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Nitrogen Fire Supression for Cold Storage ASRS Using PSA System

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ABSTRACT: In modern cold-storage warehouses equipped with automated storage and retrieval systems (ASRS), the risk of fire is elevated due to tightly packed racks, flammable packaging materials and the presence of electrical or automation equipment in low-temperature dry atmospheres. This paper investigates the implementation of a continuous inert-gas purging system using nitrogen produced on-site via a pressure-swing-adsorption (PSA) nitrogen generator. The objective is to maintain the oxygen concentration in the storage zone below the ignition threshold 16 % O_2. The system comprises real-time oxygen monitoring, automatic nitrogen injection, integration with the ASRS environment, and evaluation through metrics such as oxygen concentration stability, nitrogen consumption, thermal/ignition modelling and fire-risk reduction. Results show that maintaining oxygen at 13.5–15.5 vol % reduces the potential for flash-over by an order of magnitude compared to 19.5 -23.5 % ambient air of O_2 and that on-site PSA generation is cost- effective versus cylinder supply in continuous operation. The discussion covers system design, control strategies, cold-storage temperature/volume effects, safety for personnel, maintenance issues and integration with ASRS operations. The paper concludes that continuous nitrogen purging using PSA nitrogen generation in automated cold-storage facilities offers a viable proactive fire-prevention strategy and outlines recommendations for implementation.

KEYWORDS: Nitrogen Purging, PSA Nitrogen Generation, Oxygen Reduction System, Cold Storage Automated Storage and Retrieval System (ASRS), Inert-Gas Fire Suppression.

I. INTRODUCTION

Fire is the visible result of the combustion process, which is a rapid, high-temperature exothermic (heat-releasing) chemical reaction between a fuel (the substance that burns) and an oxidant (usually oxygen in the air). For combustion to occur and be sustained, three essential elements must be present simultaneously, a concept often referred to as the "fire triangle" fuel, oxygen, and sufficient heat to reach the fuel's ignition temperature.

The process begins with an ignition source, such as a spark or a flame, which provides the initial energy to heat the fuel to its ignition point. For solid and liquid fuels, this heat causes them to break down into combustible vapours or gases through a process called pyrolysis or vaporization. These volatile gases then mix with the surrounding air's oxygen. Once the correct fuel-to-oxygen ratio and sufficient temperature are achieved, the mixture ignites, forming a flame. The design of a firefighting system considers numerous factors, including building occupancy, hazard classification, fire load, operational requirements, and environmental conditions, ensuring that each installation is tailored to address the unique risks of the specific site. In modern industrial, commercial, and residential developments, firefighting systems function as an essential component of risk management strategies, offering comprehensive protection and enhancing the overall resilience of the built environment. one-term asset protection.

1.2 Research Gap

Conventional deep cold storage facilities with dense material congestion face significant fire- safety challenges due to limited accessibility, poor airflow, and obstructed suppression agent distribution. In traditional cold storage, goods are typically stacked manually or using forklifts, resulting in irregular pallet alignment, blocked aisles, and uneven material height—all of which hinder effective fire detection and suppression. Water-based systems such as sprinklers often struggle in such environments because sub-zero temperatures cause freezing risks, ice accumulation, and delayed heat activation. In congested layouts, sprinkler discharge patterns are obstructed by tightly packed boxes, shrink-wrapped

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pallets, and stacked goods, leading to shadow areas where water cannot penetrate. Likewise, gaseous suppression systems perform inadequately in these settings because the cluttered layout prevents uniform gas dispersion, while frequent door operation causes leakage and reduces concentration effectiveness. Smoke and heat detection are also compromised in conventional deep cold storage because thick stacking blocks detector line-of-sight and cold air stratification slows smoke movement. As a result, fire may grow unnoticed before suppression systems activate. When compared with an Automated Storage and Retrieval System (ASRS), conventional stacking lacks the controlled structure and uniform spacing necessary for efficient fire protection. ASRS introduces organized racking, predictable pallet placement, defined air channels, and automated material handling all of which support more consistent fire detection and suppression pathways. However, while ASRS improves stacking and accessibility, traditional fire-fighting systems still remain reactive and dependent on ignition. There is limited research on how fire- prevention techniques, such as continuous oxygen-reduction or inert-gas conditioning, could perform more effectively in an ASRS environment than in conventional congested facilities. Furthermore, few studies have analyzed how reorganized stacking patterns and increased vertical density in ASRS affect fire dynamics, smoke migration, and suppression efficiency. Thus, a key research gap exists in understanding how improved storage organization alone is insufficient without a fire-fighting system that prevents ignition altogether. This gap highlights the need to explore modern, proactive fire-prevention systems particularly those capable of maintaining a controlled atmosphere that inhibits combustion regardless of storage density or layout.

1.3Proposed Research Gap

The proposed fire-fighting system introduces a proactive, prevention-based method using continuous nitrogen gas purging integrated with an on-site PSA nitrogen generation unit to maintain a reduced-oxygen atmosphere within the cold storage ASRS facility. Instead of relying on traditional detection and suppression methods that only respond after a fire has begun, this system continually reduces the oxygen concentration to a level below the ignition threshold of common cold-storage materials typically maintaining oxygen levels between 14% and 16%, where combustion cannot be sustained. A PSA nitrogen generator provides a stable and uninterrupted supply of high-purity nitrogen, eliminating dependency on high-pressure cylinders and allowing long-term, energy-efficient operation. The nitrogen is distributed through a dedicated piping and diffuser network strategically installed within the ASRS racking system as shown figure 1.4 to ensure uniform atmospheric control across high-bay storage zones, including inaccessible rack locations where conventional suppression systems perform poorly. This closed-loop control ensures stable oxygen-reduction levels under all conditions, guaranteeing continuous fire prevention without the need for discharge, downtime, or system reset. The proposed system eliminates risks associated with freezing water lines, reduces equipment exposure to water or chemical agents, and allows normal ASRS operations to continue uninterrupted. Moreover, the solution is environmentally friendly, relying on inert nitrogen gas that poses minimal risk to products and equipment when managed within safe occupational exposure limits. Overall, the continuous nitrogen purging system with PSA nitrogen generation. Offers an effective, reliable and economically sustainable fire-prevention approach tailored for the unique challenges of cold storage ASRS environments, addressing the limitations of traditional suppression methods and providing a higher level of operational safety and continuity.[1] This study of investigates the effectiveness of ultra-fine water mist in extinguishing cold storage fires involving polystyrene insulation foam. Fire behavior was analyzed through pyrolysis, temperature, and smoke measurements. Experiments varied water-mist particle size and pressure to evaluate extinguishing performance. The results identify the optimal fine-mist particle size range, providing a theoretical basis for cold-storage fire protection design.[2] This evaluates fire safety conditions in fifty cold and controlled-atmosphere stores used for long-term food preservation. It identifies key fire risks linked to storage structures, refrigerants, and packaging materials. The assessment covers technical equipment, refrigeration systems, and existing fire-fighting arrangements. Recommendations are provided to enhance fire safety, particularly in the context of increasing use of hydrocarbon refrigerants.[3] The paper reviews global and Indian cold storage trends from 2014–2023, noting rapid global growth but modest expansion in India. Regional disparities persist, with the Central region showing the highest progress. Severe infrastructure shortages in dairy and fisheries continue to drive post-harvest losses. Strengthening cold chain systems through targeted investments, partnerships, and technology is essential for reducing waste and improving food security. [4] The paper discusses how fires in hazardous-chemical (Hazchem) warehouses often escalate quickly due to late detection and the high combustibility of stored materials. It identifies key fire causes such as electrical faults, unsafe smoking, spontaneous ignition, hot-work activities, and incompatible chemical storage. The authors stress that fire behaviour of materials, storage layout, and the warehouse's structural design are the primary factors influencing fire risk. They highlight the need for proper compartmentation, ventilation, separation of high-risk goods, and well-planned drainage to control fire spread. Overall, the paper emphasizes early detection systems, automatic suppression, and fire-resistant zoning as essential measures for preventing major losses.[5] This experimental study analyses fires suppressed by sprinkler, low-pressure mist, and high-pressure mist systems using a stack of HDPE and wood pallets. Using FTIR, they detect major combustion species CO_2, CO, H_2O

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and also nitrogen oxides, light hydrocarbons, and HCN. All suppression systems reduce fire size and cool gases, but delayed extinguishment can lead to higher concentrations of NO_x, hydrocarbons, and HCN. The high-pressure mist system shows the best performance, minimizing toxic gas exposure (Fractional Effective Dose), with concentrations returning to near-ambient levels about five minutes after shutdown.[6] This paper evaluates the performance of oxygen reduction systems in large-scale fire scenarios. It studies how ORS lowers oxygen concentration to suppress combustion. Experiments in warehouse-like settings were conducted. Fire spread, flame height, and heat release rates were measured. The study confirms ORS effectiveness in fire suppression. System design parameters influencing performance were analyzed. Results support ORS as a preventive solution in high-storage facilities. Recommendations for industrial implementation are provided.[7] Develops intermediate-scale test methods for evaluating ORS performance. Bridges laboratory tests with full-scale fire scenarios. Analyzes oxygen concentration reduction and fire growth control. Results improve understanding of ORS behavior in realistic storage environments. Provides data for system design optimization. Highlights differences between small and intermediate-scale results. Suggests scaling factors for large-scale implementation. Concludes with safety performance metrics.[8] Reviews pressure swing adsorption (PSA) technology for oxygen generation. Discusses adsorbent materials, reactor designs, and operational processes. Explores potential applications in controlled environments. Analyzes efficiency, purity, and energy consumption. Highlights challenges in scaling PSA systems. Suggests future research directions for industrial oxygen production. Relevance to fire prevention through controlled oxygen levels is noted. Provides comparative analysis with alternative methods.[9] Focuses on CO_2-based fire prevention systems. Describes inerting mechanisms that reduce oxygen availability. Covers system design and operational considerations. Demonstrates application in industrial and storage facilities. Highlights performance under varying fire scenarios. Discusses safety, environmental, and cost aspects. Provides experimental and simulation data. Concludes with guidelines for effective CO_2 deployment.[10] Investigates sprinkler performance in automated storage and retrieval systems (ASRS). Evaluates parameters such as nozzle type, spray angle, and droplet size. Experiments simulate typical warehouse fire scenarios. Analyzes coverage and fire suppression efficiency. Provides recommendations for ASRS-specific sprinkler design. Highlights limitations and challenges in rack storage. Suggests strategies for enhancing system reliability. Offers data for fire protection code compliance.[11] Reviews current fire sprinkler requirements for ASRS warehouses. Explains regulatory frameworks and code compliance. Highlights challenges of automated storage systems. Discusses practical implementation strategies. Provides examples from modern warehouse designs. Offers guidance on system selection and installation. Addresses integration with fire detection systems. Emphasizes safety and efficiency balance.[12] Comprehensive review of fire sprinkler technologies and performance. Examines design considerations, activation mechanisms, and suppression efficiency. Compares traditional and modern sprinkler systems. Highlights factors affecting system reliability. Provides data from multiple case studies. Discusses research gaps and future trends. Suggests best practices for industrial and commercial applications. Evaluates effectiveness in various fire scenarios.[13] Summarizes research on ORS deployment in warehouse storage. Covers oxygen reduction mechanisms and system design principles. Reviews small, intermediate, and large-scale studies. Highlights performance in different storage environments. Discusses safety, cost, and scalability considerations. Provides design recommendations for effective implementation. Identifies knowledge gaps for future research. Emphasizes the role of ORS in preventive fire strategies. [14] Uses simulation analysis to evaluate ORS performance in cold storage facilities. Focuses on oxygen concentration control and fire prevention. Examines system response under various fire scenarios. Provides data on flame suppression efficiency. Discusses integration with existing fire safety systems. Highlights challenges of low-temperature operations. Suggests optimization strategies. Confirms ORS applicability in food and pharmaceutical storage. [15**]** Studies fire suppression using liquid nitrogen in data centers. Evaluates cooling and inerting effects on fire propagation. Experiments simulate confined electronic environments. Provides data on oxygen reduction and temperature control. Highlights safety considerations for personnel. Discusses system design for effective suppression. Suggests operational parameters for optimal performance. Confirms LN_2 as a feasible fire suppression medium. [16] Explores nitrogen injection for fire prevention in confined areas. Measures oxygen reduction and temperature changes. Evaluates fire suppression effectiveness. Discusses injector design and flow rate effects. Highlights challenges of confined-space operations. Provides experimental validation. Suggests applications in industrial hazard control. Emphasizes safety and efficiency. [17] Investigates nitrogen injection in confined underground spaces. Evaluates the impact of pipe diameter and flow rate. Measures fire suppression effectiveness and extinguishing speed. Analyzes oxygen depletion and thermal behavior. Offers recommendations for system design. Discusses limitations of confined space fire control. Provides guidance for mining and industrial applications. Confirms nitrogen's efficacy in narrow environments. [18] Studies nitrogen-based fire prevention in mining gob-side entry retaining. Focuses on oxygen reduction and fire propagation control. Experimental data demonstrates temperature and flame suppression. Evaluates system design for operational efficiency. Discusses potential hazards and mitigation strategies. Provides guidelines for industrial mining use. Confirms effectiveness for spontaneous combustion scenarios. [19] Compares CO_2 and nitrogen in controlling coal adiabatic oxidation. Measures flame retardancy and oxygen depletion. Highlights nitrogen's superior inerting effect.

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Provides experimental validation of suppression efficiency. Discusses implications for industrial fire prevention. Suggests optimal use cases for each gas. Provides insight into fire hazard mitigation. [20] Analyzes nitrogen injection in confined B-type oil pool fires. Evaluates asphyxiation effect and pressure changes. Studies oxygen reduction and flame suppression. Provides recommendations for safe operations. Discusses flow rates and nozzle design. Highlights effectiveness under confined conditions. Offers insights for chemical and storage fire hazards. [21] Reviews zirconia-based sensors for oxygen and NO_x detection. Discusses mixed-potential sensors and high-temperature performance. Summarizes material selection and sensor designs. Highlights applications in fire monitoring and industrial safety. Provides insight into sensor calibration and stability. Discusses limitations and challenges. Suggests directions for future research. [22] Investigates zirconia sensors under high temperatures. Evaluates stability and performance for oxygen measurement. Discusses suitability for fire detection applications. Provides experimental validation and analysis. Highlights material degradation effects. Suggests design considerations. Confirms potential for industrial monitoring. [23] Assesses performance of nanofibrous zirconia oxygen sensors. Evaluates sensitivity and response time in fire prevention scenarios. Discusses practical implementation in confined spaces. Analyzes durability under high-temperature conditions. Highlights industrial relevance. Provides recommendations for system integration. Confirms sensor reliability.[24] Develops zirconia-based sensor for measuring hydrogen in inert gases. Evaluates electrochemical response and accuracy. Highlights applications in fire safety monitoring. Discusses sensor calibration and environmental effects. Provides experimental validation. Confirms use for industrial hazard detection. Suggests future improvements.[25] Discusses implementation of occupational safety and health systems in food industries. Focuses on hazard identification and accident prevention. Evaluates management practices and training programs. Highlights importance of systematic safety monitoring. Provides examples of food-industry hazards. Suggests improvement strategies. Emphasizes reducing occupational risk in production environments.

Experimental Procedure

Discuss the relationship between oxygen concentration and ignition/flash-over risk. Cite literature: e.g., the 2023 Korean study showed that ignition was delayed from ~3-4 minutes at 21 % O_2 to >13 minutes at ~15.7 % O_2 in a cold-storage simulation. Explain that by maintaining O_2 at ~14–15 vol %, fire initiation probability and spread velocity drop significantly, thereby giving more time for detection and response or preventing ignition entirely. Also discuss chimney-effect in high-bay racks and how oxygen reduction mitigates.

Fire Prevention Via Oxygen Reduction

A proactive method of fire prevention involves reducing the oxygen concentration in the protected space to levels below that which can sustain ignition and growth of a fire. These systems, commonly called Oxygen Reduction Systems (ORS) or inert-gas purging systems, replace part of the ambient air (19.5-21.5 vol % O_2) with nitrogen, thereby creating a norm baric hypoxic atmosphere (14 –16 vol % O_2) that still allows human occupancy but inhibits combustion.Many studies and industrial installations have validated that while ignition and flame spread may still occur under 19.5–21.5% O_2, reducing to 15% or below significantly delays or prevents flash-over and fire propagation.

Fig 1.1 Oxygen Reduction Systems using Nitrogen

The Oxygen Reduction Systems (ORS), or inert-gas purging systems; by reducing oxygen levels to 13.5%–16%, they ensure that fire cannot ignite or spread while still allowing human occupancy. PSA nitrogen generators extract nitrogen from ambient air and inject it into the cold storage, displacing oxygen and maintaining a constant hypoxic state. Unlike traditional fire suppression systems, this system prevents fire rather than extinguishing it after ignition, thereby eliminating damage from flames, smoke, or water-based extinguishing agents.

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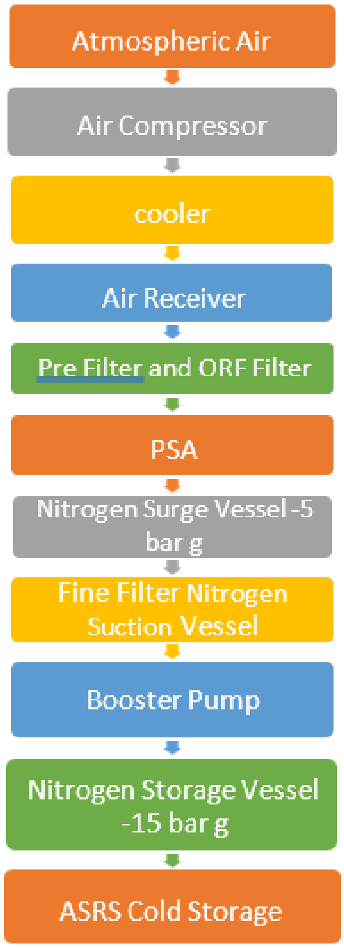

Fig1.2 Proposed Nitrogen Setup for PSA System

Inert-gas-based ORS operate through a network of nitrogen or inert gas generators—often membrane or PSA-based (Pressure Swing Adsorption)—that produce a continuous stream of high- purity inert gas onsite. This eliminates the need for bulky gas cylinders and ensures uninterrupted fire protection even in facilities operating 24/7. Precision oxygen sensors placed throughout the storage area constantly monitor atmospheric levels and trigger automated adjustments to maintain the target oxygen setpoint despite door openings, air leakage, or environmental fluctuations. Atmospheric air is the primary raw material for nitrogen generation, drawn from the surrounding environment and fed into the system through an industrial air compressor. The air compressor pressurizes the intake air and delivers it to a compressed air cooler, where the temperature is reduced to remove heat generated during compression. The cooled air then enters an air receiver, which stabilizes pressure fluctuations and ensures a constant supply of compressed air to downstream equipment. Before entering the nitrogen generation system, the air passes through a pre-filter and an oil-removal (ORF) filter, which eliminate moisture, particulates, and oil aerosols, ensuring clean air suitable for PSA operatio

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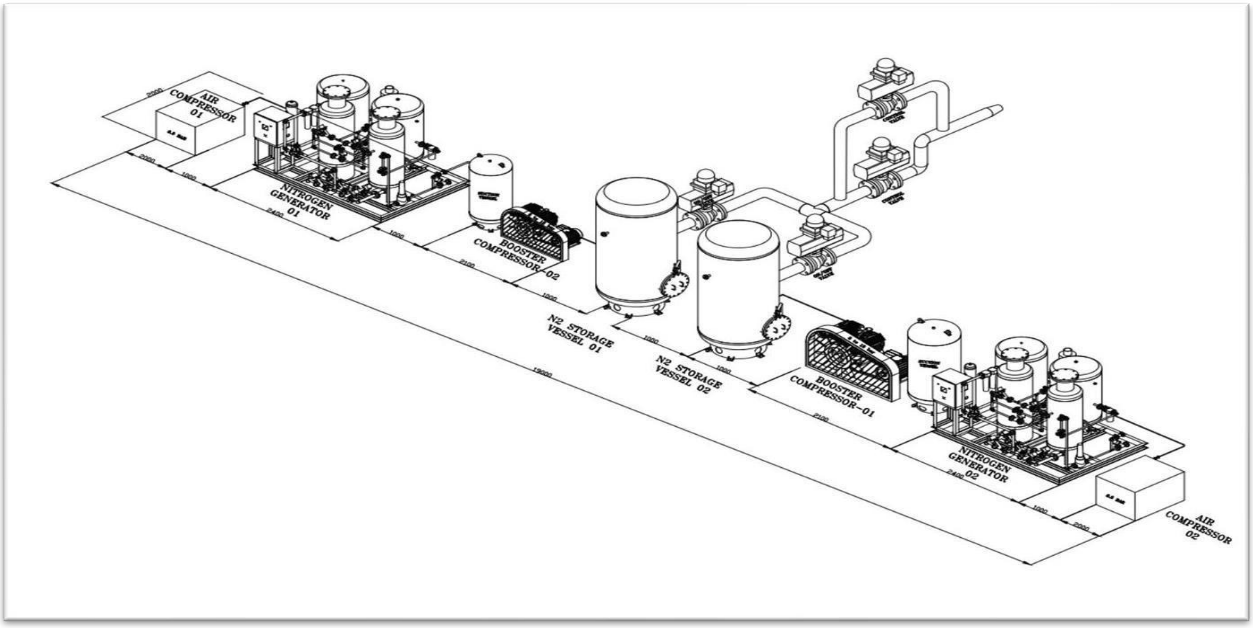

Fig 1.3 Implemented Nitrogen enabled Fire Suppression for Cold Storage ASRS

The purified compressed air is then processed through the Pressure Swing Adsorption (PSA) nitrogen generator, where oxygen, moisture, and trace gases are adsorbed, leaving high-purity nitrogen as the output. The nitrogen produced is temporarily stored in a nitrogen surge vessel pressurized at 5 bar(g), which supports stable flow during continuous purging operations. The nitrogen then passes through a fine filter to remove any residual impurities before being routed to a nitrogen suction vessel, which supplies the booster section. A booster pump further increases the nitrogen pressure for efficient delivery through the distribution network or for filling high-pressure storage vessels.

For extended storage and pressure stability, nitrogen is stored in a high-pressure nitrogen storage vessel rated at 15 bars (g), ensuring buffer capacity for peak demand or emergency purging situations. The nitrogen is then distributed through stainless-steel or insulated pipelines into the AS/RS cold storage facility, where it is delivered strategically into aisles, racks, and enclosed sections to lower oxygen concentration below fire-supporting levels. The integration with the cold storage automation system ensures continuous purging, maintaining controlled oxygen conditions for fire suppression while supporting efficient AS/RS operations.

II. NITROGEN PURGING SYSTEM

Nitrogen purging is an essential industrial process used to remove oxygen from pipelines, vessels, and process equipment before introducing chemicals, fuels, or other sensitive materials. In an automated purging system, a PLC (Programmable Logic Controller) works together with a Zirconia oxygen sensor to ensure that the oxygen level inside the system is reduced to a safe and controlled value

The Pipe Structuring Diagram of Nitrogen Purging System in ASRS. The process begins when the operator initiates the purge cycle from the PLC or HMI. Before purging starts, the PLC checks critical interlocks such as nitrogen supply pressure, valve health status, vent-line availability, and the proper functioning of the zirconia sensor. Once all conditions are met, the PLC opens the nitrogen inlet valve and the vent valve, allowing nitrogen to displace oxygen-rich air from the vessel. As the purge continues, the zirconia oxygen sensor constantly measures the oxygen concentration in the exhaust or headspace and sends a 4–20 mA signal to the PLC. If the oxygen concentration remains above the setpoint, the PLC keeps the nitrogen flowing and maintains the vent valve open as shown in the figure 1.4.

- Provide quantitative findings hypothetical actual data available such as Oxygen concentration maintenance stable at 13.5-16 vol % ± 0.2% over day based on Oxygen Monitoring sensor and no. of opening per week is 21560 times.
Nitrogen consumption: average 30 Nm³/h (≈ 0.5 Nm³/min) for single setup corresponding to PSA plant flow of both set up 60 Nm³/h at 98 % purity.
- Energy consumption approximately PSA plant consumes 11 kW average ⇒ 264 kWh/day.

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● System integration: retrieval bay door open events caused O_2 increase spikes to 16.5 vol % but system injection restores to 14.8 vol % in <90 seconds; no detectable storing-product temperature disturbance due to nitrogen injection ($\Delta T < 0.2$ °C).

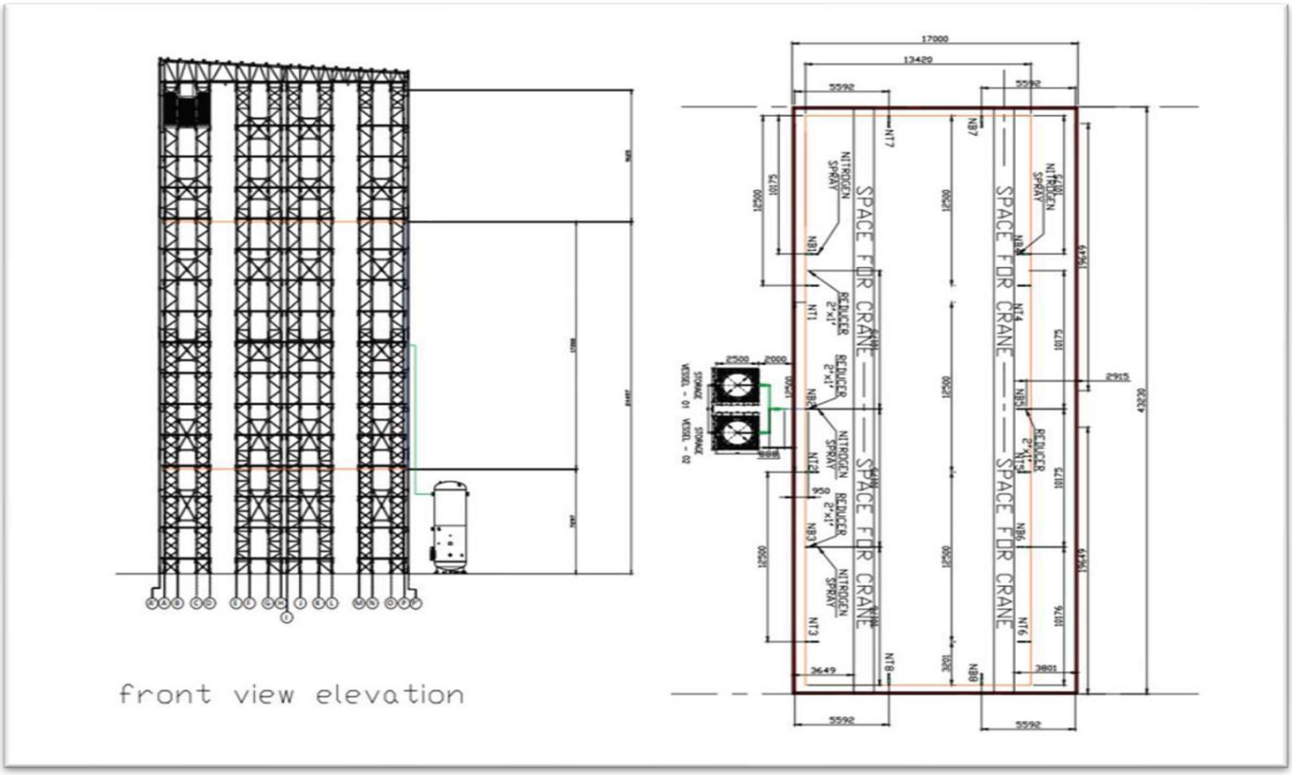

Fig 1.4 Designed layout pipelines Nitrogen Suppression System

Oxygen Concentration Fire Risk

The HypOxy Fire Prevention System is based on the principle of oxygen reduction, wherein nitrogen is Systematically introduced into the storage area to lower the oxygen concentration to levels below the combustion threshold of stored materials. Unlike conventional suppression systems, which react after a fire has ignited, the HypOxy system proactively prevents combustion from occurring.

Nitrogen Generation

- The PSA nitrogen generator extracts nitrogen from ambient air.
- Oxygen is adsorbed, and high-purity nitrogen (95–99%) is stored for controlled release.
- The control system regulates nitrogen flow based on real-time oxygen sensor readings.
- Nitrogen is evenly dispersed through the facility via an air distribution network.
- Oxygen concentration is maintained at 13.5–16%, below the ignition threshold of common cold storage materials.

Continuous Monitoring and Adjustment

- Oxygen sensors continuously measure oxygen levels.
- The Oxy-control System dynamically adjusts nitrogen injection to maintain the target oxygen percentage.
- Personnel safety is ensured through predefined exposure limits for different operational zones.

III. CONCLUSION

This paper demonstrates that continuous nitrogen-gas purging, via on-site PSA nitrogen generation, integrated into a cold-storage warehouse with automated storage and retrieval systems (ASRS), is an effective proactive fire-prevention

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strategy. By maintaining oxygen concentrations in the protected volume at 13.5-16 vol % O_2, the ignition threshold is suppressed and fire propagation is significantly inhibited, thereby reducing risk of catastrophic loss, product damage and downtime. The system can be sized to handle infiltration events (door openings, pallet movement) in an ASRS environment and is operationally viable in a cold-storage context (−20 °C to −30 °C) with proper design and controls. From an economic perspective, the on-site PSA generation offers lower life-cycle cost compared to delivered inert-gas cylinders or purely reactive suppression systems, especially in continuously-operated large storage volumes. Implementation considerations include human-safety protocols, sensor calibration in cold ambient, integration with retrieval system operations, maintenance planning and energy trade-offs. Further work is recommended to conduct long-term full-scale empirical trials in diverse cold-storage volumes and to refine guidelines for intermittent vs continuous purging strategies.

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