operations can create more inclusive, effective, and reliable safety cultures that protect workers and advance operational excellence.

REFERENCES

- Anglo American Platinum. (2023). Learning from Incidents Programme Report. Johannesburg.
- Hallowell, M.R., & Gambatese, J.A. (2009). Construction safety risk mitigation. *J. of Construction Engineering and Management*, 135(12), 1316–1323.
- International Labour Organization. (2022). Safety and Health at Work: A Vision for Sustainable Prevention. Geneva.
- Sweller, J. (1998). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, 12(2), 257–285.
- UNESCO. (2023). Global Report on Education and Literacy in the Workplace. Paris.
- van Wyk, R., & de Jager, L. (2021). Visual literacy in the South African mining sector. *J. SAIMM*, 121(1), 1–8.
- Wu, C., Lin, K.-Y., & Shiau, T.-N. (2019). Improving construction safety through visualization techniques: A literature review. *Applied Sciences*, 9(9), 1909.
- Zimplats Holdings Ltd. (2020). Contractor Training Evaluation Report. Harare.



Abednego Kholwani Bayne Chigwada

Executive Director
Abe Risk Solutions

Dr Abednego KB Chigwada is an accomplished Environmental, Health, Safety, and Risk Executive with over 25 years' experience spanning mining, manufacturing, government, and essential services across Southern Africa and Australia. He holds a PhD in the Management of Technology and Innovation, with research focused on human factors and operational performance in high-risk environments. Dr Chigwada has led transformative WHSE programs in mining giants such as Zimplats and Rio Tinto Zimbabwe, embedding critical risk management frameworks and psychological safety practices. As a Fellow of the Australasian Institute of Mining and Metallurgy and a Certified Risk Management Professional, he is passionate about integrating systems thinking and indigenous philosophies like Ubuntu to advance sustainable safety cultures. Dr Chigwada is currently a senior advisor and trainer, supporting organisations to build resilient, high-performing workforces grounded in wellbeing and shared purpose.

