An Integrated Strategy for Synergistic Control of Dust Emission and Spontaneous Combustion in Port Lignite Operations: Based on Physicochemical Characterization and CFD Simulation

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Abstract. Lignite, a major global dry bulk commodity, presents significant dual challenges of dust emission and spontaneous combustion during port operations, severely impacting safety and environmental sustainability. This study proposes an integrated strategy for the synergistic control of these risks. Initially, detailed physicochemical characterization (particle size distribution, proximate analysis, and minimum ignition temperature) was performed on 10 representative lignite samples, elucidating their distinct dust emission and spontaneous combustion propensities. Subsequently, Computational Fluid Dynamics (CFD) simulations were utilized to simulate wind speed gradients across port stockyards under seasonal conditions, thereby delineating high, medium, and low wind speed zones. Building on these insights, a novel "three-dimensional integrated" prevention and control strategy was devised. This strategy comprises: (1) optimized zoned storage based on port wind field characteristics, prioritizing high-risk lignite in low wind speed areas; (2) precise moisture content regulation via humidification during dynamic operational phases, circumventing conventional water spraying drawbacks; and (3) synergistic optimization of stack morphology and environmental conditions during static storage. This comprehensive strategy achieves source-level control and full-chain synergistic management of lignite dust emission and spontaneous combustion risks. This research provides a scientific basis and practical paradigm for domestic ports and contributes innovative solutions for the sustainable development of international dry bulk ports.

1 Introduction

Currently, China's proven lignite reserves exceed 130 billion tons, accounting for approximately 13% of the nation's total coal reserves[1]. Northeastern Inner Mongolia represents China's largest lignite production base. Influenced by variations in primary coal-forming materials and depositional environments, lignite from different geological ages exhibits substantial variations in coal quality characteristics. Nevertheless, several common features generally characterize lignite: a low degree of coalification, with an average volatile matter content of 45.21%; high moisture content, often exceeding 30%; abundant humic acids and montan waxes, with oxygen content ranging from 20-30%; high ash content, with dry basis ash typically between 10-30%. Furthermore, due to the presence of certain minerals like iron and alkali metal oxides, lignite ash generally has a low melting point. Its porous structure is well-developed, exhibiting a continuous distribution from micropores to macropores[2]. These distinctive physicochemical properties render lignite highly susceptible to dust pollution during port handling, horizontal transport, and storage, due to external factors such as wind and vibration. Concurrently, its low ignition point, high volatile matter content, and moderate moisture levels make it prone to spontaneous combustion during storage, leading to the emission of harmful gases and imposing considerable pressure on port environmental protection.

Lignite dust emission is a phenomenon where airflow near the material pile transports bulk particles[3]. When wind forces become sufficient to induce vectorial displacement of bulk particles on the pile surface, dust particles detach from their static state, become entrained in the airflow, and drift into the atmosphere.

The forces acting on dust particles in the atmosphere are highly complex. While various micro-scale forces (such as virtual mass, Magnus, Saffman, Basset, and photophoresis) contribute to particle dynamics, the primary drivers for dust transport in port environments are typically gravitational force, gas drag force, and particle impact forces[4]. Dust emission from stockyards primarily depends on wind speed magnitude and the associated turbulence intensity. As airflow passes over coal piles and the undulating, irregular surfaces of stockyards, it generates highly intricate wind speed gradient fields and rotational fields. This results in the stockyard being filled with vortices of varying scales and turbulence intensities. Under the impetus of strong winds and the suction effect of intense vortex fields, bulk materials become entrained

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in the airflow, subsequently drifting downstream and undergoing diffusion due to strong turbulence. Once the dust-laden airflow traverses the stockyard area, wind speed diminishes, turbulent kinetic energy decreases, and the relative influence of gravity increases, leading to the progressive settling of dust[5].

2 Materials and Methods

2.1 Lignite Sample Sources

This study selected 10 representative lignite types from various port areas within the Liaoning Port Group to ensure broad representativeness of the samples. The primary origins of these samples include Indonesia, Zhalainuoer in Inner Mongolia, among other locations. Specifically, six samples were obtained from Bayuquan Port Area (designated as Yingkou 01-06), two from Dalian Bay Port Area (Dalian 01-02), one from Dadong Port Area (Dandong 01), and one from Rongxing Port Area (Panjin 01). These samples encompass lignite from diverse geographical origins and with varied physicochemical properties, which is crucial for comprehensively assessing their risk behavior in port environments.

2.2 Physicochemical Characterization

The particle size distribution of lignite samples was determined using a sonic vibration automatic sieving particle size analyzer (Model SFY-D, Dongfang Huabo Technology Co.,.Ltd). Sieves conformed to GB/T 6003.1-2022. Experimental operations strictly followed the instrument's user manual, with a set vibration frequency of 50 Hz and a single sample sieving duration of 15 min. Industrial characteristics (proximate analysis) were measured using an intelligent disc ash content analyzer (TY-GHF, Hebi Tianqi Instrument and Meter Co., Ltd.) and a carbon-hydrogen element analyzer (Vario EL III, Elementar), with methods conforming to GB/T 212-2008. The Minimum Ignition Temperature was determined using an imported LIT 400 dust layer minimum ignition temperature tester from ADISN Company, with all operations conducted in strict accordance with GB/T 18511-2017.

2.3 Numerical Simulation Analysis

This study leveraged Computational Fluid Dynamics (CFD) numerical simulations to quantitatively analyze the wind speed attenuation patterns and flow field distribution characteristics within lignite stockyards across various port areas of Liaoning Port Group, considering the complex interplay between coal piles and the installed windbreak-dust suppression net systems. The following details core modeling methodologies and parameter specifications to ensure scientific rigor and experimental reproducibility. The simulations utilized a 1:1 scale rectangular computational domain, where geometric models of lignite piles, windbreak-dust suppression nets, and other structures were precisely constructed according to actual dimensions. Structured hexahedral grids were employed, with local refinement applied to regions experiencing significant airflow disturbance, followed by mesh independence verification. The mesh sizes for each port area were controlled between 1.82 million and 2.15 million elements, balancing simulation accuracy with computational efficiency. The RNG k-ε turbulence model, adapted for the high-turbulence, complex flow fields prevalent in port areas, was adopted, with solutions obtained through RNG transport equations. The inlet turbulence intensity was set at 15%, and the turbulent length scale was calibrated against measured topographical roughness for each port area. Boundary conditions were strictly defined according to established norms: the inlet was set as a velocity inlet, with a velocity profile fitted by a combined logarithmic and power law, and roughness lengths for Bayuquan, Dalian Bay, Dadong, and Rongxing port areas were 0.03m, 0.025m, 0.035m, and 0.028m, respectively. The outlet was defined as a natural outflow boundary with a relative pressure of 0 Pa. Lateral and top boundaries were set as symmetry boundaries to simulate an infinite atmospheric space. Ground surfaces, buildings, and coal piles were treated as no-slip boundaries, complemented by wall functions for near-wall treatment. Windbreak nets were modeled as porous media boundaries, with relevant parameters calibrated through on-site wind speed measurements. Meteorological boundary conditions were derived from long-term statistical data (2019) from nearby meteorological stations for each port area, covering typical wind conditions across all seasons, thereby fully aligning with actual port operational environments.

2 Results and Discussion

2.1 Physicochemical Characteristics of Lignite Samples

2.1.1 Particle Size Characteristics Analysis and Dust Emission Propensity

The particle size distribution characteristics of the 10 lignite samples are presented in Table 1. Generally, smaller coal dust particle sizes lead to greater ease of entrainment and dispersion under wind erosion and mechanical disturbance, and they remain suspended in the air for longer durations[6,7]. As shown in Table 1, the mass fraction of fine particles with diameters less than 63 μm, a critical indicator for inhalable dust, fluctuated between 0.07% and 0.92%. This directly reflects the potential dust hazard of different lignite samples.

The analysis results indicate that sample Dalian 01 exhibits the highest mass fraction of ultrafine dust (0-63 μm) at 0.92%, followed by Yingkou 01 (0.34%) and Yingkou 02 (0.31%). This suggests that samples Dalian 01, Yingkou 01, 02, 04, 06, and Dandong 01 have a higher propensity for dust emission under identical wind speeds and operational disturbances. Conversely, Dalian 02 and Yingkou 03 show consistently lower fine particle content across all size ranges, indicating a relatively lower dust emission risk.

Table 1. Proportion of each particle size range of lignite samples (%)

Sample	≥ 2000	1000~2000	500~1000	355~500	250~355	180~250	125~180	63~125	0 ~63
Y01	79.3	8.2	5.7	2.3	1.7	0.8	0.8	0.7	0.3
Y02	80.5	8.6	5.8	1.9	1.2	0.6	0.5	0.5	0.3
Y 03	90.0	6.2	2.7	0.6	0.3	0.1	0.1	0.1	0.1
Y04	74.6	11.7	7.1	2.2	1.5	0.8	0.7	0.7	0.6
Y05	83.2	8.8	4.1	1.5	0.9	0.3	0.5	0.4	0.2
Y06	79.2	10.9	6.0	1.7	1.0	0.5	0.3	0.3	0.3
D 01	76.8	9.0	5.8	2.4	1.7	1.1	1.2	1.1	0.9
D02	90.7	5.2	2.4	0.7	0.4	0.1	0.2	0.1	0.1
DD01	78.0	9.4	6.5	2.3	1.7	0.6	0.7	0.5	0.3
P01	81.2	10.2	4.6	1.4	0.9	0.5	0.4	0.4	0.3

Note: Y = Yingkou; D = Dalian; DD = Dandong; P = Panjin.

2.1.2 Proximate Analysis and Spontaneous Combustion Tendency

The results of the proximate analysis for the 10 lignite samples are detailed in Table 2. These industrial characteristics are crucial indicators for assessing both the spontaneous combustion tendency and dust emission risk of lignite.

Typically, higher ash content can potentially reduce coal hardness and toughness, making it more prone to generating fine particles during crushing and friction, thereby increasing its dust generation potential[7,8]. From Table 2, it is evident that samples Yingkou 01-06 generally exhibit high ash content (13.90%~20.70%), exceeding that of Dalian 01, 02, Dandong 01, and Panjin 01 (3.84%~4.85%). However, the influence of ash content on dust generation is not a singular factor but requires comprehensive assessment in conjunction with particle size distribution. For instance, despite the high ash content of Yingkou samples, if their original particle size distribution contains a low proportion of fine particles (e.g., Yingkou 03), their actual dust emission risk might be lower than that of low-ash but high-fine-particle content samples (e.g., Dalian 01). This explains potential apparent discrepancies between particle size and ash content analyses and underscores the necessity of a holistic risk assessment.

Table 2. Analysis results of industrial characteristics of lignite samples (%)

Sample	Moisture (Mad)	Ash (A)	Volatile Matter (V)	Fixed Carbon (FC)	Minimum Ignition Temperature (°C)
Y 01	10.59	15.56	30.94	42.91	435.6
Y 02	9.18	16.68	30.34	43.8	432.2
Y 03	11.96	13.9	31.1	43.04	375.1
Y 04	10.44	18.33	30.54	40.69	445.0
Y 05	11.77	14.52	31.02	42.69	426.6
Y 06	9.02	20.7	30.41	39.87	446.7
D 01	13.02	4.85	38.99	43.14	375.2
D 02	12.84	4.5	39.93	42.73	241.8
DD 01	10.22	3.84	45.64	40.3	442.8
P 01	19.55	4.6	40.83	35.02	428.5

Note: Y = Yingkou; D = Dalian; DD = Dandong; P = Panjin.

Higher degrees of coalification, corresponding to greater fixed carbon content, typically correlate with higher characteristic temperatures and activation energies, indicating a lower propensity for spontaneous combustion[9,10]. Concurrently, complex relationships exist between moisture, ash, volatile matter content, and spontaneous combustion activation energy. In terms of fixed carbon content, Yingkou 01-06 (39.87%~43.80%) and Dalian 01-02 (42.73%~43.14%) are relatively high, while Dandong 01 (40.30%) and Panjin 01 (35.02%) are relatively low. Considering the volatile matter content (Dandong 01 at 45.64% and Panjin 01 at 40.83%, both higher than other samples), the preliminary order of spontaneous combustion propensity can be determined as: Panjin 01 ≈ Dandong 01 > Dalian 01 ≈ Dalian 02 > Yingkou 01-06. Higher volatile matter content implies more active functional groups, which are more susceptible to oxidation reactions and heat release; conversely, lower fixed carbon content indicates a lower degree of coalification and poorer oxidative stability.

The Minimum Ignition Temperature serves as a direct and indispensable parameter for quantifying the intrinsic thermal stability and spontaneous combustion susceptibility of lignite, where lower values signify higher intrinsic risk. Our findings reveal Dalian 02 possesses an exceptionally low MIT of 241.8°C, dramatically elevating its spontaneous combustion propensity beyond predictions from proximate analysis alone. Yingkou 03 (375.1°C) and Dalian 01 (375.2°C) also exhibit moderate to high risk. Notably, Panjin 01 and Dandong 01, despite high volatile matter, show higher MITs (428.5°C, 442.8°C), indicating greater resistance to initial ignition, which refines our preliminary assessment. Considering all these factors, the revised order of spontaneous combustion propensity is more accurately represented as:

Dalian 02 >> Yingkou 03 ≈ Dalian 01 > Panjin 01 ≈ Dandong 01 > other Yingkou samples.

2.2 Port Wind Field Optimization and Zoned Storage Strategy

To achieve source-level control of lignite dust emission and spontaneous combustion risks, this study conducted a detailed characterization of the wind field environment in the stockyards of various Liaogang Group port areas, leveraging CFD numerical simulations. By considering seasonal dominant wind field characteristics and the attenuation effect of multi-stack interference on the stockyard flow field, a three-dimensional flow field model was constructed. This model allowed for a qualitative analysis of the wind speed gradient distribution characteristics within the stockyard under the shielding effect of windbreak-dust suppression nets, as illustrated in Figure 1.

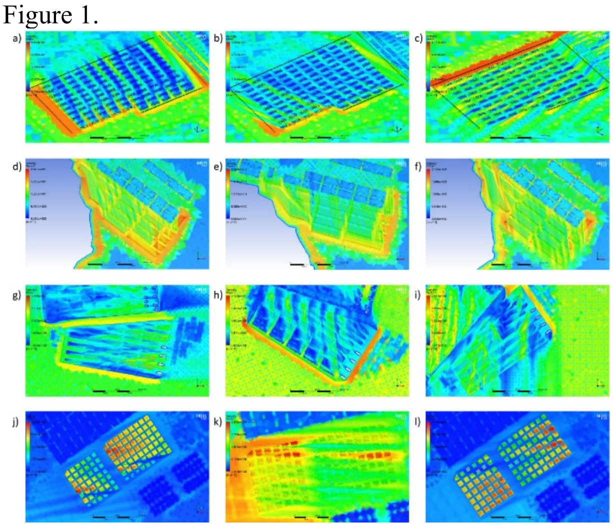

Fig. 1.. Characteristics of Wind Speed Gradient Distribution in Various Port Stockyards (a~c: Bayuquan Port Area in Spring, Summer, and Autumn/Winter; d~f: Dalian Bay Port Area in Spring, Summer, and Autumn/Winter; g~i: Dadong Port Area in Spring, Summer, and Autumn/Winter; j~l: Rongxing Port Area in Spring, Summer, and Autumn/Winter)

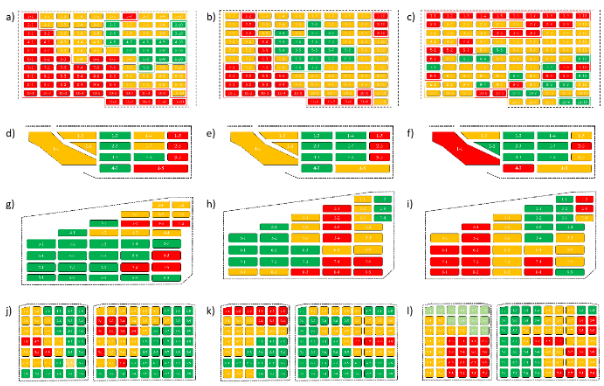

Fig. 2. High, Medium, and Low Wind Speed Zones in Various Port Stockyards (a~c: Bayuquan Port Area in Spring, Summer, and Autumn/Winter; d~f: Dalian Bay Port Area in Spring, Summer, and Autumn/Winter; g~i: Dadong Port Area in Spring, Summer, and Autumn/Winter; j~l: Rongxing Port Area in Spring, Summer, and Autumn/Winter)

Taking the Bayuquan Port Area as an example, under typical meteorological conditions in spring (Figure 1 a), the southwest region of the stockyard exhibits higher wind speeds. Wind speeds transition and decrease in the northwest, northeast, and southeast regions, with the lowest wind speed observed in the central eastern area. Based on the numerical simulation results, the stockyard was divided into three wind speed zones—high, medium, and low—according to actual stack dimensions. Red represents areas with higher wind speeds, yellow indicates transitional areas with reduced wind speeds, and green denotes areas with the lowest wind speeds. The high, medium, and low wind speed zones for each port area are shown in Figure 2.

This refined wind speed zoning is the core basis for the "zoned storage in low wind speed areas" strategy proposed in this paper. We prioritize the storage of lignite with high spontaneous combustion propensity (e.g., Dalian 02, Yingkou 03, Dalian 01, which consistently show lower MIT values) and high dust emission propensity (e.g., Dalian 01, Yingkou 01) in low wind speed zones. This measure reduces the driving force of wind on dust particle dispersion, thereby decreasing dust concentrations in the operational environment. Concurrently, a low wind speed environment can, to some extent, reduce the oxygen supply rate to the coal pile surface, decelerate the lignite oxidation exothermal process, and aid in inhibiting the occurrence of spontaneous combustion. For medium to high wind speed zones, coal types with relatively lower dust emission and spontaneous combustion risks can be stored, or more stringent and proactive auxiliary prevention and control measures can be implemented.

2.3 Precise Moisture Content Regulation during Dynamic Operational Phases

During dynamic lignite operations in ports particulate matter is highly prone to instantaneous dust generation due to mechanical disturbances. This study innovatively proposes advancing the moisture content enhancement points to these dynamic operational phases, employing precise regulation to achieve synergistic control of dust and spontaneous combustion, thereby circumventing the spontaneous combustion risks potentially induced by crude water spraying during traditional static storage.

In the dynamic operational processes of lignite, precise and uniform water spraying or misting is applied to the lignite surface through advanced technical means such as mobile intelligent mist dust suppression funnels, mobile windproof spray dust suppression funnels, dust suppression water cannons, and dust suppression sprays at conveyor belt transfer points. This increases the cohesion of coal particle surfaces, inhibiting the dispersion of fine particulate dust and reducing PM_{10} and $PM_{2.5}$ concentrations in the operational environment. Compared to conventional water spraying, these refined devices ensure uniform moisture coverage and appropriate penetration, avoiding localized over-wetting.

The uniform humidification during dynamic operations helps agglomerate fine particles, reducing the total reactive surface area of lignite, thereby lowering its initial oxidation activity and delaying the exothermic process.

Unlike the potentially crude water spraying that might occur during static storage, the "micro-mist" or "spray" application during dynamic operations aims to provide an appropriate and uniform amount of moisture, ensuring that the water primarily remains on the coal particle surface, preventing localized moisture enrichment and deep penetration into the pile. This avoids anaerobic spontaneous combustion (hydrolytic oxidation) or corrosion risks that might be induced by moisture penetration, as well as the problem of exacerbated spontaneous combustion when the pile re-dries after moisture evaporation carries away heat. A moderate increase in initial moisture content also elevates the latent heat of vaporization required for lignite to rise from ambient to spontaneous combustion temperature, objectively extending the induction period for spontaneous combustion, especially for those with lower intrinsic thermal stability as indicated by MIT, thus gaining valuable time for subsequent static management. Through these refined moisture content regulation measures, this study achieves effective dust suppression while minimizing negative impacts on spontaneous combustion risk, demonstrating the synergistic advantage of a "dual-control" strategy.

2.4 Synergistic Optimization of Stack Morphology and Environmental Conditions during Static Storage

For lignite that has completed dynamic operations and entered the static storage phase, dust risk primarily originates from wind erosion, while spontaneous combustion risk mainly stems from slow oxidative heat accumulation within the coal pile. This study proposes the following optimized management measures for static stacks to achieve synergistic control of these two major risks (Table 3). These measures, by combining physical, chemical, and managerial approaches, establish a multi-layered risk barrier.

In summary, the integrated synergistic prevention and control strategy for port lignite dust emission and spontaneous combustion constructed in this study, through its three main pillars—"port wind field optimization and zoned storage, precise moisture content regulation during dynamic operational phases, and synergistic optimization of stack morphology and environmental conditions during static storage"—achieves full-chain, multi-dimensional risk management from macroscopic layout to microscopic operation, and from dynamic processes to static storage. This strategy fully utilizes the synergistic effects between various measures, avoiding potential negative impacts of single measures, and provides a scientific and feasible optimization path for the safe and efficient operation of port lignite.

Table 3. Optimized management measures for stacks during static storage

	Spontaneous Combustion Control	Dust Control
Regular Compaction	Reduces internal void space within the coal pile, limiting oxygen penetration depth, thereby inhibiting the rate of oxidation reactions and reducing heat accumulation.	Densifies the pile surface, increases cohesion between coal particles, enhances the pile's resistance to wind erosion, and reduces wind-induced dust generation.
Low-Angle Stacking	Optimizes heat dissipation conditions on the pile surface, promoting heat release and reducing internal heat accumulation; facilitates rapid rainwater runoff, preventing moisture infiltration into deeper layers that could trigger anaerobic spontaneous combustion.	Forms a gentler pile surface, reducing wind resistance and localized turbulence, diminishing wind erosion areas and wind shear forces, thereby reducing dust emission.
Reduced Storage Duration	Decreases the duration of coal exposure to an oxidative environment, lowering the risk of heat accumulation.	Shortens the time coal piles are exposed to wind erosion, reducing the likelihood of wind-induced dust generation.
Application of Inhibitors	Inhibits low-temperature oxidation reactions of lignite through chemical or physical action, forming a protective layer to isolate oxygen or passivating active functional groups, fundamentally delaying the spontaneous combustion process.	Some inhibitors possess film-forming and binding properties, which can assist in enhancing surface stability of the pile.
Application of Dust Suppressants	Forms a tough film or cohesive layer on the coal pile surface, binding surface particles and increasing the threshold wind speed for dust generation, suppressing wind erosion dust.	The formed physical barrier can, to some extent, prevent oxygen-coal contact, assisting in inhibiting oxidation reactions.
Covering with Film	Completely covers coal piles with professional dustproof film materials, thoroughly isolating wind erosion and fundamentally eliminating wind-induced dust.	Completely blocks oxygen supply, inhibiting oxidation reactions; simultaneously prevents rainwater infiltration, avoiding moisture-induced spontaneous combustion risks.
Ancillary Management	Establishes an institutionalized risk assessment system, implements zoned storage management, deploys real-time monitoring systems (temperature, gas composition, wind speed, etc.), and formulates comprehensive emergency response plans to ensure all measures work synergistically, comprehensively reducing overall risks.	

4 Conclusions

This study comprehensively addressed the coupled risks of dust emission and spontaneous combustion in port lignite operations by integrating systematic physicochemical characterization, Computational Fluid Dynamics (CFD) simulation, and the development of a holistic control strategy. The key findings are summarized as follows:

(1) Detailed physicochemical analysis of ten representative lignite samples from the Liaogang Group revealed significant variations in their dust emission and spontaneous combustion propensities. Lignite samples with higher fine particle content exhibited greater dust emission risks. Crucially, the measured Minimum Ignition Temperature (MIT) values provided direct insights into the intrinsic thermal stability, with Dalian 02 exhibiting an exceptionally low MIT of 241.8°C, highlighting a paramount spontaneous combustion hazard.

(2) CFD simulations accurately characterized seasonal wind fields across various port yards, quantifying the mitigating effects of wind fences and precisely delineating high, medium, and low wind speed zones. This critical insight informed a novel zoned storage strategy, prioritizing the allocation of lignite identified with high spontaneous combustion propensity (particularly those with lower MIT values like Dalian 02, Yingkou 03, and Dalian 01) and high dust emission propensity to low wind speed areas. This approach achieves synergistic source control for both risks while optimizing the spatial utilization of yard resources.

(3) In dynamic operational phases, advanced technologies such as smart mist and spray funnels enabled precise moisture content regulation. This suppresses instantaneous dust generation while concurrently avoiding the aggravated spontaneous combustion risks often associated with traditional, indiscriminate bulk watering. For static storage, a multi-faceted approach involving optimized pile morphology, physical covering, and enhanced auxiliary management established a comprehensive physical and chemical defense system against both dust emission and spontaneous combustion throughout the entire operational chain.

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