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STRATEGIES FOR THE PREVENTION AND MANAGEMENT OF EXPLOSIVE DETONATION FAILURES AND INITIATION SYSTEMS IN MINING OPERATIONS (MISFIRE)

Raúl RODRÍGUEZ DE LA FUENTE (ORCID: 0009-0007-6066-3075)*,
Manuel CASTEJÓN LIMAS, Javier Alfonso CENDÓN,
Gabriel MEDINA MARTÍNEZ

[1] Department of Production and Computing Engineering, University of León, León, Spain

Abstract: Misfires (failed explosive detonations) pose a critical hazard in mining by jeopardizing personnel safety and degrading operational efficiency. This study consolidates dispersed evidence from case studies, incident analyses, computational approaches and sensor-based diagnostics into a decision-oriented framework for misfire prevention, post-blast assessment and safe intervention. Rather than treating explosive selection, initiation reliability, geological and environmental controls, diagnostics and operational response as separate issues, the framework links them into a single prevention–diagnosis–management sequence. The review identifies technical, operational and environmental root causes and clarifies how optimized blast design, appropriate explosive selection, robust initiation systems, remote and real-time diagnostics, and competency-based procedures can reduce misfire probability and residual risk. The resulting synthesis provides a practical reference for mining operations where misfire-prevention and response practices remain heterogeneous, supporting safer re-entry decisions, improved operational continuity and more systematic learning from previous events.

***Keywords*:** misfire prevention, explosive detonation failure, advanced blasting technologies, mining safety protocols, operational efficiency in blasting

1. INTRODUCTION

Misfires (failures of an explosive charge to detonate as planned) critically affect safety, productivity, and cost control in mining. They create secondary detonation hazards,

* Corresponding author: rrodrd00@estudiantes.unileon.es (R. RODRÍGUEZ DE LA FUENTE)

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disrupt material handling, and jeopardize operational continuity. In U.S. surface coal mines (1978–2001), misfires accounted for 5.64% of 195 blasting accidents, whereas lack of blast area security and flyrock together represented approximately 68% of cases. These proportions are specific to blasting-related incidents in surface coal operations and should not be generalized to all sectors or underground settings (Kecojevic and Radomsky 2005). Principal drivers include initiation-system failures, adverse geological conditions, and operational errors. Incorrect delay timing causes shockwave overlap that hinders detonation propagation and degrades fragmentation (Wang et al. 2013). Although electronic detonators improve delay precision, extreme mechanical impacts (high overload) can still cause failure (for example, bridgewire rupture or internal-component damage), delivering insufficient energy to initiate the charge and increasing misfire risk (Ren et al. 2022). Undetonated charges elevate boulder yield and degrade fragmentation, raising downstream energy demand and slowing load–haul cycles; from a safety standpoint, unnoticed explosives can be disturbed by heavy equipment or reach the crusher, with latent risk of accidental initiation (Bajpayee et al. 2004).

Regulatory framework. Directive 2014/28/EU sets the EU-wide essential safety requirements for civil explosives, including conformity and traceability across the supply chain. In Spain, Royal Decree 130/2017 operationalises these duties through the Instrucciones Técnicas Complementarias (ITC, Complementary Technical Instructions): ITC 5 on end-to-end traceability and record-keeping for explosives and initiation systems; ITC 11 on the return, custody and security of unused or misfired explosives and coordination with the competent authority, including the Guardia Civil and the Intervención de Armas y Explosivos (IAE); and ITC 12 on neutralisation, destruction or recovery procedures, including controlled areas, distances and documentation (Gobierno de España 2017; European Union 2014). Beyond legal requirements, operators increasingly deploy high-speed imaging and unmanned aircraft systems (UAS, drones) to shorten anomaly detection and support safe neutralisation workflows; these tools complement preventive controls but do not replace them. The specific contribution of this study is to consolidate dispersed technical, operational, regulatory and diagnostic knowledge into an integrated framework that links misfire causation, preventive blast design, sensor-supported post-blast assessment and safe intervention procedures for mining operations where practices remain heterogeneous.

2. CONCEPT OF MISFIRES

2.1. DEFINITION AND TYPES OF MISFIRES

In blasting engineering, a misfire is a complete or partial failure of detonation that leaves undetonated product, dissipates energy, and degrades efficiency. Misfires arise chiefly from: (i) initiation-system failures (electrical/electronic malfunction, transmission faults, or inadequate priming; modern systems include electromagnetic interference (EMI) protection, yet intense radio fields or lightning can still induce parasitic currents; the partially exposed booster in Fig. 1 illustrates an initiation failure and the need for systematic post-blast inspection), (ii) sensitivity loss in ammonium-nitrate-based (AN-based) formulations due to moisture and temperature effects (low temperature can reduce reaction kinetics and initiation sensitivity, whereas heat accelerates AN decomposition and compromises stability) (Chaturvedi and Dave 2013; Izato and Miyake 2018), and (iii) rock-mass effects (discontinuities, voids, water-filled holes) that perturb wave propagation and confinement; fragmentation depends on specific charge, spacing/burden and heterogeneity (Cho and Kaneko 2004), increasing scattering, attenuation and misfire likelihood.

Fig. 1. Detail of a partially exposed booster following a misfire in a blast, associated with operational failures such as errors in layout or delay timing programming

2.2. QUANTITATIVE ANALYSIS OF MISFIRE RATES AND INFLUENCING FACTORS

Misfire frequency in large-scale operations depends on geology, explosive type and initiation technique; groundwater is often dominant via desensitisation and loss of confinement. “Water resistance” denotes an explosive’s ability to withstand water without losing power or becoming desensitised (Office of Surface Mining Reclamation and Enforcement n.d.). Water ingress increases partial reactions and misfires, especially with ammonium nitrate fuel oil (ANFO), with a context-dependent magnitude governed by formulation, charging method, and quality assurance/quality control (QA/QC) practices. Field data for electronic detonators in open-pit blasting indicate misfire rates generally below 0.03%, whereas complex tunnelling or pile-well conditions may increase rates to several thousandths without robust controls related to water, confinement and electromagnetic interference (EMI) (Leng et al. (2025). These patterns justify predictive diagnostics and environmental controls (dewatering, liners) across heterogeneous sites.

2.3. MISFIRE DETECTION AND POST-BLAST DIAGNOSTICS

Pre-blast resistance/continuity checks locate open circuits, shorts or leakage, but post-blast sequence verification relies on vibration time–frequency analysis. Using wavelet transform (WT) and Hilbert–Huang transform (HHT), instantaneous-energy peaks can be used to map actual detonation times, flagging skipped or merged delays, cut-offs and potential misfires; in a tunnel case, HHT resolved shots 27 ms apart that WT missed and informed delay redesign, reducing peak particle velocity (PPV) to 1.3 cm/s (Wang et al. 2013). High-speed video and unmanned aircraft systems (UAS, drones) can support early anomaly detection and faster situational assessment by enabling remote visual review of the blast area before personnel re-entry; however, diagnostic reliability remains site-specific and depends on visibility, dust dispersion, access geometry, sensor payload and the quality of the pre-blast reference data (Kecojevic and Radomsky 2005;Wang et al. 2013). UAS-supported monitoring should therefore be treated as a complementary diagnostic layer: RGB imagery can help identify abnormal crater geometry, unbroken zones, visible remnants of initiation systems, displaced stemming, residual fumes or access hazards, whereas thermal or infrared (IR) payloads may highlight residual heat, incomplete reaction, smouldering material or gas-emission zones requiring closer assessment. Video--assisted review (VAR)-type workflows can compare blast video, UAS imagery, vibration records, firing logs and planned borehole maps to support decisions on exclusion, qualified inspection or escalation to misfire-management procedures. However, the absence of a visual or thermal anomaly does not exclude a misfire, because dust, smoke, weather, sensor resolution, viewing angle, distance and muckpile occlusion may mask relevant evidence. Consequently, UAS, thermal/IR imaging and VAR-type review must complement, not replace, waiting periods, exclusion zones, authorized post-blast inspection, vibration diagnostics and regulatory re-entry protocols. In parallel, standardized manual protocols, including the marking of uninitiated boreholes with warning signs and beacon systems (Fig. 2), remain mandatory safeguards for controlled handling during excavation.

Fig. 2. Warning sign and beacon used to mark an uninitiated borehole, ensuring safety measures during the handling of undetonated explosives

2.4. REGULATORY AND OPERATIONAL IMPLICATIONS

Directive 2014/28/EU defines EU-wide traceability, safe management and disposal of unexploded explosives, transposed in Spain by Royal Decree 130/2017 and its ITC (Gobierno de España 2017; European Union 2014. Under the applicable ITC provisions, sites must perform post-misfire risk assessment, verify sequence completion before excavation, and coordinate custody or return with the Guardia Civil/IAE when required; ITC 12 governs in-situ destruction or chemical inerting when retrieval is unsafe (Bajpayee et al. 2004). This framework enforces identification, tracking and neutralisation of undetonated charges while reducing residual risk and securing compliance.

3. RISKS ASSOCIATED WITH MISFIRES

Misfires jeopardize worker safety, geotechnical stability, and economic performance. Undetonated charges create unpredictable conditions (high-pressure shock waves, high--velocity projectiles, toxic fumes from incomplete combustion), while poor management disrupts production, accelerates equipment wear, and compromises rock-mass integrity, increasing downtime, maintenance costs, and overall operational risk.

3.1. OPERATIONAL AND ECONOMIC CONSEQUENCES

Each misfire forces an immediate stand-down, with downtime from hours to most of a shift depending on fleet flexibility, alternative tasks, and emergency-response efficiency. The economic impact scales with unit production costs, labour and lost utilisation. A critical hazard arises when undetonated charges interact with equipment, potentially causing unintended secondary detonations that compound safety and productivity losses; as illustrated in Figs. 3 and 4 contact with misfired product can directly precipitate secondary initiation, amplifying risk and cost.

Fig. 3. Bulldozer destroyed after encountering a misfire during ripping, highlighting the hazard of uncontrolled detonations to heavy equipment and operator safety

Fig. 4. Front-end loader severely damaged while excavating a booster from an unmarked misfire, underscoring the need for proper marking and strict inspection protocols

Combustion and detonation are oxidation reactions that release heat because product molecules have lower internal energy than reactants; in explosives, this heat is expressed as the heat of explosion (Cooper 1996, Chapter 2). For high-consequence misfire interactions, the severity envelope can be described using the Chapman–Jouguet detonation pressure, which can be estimated with the Davis equation (Andrews et al. 2024):

$$P_{CJ} = k\rho_0 D^2, \qquad (1)$$

where P_{CJ} is in Pa, ρ_0 in kg·m^{-3}, and D in m·s^{-1}. For civil blasting formulations, k typically ranges 0.20–0.30.

Example (emulsion):

$$\rho_0 = 1{,}200 \text{ kg·m}^{-3}, D = 6000 \text{ m·s}^{-1} \rightarrow \rho_0 = 4.32 \times 10^{10} \text{ Pa} = 43.2 \text{ GPa},$$

thus

$$P_{CJ} \approx\sim (0.20\text{–}0{,}30) \times 43{,}2 \text{ GPa} = 8.6\text{–}13.0 \text{ GPa (e.g., } k = 0.25 \Rightarrow 10.8 \text{ GPa).} \qquad (2)$$

These magnitudes are consistent with published Chapman–Jouguet (CJ) pressures (*emulsions* ≈ 10 GPa; ideal crystalline *HE like PETN*/*TNT* = 20 GPa). In practice, borehole pressure P_b is typically a fraction of P_{CJ} and field non-idealities further reduce effective values.

3.2. GEOTECHNICAL IMPLICATIONS

Misfires degrade rock-mass stability by perturbing the in situ stress field and generating irregular compaction zones. Incomplete or poorly sequenced initiation concentrates stresses and can trigger uncontrolled movements, notably backbreak. Backbreak typically arises when confinement is deficient because adjacent holes misfire or partial initiation (for example, due to intermediate stemming or column discontinuities) redirects energy without an adequate free face; energy then follows paths of least resistance (often upward or laterally), producing off-limit fragmentation.

To estimate internal borehole pressure during detonation, the ideal-gas law applies

$$P = \frac{nRT}{V}, \qquad (3)$$

where P is borehole pressure (Pa), n the moles of gas, R = 8.314 J/(mol·K), T = 2500 K and V = 0.01 m^3.

For a 3 kg charge generating approximately 130 moles of gas:

$$P = \frac{(130)\,(8.314)\,(2.500)}{0.01}, \qquad (4)$$

$$P = \frac{2.7 \cdot 10^6}{0.01} = 270 \cdot 10^6 \text{ Pa} = 270 \text{ MPa} \qquad (5)$$

assuming complete confinement and instantaneous gas generation (field peaks vary with porosity, stemming, and detonation behavior).

The ideal-gas estimate provides an upper-bound order of magnitude; it is not equivalent to P_{CJ} and overpredicts sustained pressures in actual blast holes due to non-ideal chemistry and venting.

Flyrock and operational setbacks. Misfires or incomplete initiation can produce flyrock: when a blasthole fires without a proper free face (e.g., adjacent misfire or wrong sequencing), high-pressure gases eject fragments unpredictably. The "vacuum" range from the ballistic relation (6) is an ideal upper bound (ignores drag, breakup, terrain); field ranges are typically hundreds of metres. Operational standoff distances must be risk-informed and paired with strict exclusion-zone control (guarded perimeter, time-locked re-entry, line-of-fire discipline). For surface blasting, 500–1,000 m setbacks cover most scenarios; > 1,000 m are rare, case-specific outliers (e.g., unusual confinement or design errors) and should not be generalised without site-specific evidence and documented cases (Kecojevic and Radomsky 2005; Bajpayee et al. 2004).

$$R = \frac{v_0^2 \sin(2\theta)}{g}, \tag{6}$$

where R is range (m), v_0 the initial velocity (m/s^{-1}), θ the launch angle (45° for maximum range), and g =9.81 m/s^2. For v_0 = 200 m/s^{-1}:

$$R = \frac{(200)^2 \sin(90)}{9.81}, \tag{7}$$

$$R = \frac{40,000}{9.81} \approx\sim 4077 \text{ m} \tag{8}$$

an idealized value (~4 km) that underscores the need for precise design, adequate stemming, and correct sequencing; in practice, atmospheric drag, fragment shape, and heterogeneous breakage limit ranges to ~500–1,500 m.

Misfires also elevate toxic-gas hazards (chiefly NO_2 and CO) via incomplete combustion. Under ideal conditions, ammonium nitrate decomposition is:

$$2NH_4NO_3 \rightarrow 2N_2 + 4H_2O + O_2\,. \tag{9}$$

Under oxygen-deficient or fuel-rich conditions typical of partial initiation, the pathway may shift to:

$$2NH_4NO_3 \rightarrow 2N_2O + 4H_2O\,. \tag{10}$$

Side products include NO, NO_2 and CO depending on oxygen balance, confinement and moisture; the above stoichiometries are idealised and do not capture kinetic/transport limitations in the borehole. With side reactions generating NO and NO_2. The latter produces the characteristic orange–brown fumes and poses an acute inhalation hazard. According to the National Institute for Occupational Safety and Health (NIOSH) Pocket Guide (NIOSH 2019), the short-term exposure limit (STEL) for NO_2 is 1 ppm (15 min) the Occupational Safety and Health Administration (OSHA) ceiling is 5 ppm, and the NIOSH IDLH is 13 ppm. In blast operations, any post-blast measurements at or above the IDLH (13 ppm) require immediate evacuation, forced ventilation, and controlled re-entry only after consecutive readings fall back below the short--term limit (1 ppm), verified with calibrated NO/NO_2 monitors (NIOSH 2019).

4. PREVENTION OF MISFIRES

Preventing misfires requires an integrated approach that couples precise blast design, appropriate explosive selection, and strict compliance with operational safety standards. A well-structured strategy improves energy distribution, lowers the probability of undetonated charges, and protects personnel, equipment, and project continuity.

4.1. BLAST DESIGN AND PLANNING

Design begins with a rigorous geomechanical assessment (intact strength, discontinuity networks, hydrogeology, in situ stress anisotropy). Explosive type, priming, and initiation architecture are then tailored to the rock mass to ensure uniform energy propagation and consistent breakage. A critical optimization variable is the configuration of burden (B) and spacing (S), which governs energy transfer within the rock matrix (Hustrulid and Wanger 2002). The optimal burden is commonly expressed as

$$B = k\,d\,, \tag{11}$$

where B is the burden (m), d the borehole diameter (m), and k an empirical multiplier typically 20–35 borehole diameters, depending on rock mass quality, confinement and blast objectives. Spacing S is selected consistently with B (e.g., $S \approx 1.0–1.4B$.

For timing, precise delay sequencing minimizes wave superposition and prevents desensitization of adjacent columns. The inter hole delay is typically

$$t = \frac{S}{V_p}, \tag{12}$$

where t is the inter-hole delay (ms), S the spacing (m), and V_p the target propagation/scaling parameter ($m \cdot ms^{-1}$). In practice, designers often target ≈ 0.8–1.5 ms per metre of spacing to balance fragmentation and *PPV* control; broader ranges reported in the literature span ≈ 3–8 $m \cdot ms^{-1}$ depending on geology and confinement. Adjust to site vibration limits and the selected burden/spacing.

4.2. SELECTION AND PROPER HANDLING OF EXPLOSIVES

Charge performance depends on thermochemical stability, water resistance, and detonation velocity. Formulation follows site characterisation, including porosity, uniaxial compressive strength (UCS), and discontinuity patterns: higher-density products are generally preferred in competent rock, whereas water-resistant emulsions are more appropriate in saturated ground. The Chapman–Jouguet pressure P_{CJ} scales with $\rho_0 D^2$ losses in D moisture ingress, poor priming, mismatched product) reduce breakage energy and raise misfire risk. Handling is critical: accurate priming with a booster and non-electric/electronic initiation ensures efficient energy transfer (Fig. 6), storage must remain dry, ventilated and isolated from heat. During loading, maintain cartridge alignment, avoid bridging/over-compacted stemming, and position the primer within the column's detonation path to maximise reliability.

4.3. TRAINING AND OPERATIONAL PROTOCOLS

Because human factors dominate misfire causation, competency-based training should cover energetic behaviour under confinement, delay sequencing to avoid wave superposition, and misfire detection with emergency neutralisation. Figure 5 underlines disciplined priming; Fig. 6 shows correct fastening and assembly of initiation systems. Use standardised checklists, pre-/post-blast audits, and simulations/drills to improve response times and procedural compliance. Strict adherence to documented standards, together with optimised design and rigorous product selection, reduces misfires, improves fragmentation, lowers costs, and strengthens regulatory compliance.

Fig. 5. Operator performing priming tasks with a booster and a Nonel detonator, emphasizing the importance of technical training to ensure safe and efficient procedures

Fig. 6. Example of a correct connection with tubes securely fastened, illustrating the need for proper handling of initiation systems to prevent detonation failures

5. PROCEDURES IN CASE OF MISFIRE

5.1. INTRODUCTION AND THEORETICAL BACKGROUND

Within this study, misfires are treated as a coupled safety–operations problem rather than as isolated product or initiation failures. The proposed workflow (Supplementary Figure S1) integrates geotechnical, explosive, environmental and operational variables with diagnostic evidence, risk assessment, intervention criteria and feedback loops, thereby converting dispersed good practices into a decision-oriented framework for prevention, post-blast assessment and safe response.

5.2. QUANTITATIVE RISK ASSESSMENT AND DIAGNOSTIC METHODOLOGY

Risk appraisal integrates geotechnical, explosive, environmental, and operational variables. Rock integrity, discontinuities and groundwater condition the propagation of stress waves, while deviations in sensitivity or initiation sequencing promote incomplete combustion or desensitization. A structured framework quantifies misfire probability by combining empirical field data with numerical models to define acceptable thresholds. When risk exceeds limits, corrective measures are implemented (retiming delays, revising initiation sequence, modifying stemming) to preserve charge integrity. Electronic logging, acoustic or vibration monitoring, and UAS-supported RGB/thermal imaging provide complementary diagnostic inputs for identifying partial or failed detonation, while post-blast analysis, including high-resolution fragmentation mapping, borehole-residual checks, and video-assisted review (VAR)-type comparison of blast records against the planned borehole map, supports mitigation validation. A decision matrix formalizes escalation; as shown in Supplementary Figure S1, the workflow proceeds from initial assessment to corrective action with emphasis on integrated diagnostics and adaptive mitigation.

5.3. DEVELOPMENT OF INTERVENTION PROTOCOLS

Once a misfire is identified or suspected, an immediate structured response must maintain the exclusion zone, integrate remote diagnostic evidence where available, and only then define the safest intervention pathway to neutralize hazards and restore operational continuity. Protocols based on quantitative risk and predefined thresholds must consider charge integrity, ground stability, and the feasibility of secondary initiation or controlled removal. Method selection is site specific: secondary initiation applies when the column remains intact and confined; mechanical extraction or chemical inertization is indicated for desensitized or compromised charges; where recovery poses excessive risk, controlled re-blasting removes residual energy while limiting ground disturbance.

Proper demarcation and field marking of undetonated holes are essential to prevent unauthorized access and ensure compliance (see Fig. 7), For consistent execution, a decision flowchart should set criteria for secondary initiation, mechanical extraction, or chemical inertization and include cases requiring manual retrieval with non-sparking tools to prevent accidental initiation and ensure safe handling (see Fig. 8).

Fig. 7. Example of demarcation and marking of a zone with an undetonated borehole, using visual signals such as warning tapes and flashing lights to ensure safety in the area

Fig. 8. Flexible tool designed for retrieving cartridges from boreholes. Manufactured from non-sparking materials, such as brass, to ensure safe handling and prevent spark generation

5.4. IMPLEMENTATION AND CASE STUDIES

Implementation requires a systematic workflow that integrates diagnostics with real-time decision making. Because scenarios are context specific (governed by geology, formulation, and initiation performance), protocols should be validated through controlled field deployments across diverse settings to ensure transferability. Historical blast records and quantitative key performance indicators (KPIs), such as misfire resolution time, secondary-initiation efficiency and post-blast material displacement, provide

Fig. 9. Sequence of controlled destruction of extracted explosives. The images illustrate the initial ignition, detonation propagation, and energy release in a secure location, adhering to strict safety protocols under expert supervision

objective performance measures and support continuous improvement (MineExcellence 2015). Comparative assessments versus conventional practice show gains in safety, operational efficiency, and overall blast outcomes. Controlled destruction of extracted explosives is among the most effective measures, safely neutralizing residual energetic material under strict procedures (see Fig. 9), To consolidate applied knowledge, a curated case-study compendium is recommended, documenting successful resolutions under varied geological and operational conditions.

6. CASE STUDIES

6.1. MISFIRE ANALYSIS

Example 1. Human Error in Nonel Detonator Connection

Incident Description. In an underground blast using a Nonel initiation system, an incorrect detonation-line connection caused a misfire, leaving a tunnel sector undetonated; operations were halted, manual neutralization was required, personnel were exposed to elevated risk, and downtime increased markedly.

Case Analysis. The investigation attributed the event to insufficient training of the tie-in crew; an inexperienced operator misconnected one initiation line, disrupting the firing sequence, and inadequate supervisory oversight during preparation failed to detect the error.

Evidence. Figure 10, shows a transmission tube with a mid-length burn mark at an unintended initiation point, consistent with cross-initiation from an adjacent tube or an intrinsic defect; Fig. 11 presents remnants of a tube that did not initiate, with three segments later sectioned to assess residual energetic material, corroborating a break in the detonation sequence.

Fig. 10. Transmission tube with an initiation point caused by an incorrect connection, which prevented the tube from activating and resulted in a misfire

Fig. 11. Remnants of transmission tube that failed to initiate during the blast, highlighting a disruption in the detonation sequence

Improvements Implemented. The implemented measures comprised an enhanced training program for all blast-preparation personnel, with emphasis on safe handling and correct NONEL connections; a double-verification protocol requiring independent inspection and sign-off by two experienced operators on every detonation-line connection prior to authorization; reinforced supervision during critical preparation phases to ensure continuous oversight by qualified staff; and a standardized verification workflow (Fig. 12) that defines the sequential steps from initial system review to final supervisory approval before blast initiation.

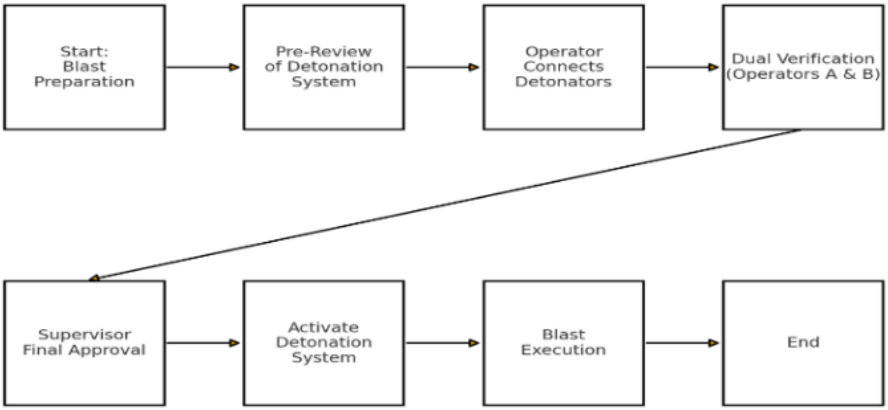

Fig. 12. Compact flowchart illustrating the sequential steps to ensure safe detonator connections: blast preparation, system pre-review, detonator connection, dual verification, final approval, and blast execution

Example 2. Impact of Environmental Conditions on Explosive Efficiency

Incident Description. In a granite quarry with high humidity and large diurnal temperature swings, a planned blast misfired. The event was linked to partial decomposition and performance loss of the explosive; elevated humidity and low overnight temperatures degraded stability, impeded initiation and contributed to incomplete detonation.

Case Analysis. Inadequate storage/handling allowed moisture ingress; hygroscopic uptake reduced sensitivity and detonation capability. Procedures deviated from humid-climate best practice, and the blast design was not adjusted to prevailing conditions.

Evidence. Figure 13 shows booster remnants with the detonator still seated, indicating failure to initiate under adverse conditions; Fig. 14 details booster debris and non-electric (NONEL) initiation-system fragments, corroborating incomplete initiation and environmental degradation.

Fig. 13. Remnants of a booster retaining its detonator, indicative of inadequate initiation likely caused by moisture-induced instability

Fig. 14. Detailed view of booster remnants and a NONEL detonator that did not initiate, evidencing incomplete initiation under adverse environmental conditions

Improvements Implemented. Upgraded storage/handling (hermetic containers, temperature control) to prevent moisture ingress; a daily climate protocol now adjusts the blast plan to forecasts; and targeted training emphasises integrating environmental variables into planning and execution.

7. CONCLUSIONS AND RECOMMENDATIONS

Misfires remain underrepresented in the scientific literature despite their impact on safety, operational continuity and blast performance, resulting in heterogeneous prevention and response practices. The principal contribution of this study is the consolidation of dispersed technical, operational, environmental, geotechnical and diagnostic knowledge into a single decision-oriented framework linking prevention, post-blast assessment, intervention and feedback. This framework clarifies how blast design, product selection, initiation-system reliability, environmental controls, UAS/thermal/IR and VAR-assisted review, vibration diagnostics and trained response protocols should operate as complementary layers rather than isolated measures. The case studies illustrate the multifactorial nature of misfires and show how human error, environmental degradation and sequencing deficiencies can be translated into corrective actions, including verification workflows, climate-sensitive planning and structured field demarcation. Overall, early risk identification, disciplined inspection and evidence-based escalation improve safety, operational continuity and the replicability of misfire-management practices across heterogeneous mining operations.

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