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Integrated Prevention of Gas and Spontaneous Combustion in Goaf Areas: Sealing Techniques, Inertization and Pressure Balance

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ABSTRACT

Deep goaf areas (>600 m) present compounded hazards where methane accumulation (>30%) and coal spontaneous combustion (spon-com) coexist through synergistic mechanisms including competitive gas adsorption (O_2 > CH_4 > N_2 affinity) and fracture-mediated flow (permeability anisotropy >5.8). Conventional mitigation strategies exhibit intrinsic conflicts: gas extraction induces oxygen ingress (threshold ⩽7%), while inertization inhibits methane desorption. This study establishes an integrated technical framework resolving this contradiction via three innovations: (1) Composite sealing combining polyurethane foam bag-walls (⩾5 m thick, adhesion grade 4B) and overburden grouting, reducing leakage to <0.8%/year; (2) Optimized alternating inertization (N_2: 0.8–1.2 MPa × 48 h; CO_2: 750 m^3/h × 6–8 h) maintaining O_2<7% and CH_4>30%; and (3) Dynamic pressure balance (ΔP ⩽50 Pa) using nitrogen curtains (velocity >3 m/s). Validated through 18-month field trials at Pingdingshan Mine (650 m depth), the framework achieved 78% CO reduction (120→26 ppm) with zero spon-com incidents, while sustaining gas drainage purity at 38–42%. Critical synergies include CO_2-driven thermal quenching (12–20°C cooling) and N_2-enhanced methane extraction (2.3× volume increase), enabling concurrent hazard control and potential CO_2 storage in decommissioned goafs.

KEYWORDS

Goaf hazard coupling; Alternating inertization; Pressure balance optimization; Methane extraction enhancement; Spontaneous combustion suppression

1 Introduction

Goaf areas constitute complex dual-hazard environments where methane (CH_4) accumulation and coal spontaneous combustion (spon-com) coexist, creating synergistic threats to mining safety. In deep coal seams (>600 m), high gas pressure (up to 1.2 MPa) and low permeability (<0.1 mD) impede efficient gas drainage, while tectonic fractures facilitate oxygen intrusion, triggering exothermic oxidation reactions that elevate temperatures beyond the critical 70 °C threshold for spon-com initiation. This hazard coupling is exacerbated by competitive adsorption between CH_4 and O_2 at coal surfaces, where oxygen influx displaces adsorbed methane, simultaneously increasing explosion risks and accelerating oxidative heating. Field measurements from Pingdingshan Mine (650 m depth) recorded CH_4 concentrations exceeding 30% alongside CO emission peaks of 540 ppm, confirming concurrent gas-spon-com dynamics[1].

Conventional mitigation strategies exhibit intrinsic conflicts: gas extraction requires negative pressure gradients to enhance CH_4 desorption, yet this induces oxygen ingress through sealants or rock fractures, reducing the spon-com oxygen threshold to ⩽7%. Conversely, inertization (e.g., N_2 injection at >97% purity) suppresses combustion but elevates goaf pressure, inhibiting further methane release. Technical limitations include: (1) Sealing integrity deficits: Cement-based grouts degrade under mining stress, with leakage rates exceeding 5%/24 hours in Y-type ventilation systems, as observed in Fale Mine 50105 where airflow leakage surpassed 300 m^3/min; (2) Inertization trade-offs: While N_2 boosts CH_4 extraction by 2.3× via partial pressure reduction, its oxygen displacement efficiency drops significantly above 70° C, whereas CO_2 effectively suppresses combustion (85 – 93% O_2 displacement) but adsorbs onto coal, blocking methane diffusion; and (3) Dynamic pressure imbalances: Ventilation-induced differentials (>50 Pa between goaf and working face) destabilize oxygen distribution zones, with manual regulation delays (>2 hours) failing to maintain asphyxiated zones during mining advance. These challenges intensify in deep or water-rich goafs, where liquid CO_2 injection achieves rapid inertization but requires complementary sealing for sustained low-O_2 environments.

This study establishes an integrated technical framework to resolve the gas-spon-com contradiction through three interlocked innovations: (1) Advanced composite sealing combining bag-wall structures (⩾5 m thickness) and overburden grouting (cement-fly ash mixtures) to achieve leakage rates <0.8%/year, validated by SF_6 tracer tests; (2) Optimized dual-mode inertization employing alternating N_2/CO_2 cycles (N_2 at 0.8 – 1.2 MPa for 48 hours followed by CO_2 pulses) to maintain O_2<7% and CH_4>30%[2]; and (3) Dynamic pressure regulation using adjustable airflow regulators and nitrogen curtains (velocity >3 m/s, coverage ⩾90% roadway width) to limit goaf-face pressure differentials to ⩽50 Pa, stabilizing the asphyxiated zone across >60% of goaf volume. Validated via an 18-month field trial at Pingdingshan Mine, this framework targets a 75% reduction in CO emissions with zero spon-com incidents while sustaining gas drainage concentrations >

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35%, concurrently enabling potential CO_2 storage in decommissioned goafs (Table 1).

Table 1 Synergistic Interactions of Gas and Spon-Com Hazards in Deep Goafs

InteractionMechanism	PhysicalProcess	TechnicalConsequence
Gas-Heat Coupling	CH_4 adsorption exotherm elevates coal temperature	Accelerates oxidation to 150–250°C critical stages
O_2-CH_4 Competition	O_2 displaces CH_4 at adsorption sites	Reduces gas drainage efficiency (<30% concentration)
Fracture Flow	Stress fractures connect gas/O_2 reservoirs	Seal failure under dynamic pressure gradients

2 Synergistic Mechanism of Gas and Spon-com Hazards in Goaf

2.1 Gas Migration Dynamics

In goaf environments, methane (CH_4) migration exhibits multiphase flow characteristics dominated by pressure gradients and fracture network topology. Following coal extraction, stress redistribution generates three distinct fracture zones: caved, fractured, and continuous bending zones, each with permeability varying by 2–3 orders of magnitude (10^{-4} to 10^{-1} mD). Gas transport obeys Darcy-Forchheimer dynamics, where CH_4 desorption from residual coal (adsorption capacities: 12–25 m^3/t for medium-volatile bituminous coal) creates local pressure differentials up to 1.2 kPa/m, driving flow toward low-pressure regions such as extraction boreholes or working faces. Critically, gas accumulation peaks in the oxidation zone (20–60 m behind working face), where CH_4 concentrations exceed 30% due to restricted convection—a key precondition for explosive mixtures when oxygen intrusion occurs. Field measurements at Pingdingshan Mine revealed that permeability anisotropy (horizontal/vertical ratio >5.8) channels 75% of gas flow through upper fracture networks, directly influencing oxygen distribution patterns and spon-com risk.

Oxygen transport, conversely, is governed by ventilation-induced leakage through sealing defects and overburden fractures. In Y-type ventilation systems, airflow leakage exceeding 300 m^3/min sustains oxygen concentrations >8% in spon-com prone zones, even with conventional seals. Oxygen diffusion follows Fickian dynamics in porous media, with an effective diffusion coefficient De empirically expressed as:

$$D_e = \frac{\Phi^{1.5}}{\tau} D_0 \left(\frac{T}{273}\right)^{0.7}$$

Where ϕ denotes porosity (0.2–0.35), τ tortuosity (2.1–3.5), D_0 free-air diffusivity (1.8×10^{-5} m^2/s), and T temperature (K)[3]. This establishes a direct link between goaf temperature and oxygen supply—higher temperatures accelerate oxygen ingress, creating positive feedback for spon-com (Table 2).

Table 2 Key Parameters Governing Gas Migration in Goafs

Parameter	Range/Expression	InfluenceonHazards
Permeability (k)	10^{-4}–10^{-1} mD	Controls gas drainage efficiency & O_2 ingress
CH_4 Concentration	18–42% in accumulation zones	Determines explosive potential (5–16% CH_4)
O_2 Diffusion (D_e)	0.8–2.7×10^{-6} m^2/s at 50°C	Governs oxidation reaction rates
Pressure Gradient	0.8–1.2 kPa/m	Drives gas flow toward low-pressure regions

2.2 Coal Oxidation Process

Coal oxidation initiates through chemisorption of O_2 molecules at active sites (aliphatic hydrocarbons, hydroxyl groups), releasing 50–90 kJ/kg heat at 30–70°C—the onset of self-heating. This process exhibits rank-dependent kinetics: low-rank coals ignite at 60–70°C due to higher oxygen-containing functional groups, whereas anthracite requires >100°C initiation. Critical temperature thresholds demarcate reaction regimes: ① 70° C: Onset of accelerated oxidation; CO emission >50 ppm; ② 150°C: Entering pyrolysis stage; C_2H_4 appears; ③ 250°C: Transition to open combustion; CO/CO_2 ratio >0.05.

Adsorbed methane fundamentally alters oxidation pathways through three mechanisms: ① Competitive adsorption: CH_4 occupies 40–60% of micropores (<2 nm), reducing O_2 adsorption capacity by 15–30% and delaying oxidation onset. ② Exothermic displacement: Methane desorption (heat release: 16.7 kJ/mol) elevates coal temperature during O_2 adsorption, particularly in high-gas-content goafs (>12 m^3/t). ③ Reaction inhibition: Above 70° C, methane partially oxidizes to formaldehyde (HCHO), consuming active oxygen radicals and suppressing chain reactions—evidenced by 22–35% lower CO production in gassy coals versus degassed samples.

Laboratory studies reveal that adsorbed CH_4 (2–8 m^3/t) increases apparent activation energy by 8–15 kJ/mol across 50–150°C, demonstrating its retarding effect on oxidation kinetics[4]. However, this inhibition diminishes beyond 150°C when thermal decomposition dominates.

2.3 Hazard Coupling Effects

The coexistence of CH_4 and spon-com hazards creates three synergistic loops that amplify disaster risks.

2.3.1 Competitive Adsorption-Desorption Dynamics

Methane and oxygen exhibit competitive adsorption on coal surfaces, with adsorption affinity $O_2 > CH_4 > N_2$ due to molecular polarity differences. Oxygen partial pressure exceeding 3 kPa displaces adsorbed CH_4, releasing methane into pore spaces while simultaneously accelerating oxidation. This dual effect creates explosive mixtures (CH_4: 5–16%; O_2: > 12%) precisely where temperatures peak—a "perfect storm" scenario observed in 82% of compound disasters. Field data from Wuhai Mine 1012 confirm that oxygen influx >4 m^3/min elevates CH_4 concentrations by 18–32% in oxidation zones through displacement effects.

2.3.2 Thermophysical Coupling

Gas adsorption/desorption and coal oxidation form a closed heat feedback loop:①CH_4 adsorption exotherm: Releases 16.7 kJ/mol, elevating coal temperature; ②Temperature rise: Accelerates oxidation rate (10°C increase doubles reaction speed); ③Enhanced oxidation: Further heats coal, promoting CH_4 desorption. This loop causes temperature escalation rates >1.5° C/h in high-gas goafs, 3× faster than gas-free environments. At >70° C, oxidized coal surfaces generate additional active sites, intensifying both CH_4 release and O_2 consumption—a process confirmed via in situ ESR spectroscopy showing 40–90% increase in free radical concentrations[5].

2.3.3 Fracture-Mediated Flow Interactions

Mining-induced fractures dynamically reconfigure gas/oxygen pathways: ①Compaction zones (120 – 200 m behind face): Low permeability (<0.1 mD) traps CH_4, creating accumulation pockets; ②Fracture networks (20 – 120 m): High permeability (10–100 mD) channels oxygen influx; ③Stress cycling: Periodic roof collapse opens new fractures, suddenly connecting CH_4 reservoirs with oxygen pathways.

This spatial-temporal coupling explains why 70% of compound disasters occur during periodic weighting—fracture reorganization suddenly bridges otherwise isolated hazard zones. Computational fluid dynamics (CFD) simulations at 22101 demonstrate that fracture connectivity >35% enables CH_4-O_2 mixing within 30 minutes, reducing the ignition energy threshold to 0.28 mJ (Table 3).

Table 3 Synergistic Effects in Gas-Spon-com Compound Disasters

CouplingMechanism	FieldEvidence	DisasterConsequence
CH_4 displacement by O_2	CH_4 surge >32% after O_2 ingress in Fale Mine	Explosive mixture formation in <2 hours
Adsorption exotherm loop	2.8°C/h temperature rise in Xinjiang goafs	Spon-com advancement to critical stage (150°C) in 48h
Fracture-mediated flow	86% of explosions during periodic weighting	Sudden mixing of CH_4/O_2 reservoirs

2.4 Case Validation: Pingdingshan 111811 Working Face

Field observations at Pingdingshan 111811(depth: 650 m; gas content: 12.8 m^3/t) quantified coupling mechanisms: ① Without extraction, CH_4 concentrations reached 34% in oxidation zones (20 – 45 m behind face), with CO emissions peaking at 540 ppm—confirming concurrent gas/spon-com hazards. ②After implementing borehole extraction (negative pressure: 4.5 kPa), CH_4 at upper corner decreased to 0.5%, but oxygen leakage increased by 40%, expanding the oxidation zone from 28 m to 52 m. ③Intermittent CO spikes (120 – 260 ppm) occurred despite low average concentrations (<10 ppm), indicating micro-oxidative hotspots sustained by gas displacement effects—validating the competitive adsorption model. These findings underscore the inherent trade-off between gas control and spon-com prevention: interventions targeting one hazard often exacerbate the other.

3 Advanced Sealing Techniques for Goaf Isolation

3.1 Material Selection Criteria

Polymer-based foams exhibit superior adaptability to complex fracture networks due to tunable expansion ratios and penetration capabilities. Polyurethane foam (PUF) demonstrates exceptional performance, with expansion rates reaching 10× within 2 min and adhesion strength achieving 4B classification (coal detachment area <4%) under mine ventilation dynamics (25 m/s wind speed). Its efficacy is enhanced by additives: ① Antistatic agents: Incorporating 1.5 wt% conductive carbon black reduces resistivity to 10^7 Ω·m, mitigating electrostatic ignition risks. ②Flame retardants: Adding 21 wt% retardant 8316 elevates the oxygen index to 29.2%, suppressing combustion propagation[6].

Inorganic composites, particularly cement-fly ash grouts, provide structural stability in high-stress zones. When injected into borehole sealing sections, they form graded composite structures (original coal – grout body – cementing body) that inhibit gas leakage through "water-plug effects." This phenomenon arises from moisture-dependent permeability reduction, where higher equivalent Talbot indices in lower composite coal (LPC) decrease permeability by 15 –40%, effectively blocking methane migration.

Flexible membrane materials enable rapid response in disaster scenarios. PVC-based airbags with dual anti-tear

coatings withstand deformations up to 42.5% and impact energies >2×10^4 J, while maintaining flame resistance. Their lightweight design (<15 kg/m^2) facilitates quick deployment in working face corners, reducing labor intensity by 70% compared to conventional sandbag sealing (Table 4).

Table 4 Key Sealing Material Parameters and Design Criteria

Material	CriticalParameters	PerformanceTarget
Polyurethane Foam	Expansion ratio: 10×; Setting time: 2 min	Adhesion grade ⩾4B; O_2 index >28%
Cement-Fly Ash	Water-cement ratio: 0.8–1.0; Fly ash: 30–40%	Permeability reduction >35% in LPC
Flexible Membranes	Tensile strength: >18 MPa; Tear resistance: >150 N/mm	Deformation tolerance: >40%

3.2 Key Sealing Structures

Bag-wall sealing systems combine mechanical stability with adaptive sealing. In intake/return roadways, ⩾5 m thick bag-walls filled with PUF or cementitious composites create isolation barriers. Field trials at Pingdingshan demonstrated that integrating hydraulic supports with embedded hinge buckles enhances structural integrity, limiting leakage to <5 m^3/min under 600 Pa pressure differentials. For corner sealing, Y-type ventilation layouts employ lightweight airbags secured by hydraulic props, increasing goaf CH_4 concentrations by 18–25%—confirming effective oxygen exclusion.

Overburden grouting targets fracture connectivity between surface and goaf. The comprehensive method includes: ① Surface fracture mapping: Identifying fissures >50 mm width with leakage velocities >0.5 m/s using tracer gas (SF_6). ② Targeted grouting: Injecting cement-fly ash slurries (viscosity: 500–800 cP) into high-permeability zones, reducing surface-goaf airflow by 65 – 80%. ③ Artificial roof caving: For non-collapsing roofs in intake/return tunnels, controlled blasting induces caving, eliminating oxygen pathways[7].

Positive-pressure chambers revolutionize traditional sealing by reversing leakage dynamics. By maintaining nitrogen pressure at 20 – 30 Pa within sealed chambers adjacent to goafs (achieved via 0.15 – 0.20 m^3/min N_2 injection), airflow reverses—venting N_2 outward instead of oxygen ingress. At Hengda Mine 5333 goaf, this technique reduced CO concentrations below 5 ppm within 72 hours by eliminating leakage pathways. The system synergizes with sand-wall seals, where graded particle distributions (Talbot index *n* = 0.4–0.6) enhance compaction and gas-blocking effects.

3.3 Integrity Evaluation Methods

Tracer gas diagnostics quantify leakage with high sensitivity. SF_6 injection at suspected leakage points (e.g., coal pillar joints or overburden fractures), coupled with multi-point sampling in goafs, detects concentrations as low as 10^{-9} vol%. At Fale Mine 50105, this method identified 23 leakage paths in Y-ventilation systems, enabling targeted repairs that reduced airflow leakage from 300 m^3/min to 45 m^3/min.

Pressure decay monitoring assesses seal durability under mining-induced stress. The standardized test involves: ① Pressurizing sealed zones to 1.2× operational pressure (typically 1.5 kPa). ② Recording pressure drop over 24 hours. ③ Calculating decay rates (R):

$$R = \frac{\Delta P}{P_0} \times 100\%$$

Acceptable integrity requires R < 5%/24 h. Advanced systems integrate pressure sensors with PLC controls to trigger automatic N_2 compensation when R exceeds thresholds.

Two-phase foam testing evaluates dynamic sealing capacity. Foam generators produce stable bubbles (diameter: 0.5–3 mm) injected into simulated fracture networks at 200 – 400 L/min. Performance metrics include: ① Pressure tolerance: > 600 Pa without structural failure. ② Effective duration: >60 min for 2 m sealing length. ③ Distance efficacy: Sealing efficiency increases with deployment distance (e.g., 92% leakage reduction at 15 m vs. 78% at 5 m) (Table 5)[8].

Table 5 Performance Comparison of Advanced Sealing Technologies

Technique	LeakageRate	ResponseTime	FieldEfficacy
Polymer Foam Seals	0.8–2.1 m^3/min·m^2	5–10 min	85% reduction in O_2 ingress
Positive Pressure	Reversed flow (N_2 out)	15–30 min	CO elimination in 72 h 10
Airbag Systems	<5% of total airflow	<5 min	CH_4 accumulation +25% 9

3.4 Field Implementation Protocols

For operational goafs, implement a three-stage sequence: ① Primary sealing: Install bag-wall structures with embedded injection pipes during retreat mining. ② secondary grouting: Inject PUF/cement composites into overburden fractures identified by beam-tube monitoring (O_2 >8%). ③ Tertiary pressurization: Establish N_2 chambers with 20 – 30 Pa overpressure, monitored via wireless pressure transducers.

In disaster scenarios, deploy rapid-inflating airbags with hybrid foam fillers. The optimized process includes: ① Positioning hydraulic supports with embedded hinge buckles at 20 m intervals. ② Inflating abrasion-resistant airbags using wind-pressure foam generators (expansion ratio: 30×). ③ Maintaining integrity via remote PLC-controlled N_2

compensation, achieving >95% airflow blockage within 5 min.

Long-term integrity management requires quarterly evaluations: ① SF_6 tracer tests to map new leakage paths after periodic weighting. ② Core sampling of grouted zones to measure material degradation (<0.8%/year acceptable). ③ Pressure decay audits, with automatic regulator adjustments when R > 3%/24 h.

4 Inertization Technology for Dual-functional Control

4.1 N_2 Injection for Enhanced Gas Drainage

Nitrogen injection primarily enhances methane extraction through partial pressure reduction and gas displacement dynamics. When injected at purities >97% and pressures of 0.8–1.2 MPa, N_2 reduces the partial pressure of CH_4 in coal matrices, accelerating desorption kinetics by 25–40% compared to non-inertized conditions. Field implementations at Pingdingshan Mine demonstrate that continuous N_2 injection (48-hour cycles) elevates gas drainage concentrations from <15% to 35–42%, while extraction volumes increase by 2.3×. The efficacy is governed by two mechanisms: ①Viscous displacement: High-flow N_2 (velocity >0.5 m/s) displaces free methane from fracture networks, directing it toward extraction boreholes. ②Adsorption equilibrium shift: N_2 competes with CH_4 for adsorption sites, with affinity ratio K_{CH_4/N_2} = 1.8–2.5, forcing methane into gaseous phase.

Critical limitations emerge at elevated temperatures (>70°C). Nitrogen's oxygen displacement efficiency declines by 30–50% due to reduced density and increased buoyancy, allowing residual O_2 accumulation in upper fracture zones—a key trigger for spon-com[9]. This necessitates integration with complementary sealing or CO_2 injection for sustained hazard control.

4.2 CO_2 Injection for Spon-com Suppression

Liquid CO_2 injection excels in oxygen isolation and thermal quenching, leveraging its higher density and adsorption affinity. When injected at -20°C to -30°C, liquid CO_2 undergoes rapid phase change, absorbing 573 kJ/kg latent heat during vaporization, which cools coal surfaces by 12–20°C within 1 hour. Optimal parameters identified through CFD modeling include: ①Injection position: 60–80 m behind working face (targeting oxidation zones) ②Buried pipe depth: 50 m ③Flow rate: 750–800 m^3/h.

CO_2 outperforms N_2 in oxygen displacement due to molecular weight (44 g/mol vs. 28 g/mol) and adsorption affinity (K_{CO_2/O_2} ≈ 3.1). At 800 m^3/h injection rates, CO_2 reduces O_2 concentrations in goaf oxidation zones by 85–93%, shrinking spon-com risk areas by >15% relative to untreated goafs. However, CO_2 adsorption blocks micropores (<2 nm), inhibiting methane diffusion and reducing drainage efficiency by 18–25%—a trade-off requiring strategic protocol design.

4.3 Alternating Injection Protocol

The dual-hazard challenge necessitates alternating N_2/CO_2 injection to leverage synergistic benefits while mitigating individual limitations: ① Phase 1 (N_2 dominant): Inject N_2 at 0.8–1.2 MPa for 48 hours to enhance methane drainage, maintaining CH_4 >30% and O_2 <10%. ② Phase 2 (CO_2 pulse): Switch to liquid CO_2 at 750 m^3/h for 6–8 hours, targeting oxidation zones identified by thermal sensors (≥50°C). CO_2 pulses rapidly suppress residual oxidation and cool hotspots. ③ Cycle optimization: For deep goafs (>600 m), employ 3:1 N_2/CO_2 duration ratio; for water-rich goafs, prioritize CO_2 due to its solubility and penetration advantages.

Field trials in Yangcheng Mine demonstrated this protocol reduced CO emissions by 78% (from 120 ppm to 26 ppm) while sustaining drainage concentrations at 35–42%, achieving zero spon-com incidents over 18 months (Table 6).

Table 6 Performance Comparison of Inert Gases in Goaf Applications

Parameter	N_2	CO_2	AlternatingN_2/CO_2
O_2 Displacement	60–75% (<70°C)	85–93%	88–95%
CH_4 Extraction	+230% vs. baseline	-18% vs. baseline	+190% vs. baseline
Cooling Capacity	Limited (adiabatic)	12–20°C reduction	15–22°C reduction
Optimal Injection	0.8–1.2 MPa, 48 h	750–800 m^3/h, 6–8 h	3:1 N_2/CO_2 ratio

4.4 Gas Migration Monitoring and Control

Distributed fiber-optic sensing enables real-time tracking of inert gas distribution. Temperature resolution of ±0.1°C and spatial resolution of 1 m detect cooling fronts during CO_2 injection, identifying under-inertized zones (O_2 >8%) within 20 minutes. Multi-point gas sampling systems validate inertization efficacy through: ① $O_2/CH_4/CO$ ratio analysis: Target thresholds: O_2 <7%, CH_4 >30%, CO <50 ppm; ② Isotope tracers: SF_6 injected with N_2 quantifies leakage rates; concentrations >10^{-9} vol% trigger seal repairs.

CFD simulations reveal that seam orientation critically influences gas distribution. In steeply inclined seams (>25), CO_2 migrates downward, accumulating in lower goaf sections, while N_2 rises toward upper fractures. Regardless of inclination, nitrogen reduces oxidation zone area by 10–15% more than CO_2 in shallow seams (<300 m), but CO_2 prevails in deep,

high-gas goafs.

4.5 Field Validation: Yaoqiao Mine 7271 Goaf

Implementation in a narrow-pillar compound goaf (7269 and 7271 goafs) demonstrated: ① At 750 m^3/h CO_2 injection from intake side, O_2 concentrations decreased from 18.2% to 5.7% within 4 hours, with oxidation zone width shrinking from 26.2 m to 18.5 m. ② Coal pillar oxidation width reduced from 3.77 m to 1.76 m, enhancing O_2 isolation. ③ CO_2 exhibited wider diffusion along the strike (72 m range) than dip direction (38 m), effectively suppressing O_2 ingress from adjacent goafs.

Post-injection, drainage concentrations stabilized at 35–38% with no spon-com indicators (C_2H_4 or HCHO) detected over 12 months—validating the dual-functional control efficacy.

5 Pressure Balance Optimization

5.1 Fundamental Principles and Critical Parameters

Pressure balance in goafs aims to eliminate oxygen intrusion by minimizing pressure differentials between working faces and adjacent goaf zones. The core parameter is the pressure gradient (ΔP), with field studies confirming that maintaining $\Delta P \leqslant 50$ Pa suppresses leakage velocities below 0.1 m/s—the threshold for sustaining coal oxidation. This equilibrium is governed by:

$$\Delta P = P_{face} - P_{goaf} = RQ^2 + Hn$$

Where R denotes ventilation resistance (Ns^2/m^8), Q airflow (m^3/s), and Hn natural wind pressure (Pa). Key influencing factors include: ① Seam inclination: Steep seams (>25) induce buoyancy-driven flows, requiring ΔP adjustments of 15–20% to counteract gas stratification. ② Multi-goaf interactions: Overlying goafs (e.g., at 25–35 m above the working seam) exert additional pressure through interconnected fractures, necessitating cascaded regulation to balance pressures across layers. ③ Atmospheric fluctuations: Diurnal barometric changes (±200 Pa) trigger "breathing effects" in sealed goafs, exacerbating O_2 ingress during low-pressure cycles (Table 7)[10].

Table 7 Key Control Parameters for Pressure Balance

Parameter	TargetValue	FunctionalRole
Goaf-Face ΔP	⩽50 Pa	Prevents O_2 intrusion velocity >0.1 m/s
Regulator Response	<2 min	Counters atmospheric fluctuations
N_2 Curtain Velocity	>3 m/s	Blocks airflow in roadways ⩾90% width
Asphyxiated Zone	>60% goaf volume	Maintains O_2 <7% via inert gas accumulation

5.2 Dynamic Balance Control Systems

Automated pressure regulation integrates real-time monitoring with actuation systems to maintain ΔP thresholds: ① Differential pressure sensors mounted on seals detect pressure deviations >±20 Pa, triggering PLC-controlled responses within 15 s. ② Dual-action pneumatic actuators adjust ventilation dampers or nitrogen valves: When ΔP > +50 Pa goaf overpressure, extraction pipelines open to vent CH_4, preventing gas exceedance. When ΔP < -30 Pa goaf underpressure, N_2 injection lines activate, injecting nitrogen at 0.15–0.20 m^3/min to create positive pressure and reverse leakage direction.

Nitrogen curtain technology establishes active barriers in intake/return roadways. Optimized configurations achieve: ① Flow velocity >3 m/s across 90% of roadway cross-sections, reducing oxygen influx by 85%. ② Directional injection via slotted pipes (aperture ratio: 0.6–0.8), ensuring coverage depths >15 m into fracture zones.

Field trials at Laiyegou Mine demonstrated that combining automated ΔP control with N_2 curtains reduced CO emissions from 120 ppm to undetectable levels within 72 hours, while stabilizing the asphyxiated zone at 65% of goaf volume.

5.3 Multi-Goaf Coordinated Pressure Regulation

In overlapping goafs (e.g., shallow multi-seam mines), cascaded pressure management synchronizes controls across layers: ① Upper goaf depressurization: Extract gas from overlying goafs using surface wells, creating negative pressure (-100 to -300 Pa) to contain gases within upper voids. ② Working face compensation: Deploy local fans with frequency converters to dynamically adjust face pressure, offsetting influences from upper goafs. CFD simulations at Chahasu Mine revealed that maintaining a pressure gradient ratio of 0.8 – 1.2 induces gas self-circulation within goafs, preventing interlayer mixing.

Mathematical optimization employs Darcy's law for porous media flow:

$$\nabla \cdot \left(\frac{k}{\mu} \nabla P \right) = 0$$

Where k is permeability (mD) and μ gas viscosity (Pa·s). Solving this with boundary conditions from goaf geometry yields optimal fan frequencies and damper angles, achieving ΔP stability within ±5%.

5.4 Field Implementation and Validation

5.4.1 Sitai Mine (Shallow Multi-Goaf)

Challenge: Interconnected goafs caused O_2 leakage >8% and CH_4 migration into active faces. Solution: Installed adjustable regulators in return airways and surface grouting (cement-fly ash) to seal overburden fractures. N_2 curtains (velocity: 3.2 m/s) were activated in intake tunnels. Outcome: Reduced ΔP from 126 Pa to 10 Pa, eliminating CO emissions and sustaining gas drainage at 38% purity over 12 months.

5.4.2 11501 Goaf (Deep High-Stress Mine)

Challenge: Mining at 650 m depth induced stress fractures, increasing leakage to 300 m^3/min. Solution: Deployed positive-pressure chambers with 180 Pa N_2 overpressure, coupled with automated extraction-balance valves. Outcome: O_2 concentration dropped from 19.2% to 4%, with ΔP stabilized at 10 Pa—validated by SF_6 tracer tests showing leakage reduction from 5%/h to 0.8%/h(Table8).

Table 8 Performance Metrics of Pressure Balance Systems

Indicator	Pre-Implementation	Post-Implementation	Improvement
O_2 Concentration	18.2–19.2%	4.0–5.7%	70–78% reduction
Leakage Velocity	0.25–0.40 m/s	<0.08 m/s	>68% reduction
Response Time	>120 min (manual)	<2 min (auto)	98% faster
Spon-com Incidents	3–5/year	0 over 18 months	100% elimination

5.5 Integrated Protocol for Hazard Control

There are four steps. Step 1: Baseline assessment: Map fracture networks using SF_6 tracer tests and UAV thermal imaging. Establish ΔP monitoring points at 20 m intervals along seals. Step 2: System commissioning: Install frequency-convertible fans and N_2 injection arrays. Set ΔP thresholds: +50 Pa (extraction trigger), -30 Pa (N_2 injection trigger). Step 3: Dynamic optimization: For multi-goaf systems: Prioritize upper-layer depressurization before face compensation. During periodic weighting: Increase N_2 curtain velocity by 20% to counter fracture expansion. Step 4: Long-term management: Quarterly pressure decay tests (R < 3%/24 h required). Material degradation audits (grout strength loss <0.5 MPa/year).

6 Field Application and Validation

6.1 Pingdingshan High-Gas Goaf with Spon-com Risk

Geological Context: The Pingdingshan mining area (depth: 650 m; gas content: 12.8 m^3/t; coal seam thickness: 3.5 m) exhibited dual hazards: CH_4 accumulation >30% in oxidation zones and CO emissions peaking at 540 ppm, indicating active spon-com reactions.

Integrated Technical Scheme: ①Composite Sealing: Deployed 5 m-thick polyurethane foam (PUF) bag-walls in intake/return roadways, with surface overburden grouting (cement-fly ash ratio 1:0.8). PUF achieved 4B adhesion grade (coal detachment <4%) and oxygen index of 29.2% via 21 wt% retardant 8316 additive. ②Alternating Inertization: Cyclic N_2 injection (0.9 MPa, 50 h) followed by liquid CO_2 pulses (750 m^3/h, 8 h) targeting oxidation zones identified by fiber-optic thermal sensors. ③Pressure Balance: Installed adjustable regulators in return airways and nitrogen curtains (velocity 3.5 m/s), limiting goaf-face ΔP to 15±3 Pa.

Performance Metrics (18-month monitoring): ①CO emissions reduced by 78% (120 ppm → 26 ppm), with zero spon-com incidents. ②Gas drainage concentration stabilized at 38–42%, extraction volume increased 2.1×. ③SF_6 tracer tests confirmed leakage rate <0.6%/year, meeting integrity targets(Table 9).

Table 9 Key Performance Indicators at Pingdingshan Site

Parameter	Pre-Treatment	Post-Treatment	Improvement
O_2 in Oxidation Zone	18.5%	5.2%	72% reduction
CH_4 Drainage Purity	<15%	38–42%	2.1× increase
Leakage Velocity	0.32 m/s	0.07 m/s	78% reduction
Seal Degradation	>5%/year	<0.6%/year	88% slower

6.2 Yangquan Multi-Goaf Interaction Scenario

Challenge: Overlapping goafs at Laiyegou Mine induced cross-layer gas migration (O_2 leakage >8% to lower seams) and pressure fluctuations up to ±200 Pa from atmospheric "breathing effects".

Innovative Solutions: ① Cascaded Pressure Control: Upper goaf depressurized to -250 Pa via surface wells, while working face fans adjusted dynamically (pressure gradient ratio ΔP_upper/ΔP_lower = 0.9). ② Automated Sealing: Deployed hydraulic-activated bag-wall systems with embedded hinges, achieving <2 min response to ΔP >50 Pa deviations. ③Two-Phase Foam Backup: Injected polymer foam (expansion ratio 10×) into newly formed fractures during periodic weighting, maintaining pressure tolerance >600 Pa.

Outcomes: ① Asphyxiated zone expanded to 68% of total goaf volume, suppressing oxidation hotspots. ② Main fan energy consumption reduced by 15% through optimized ventilation resistance.

6.3 Shallow Coal Seam with Water Inundation

Site Specificity: Shendong mining area (depth <300 m, water inflow >30 m^3/h) faced liquid CO_2 dilution issues, reducing O_2 displacement efficiency by 40%.

Adaptive Modifications: ① Hydrophobic Sealants: Used fly ash-cement composites with Talbot index *n* =0.5 for graded compaction, reducing permeability by 35% in water-rich zones. ② CO_2-N_2 Synergy: Injected liquid CO_2 (-25°C) for rapid cooling, followed by N_2 purging to maintain drainage efficiency; cycle ratio adjusted to 1:2 (CO_2:N_2). ③ Water-Pressure Equilibrium: Designed positive-pressure chambers with 180 Pa N_2 overpressure, reversing flow direction to prevent water seepage into seals.

Validation Data: ① CO_2 diffusion range extended to 72 m along strike (vs. 38 m in dry goafs), enhancing inert gas coverage. ② No seal degradation detected after 12 months in humid conditions—exceeding conventional cement grouts' lifespan by 3×.

7 Conclusion

This study establishes an integrated technical framework for synergistic gas and spontaneous combustion prevention in goaf areas, yielding four principal conclusions: (1)Hazard Coupling Mechanism Quantification: Competitive adsorption dynamics (O_2 > CH_4 > N_2 affinity) and fracture-mediated gas migration (permeability anisotropy >5.8) drive compound disasters, with field data confirming temperature escalation rates >1.5 C/h in high-gas goafs—3× faster than gas-free environments. (2)Engineering Parameter Optimization: Alternating inertization protocols (N_2: 0.8–1.2 MPa × 48 h; CO_2: 750 m^3/h × 6–8 h) combined with pressure balance thresholds ($\Delta P \leqslant 50$ Pa, N_2 curtain velocity >3 m/s) simultaneously achieve O_2 <7% and CH_4 >30%, resolving the gas-spon-com control conflict. (3)Field Validation Efficacy: 18-month trials demonstrated 78% CO reduction (120→26 ppm), zero spon-com incidents, and sustained gas drainage at 38–42% purity, with composite sealing exhibiting <0.8%/year degradation—surpassing conventional methods by >80% in leakage control. (4)Technical Limitations: Current constraints include compromised seal integrity under ultra-deep conditions (> 1000 m, >25 MPa stress) reducing inert gas diffusion by 30–50%, and material longevity uncertainties in cyclic wet-dry environments accelerating grout strength loss by 1.2 MPa/year.

The Data Availability Statement

The datasets generated and analysed during the current study are available in Lin Wang at Intergrated Prevention of Gas and Spontaneous Combustion in Goaf Areas: Sealing Techniques, Inertization and Pressure Balance.

About the Author

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