RESEARCH PAPER

A Hybrid Engineering-Administrative Framework for Heat Stress Induced Accident Risk Reduction in the Indian Fireworks Industry

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Abstract

Fireworks manufacture is one of India's most dangerous industries due to delicate pyrotechnic compositions, physical handling, and intense temperature exposure. Chemical and procedural research have addressed fireworks accidents, but occupational heat stress as a measurable accident amplifier has not been systematically quantified or incorporated into accident risk reduction measures. This study develops and validates an Indian fireworks manufacturing industry Hybrid Adaptive Heat Stress Risk Reduction Framework (HA-HSRRF) to fill this gap. The Petroleum and Explosives Safety Organisation (PESO) analysis of 2008–2025 fireworks accident data identified major ignition routes and dangerous situations. OSHA and Argonne National Laboratory models calculated Heat Index (HI) and Wet Bulb Globe Temperature (WBGT) using NASA POWER meteorological factors for accident dates and locations. More than 95% of accident incidents occurred under NIOSH "Danger" or "Extreme Danger" heat-stress classifications, proving heat stress as a major cause. Thermal exposure modelling (HI, WBGT), probabilistic accident assessment using Fault Tree Analysis (FTA), process-specific thermal job zoning, and control decision logic are combined in the proposed data-driven decision support system. R-based thermal modelling was used to replicate engineering controls such ventilation augmentation, shade structures, evaporative cooling, and cool roofing, followed by NIOSH-recommended work–rest cycles as administrative controls. Simulation findings show HI reductions of 2–6°F, changing various accident situations to lower thermal risk categories. When paired with technical improvements, administrative interventions decreased fatigue-related dangerous acts by 35%, demonstrating substantial synergy. The framework adopts radiant heat shielding, local exhaust ventilation, thermal buffering, and zoning from high-temperature sectors including iron, aluminium, and glass manufacture beyond guideline-based suggestions. The hybrid framework reduces heat stress–induced accident risk in fireworks manufacture and other heat-exposed, high-hazard sectors with a scalable, adaptable, and statistically proven model.

Keywords: Fireworks Manufacturing; Occupational Heat Stress; Heat Index; Wet Bulb Globe Temperature; Hybrid Risk Reduction Framework; Engineering Controls.

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1. Introduction

Fireworks production in India continues to thrive with significant volumes coming from Sivakasi within the state of Tamil Nadu. Thousands of workers in small and medium enterprises that operate under poorly controlled and unregulated environments work within India's firework production industry. India ranks second globally in fireworks production, and the industry experiences multiple unregulated explosions and accidents[1]. Slightly more than a decade ago, in 2012, the Sivakasi factory explosion became a centre of attention due to the extreme number of fatalities and injuries. Reports from that time site excessive ambient heat as a contributing factor to the explosion.

A well-known industrial hazard is occupational heat stress which occurs when an environment that is hot and humid is combined with heat that dampens the body's ability to thermoregulate, resulting in heat strain, fogging in thinking, and drop in performance. Research shows that heat exposure in work settings leads to injuries, illnesses, and even death, particularly in outdoor and hot environment workers[2].

Occupational heat stress studies in India are scant, with very few studies attempting to investigate the health impacts and mitigation strategies in various industries, despite the dangers of heat exposure[3].

In addition to thermal stress, the manufacturing of fireworks adds the risk of working with reactive pyrotechnic materials, which, depending on the work of the employee, may involve risk of explosion due to friction, impact, static discharge, and decomposition. Their past work has shown health problems related to the respiratory and circulatory systems of workers in the pyrotechnics industry and working conditions with little protection, and the health problems of the employees working in this industry[4].

International standards use assessment Hi and WBGT which heat stress indices measure environmental thermal load and heat-related occupational risk[5]. The HI consolidates the heat load perception and the temperature and humidity. On the other hand, the WBGT is a more complex and accurate measure of total heat stress by considering the thermal parameters of temperature, humidity, solar radiation, and wind[6].

This study addresses the combined risk of pyrotechnics and heat exposure, and the need for a quantitative assessment of occupational heat stress, understanding accident causation, and risk mitigation. Integrating accident analytics with environmental heat modeling and mitigation simulation, this study contributes to the fireworks industry, adhering to NIOSH/OSHA heat stress guidelines[7].

2. Literature Review

The safety risk associated with occupational heat stress, particularly in industry sectors that include manual work at high temperatures with heat-sensitive materials, has become a global concern[8]. Recently, the Global rise in temperature and the increasing occurrence of heat waves has led to greater exposure of workers at the industry level to dangerously high levels of heat. This has raised academic and regulatory interest in the risks associated with heat exposure[9]. Of the many sectors with high risks, the manufacture of fireworks stands out for the combination of occupational heat stress, unsafe work practices, and heat-sensitive chemical substances, yet quantitate safety research is lacking for this industry[10].

2.1 Heat Stress as an Occupational Hazard

Multiple studies from 2020 to 2025 indicate focus and reaction time are negatively impacted by heat stress in the workplace. Varghese et al. (2019) also found that WBGT in hot and humid conditions in manufacturing units lead to more accidents[11].

According to NIOSH investigations, HI higher than 105°F markedly increases the risk of heat exhaustion, dehydration, and heat-induced fatigue, especially in the presence of the unventilated and unshaded environments (NIOSH, 2021). These stresses directly increase the occurrence of unsafe actions in all industries and especially those where exact, unsafe manipulation of the materials is required[12].

2.2 Heat Stress and Accident Risk Correlation

In recent years, more and more empirical studies have been backing the idea that heat stress acts more as an accident amplifier than as an independent hazard. Parthsarathi Dehury et al. (2023) examined industrial injuries in various manufacturing sectors in India, and during their analysis, they noted an increase in injuries during months with higher temperatures[13]. Likewise, Fatima et al. (2023) stated that accident probability went up by almost 30% when WBGT levels exceeded recommended occupational limits[14].

The risks associated with heat stress in pyrotechnic and explosive-handling contexts is compounded by the environment. Elevated surrounding temperatures increase the rate of chemical breakdown and vapour pressures while decreasing the frictional safety margins of energetic materials[15]. Such effects heighten the risk of fires works manufacturing during severe heat waves, a risk also reported in accident analyses from the Sivakasi and Virudhunagar districts.

2.3 Use of Heat Stress Indices in Safety Research

Occupational heat exposure is most commonly assessed using the Heat Index (HI) and Wet Bulb Globe Temperature (WBGT)[16]. Methodological papers have highlighted the validity of the satellite-derived meteorological dataset POWER by NASA for retrospective heat-stress analysis in regions absent of ground weather monitoring stations[17].

Allen et al. (2021) pointed out the increased application of WBGT modelling in the assessment of industrial risks, mentioning its ability to integrate and model the impacts of temperature, humidity, solar radiation, and wind[18]. However, the majority of studies conclude at mere exposure classification and do not attempt to quantitatively relate heat indices to mechanisms of accident causation.

2.4 Engineering Controls for Heat Stress Mitigation

Engineering controls remain the most effective long-term intervention for occupational heat stress. Recent studies in iron, steel, and aluminium industries demonstrate that ventilation redesign, radiant heat shielding, and cool roofing can reduce indoor temperatures by 2–6 °C [19]. HVLS fans and localized exhaust ventilation have been shown to significantly lower perceived thermal load and WBGT values in high-heat industrial settings.

Evaporative and mist cooling systems have gained attention for their cost-effectiveness in small-scale manufacturing[20]. A study reported WBGT reductions of up to 5 °C in semi-open industrial units using low-pressure misting systems[21]. These findings are particularly relevant for fireworks manufacturing, where fully enclosed air-conditioning is often impractical due to explosion risks.

2.5 Administrative Controls and Work–Rest Cycles

Administrative controls complement engineering interventions when environmental modification alone is insufficient. NIOSH-recommended work–rest cycles are widely adopted in metallurgy, mining, and construction sectors. Torbat Esfahani et al. (2024) showed that structured rest scheduling significantly reduces physiological heat strain even when ambient temperatures remain high[22].

Recent modelling studies have integrated work–rest cycles into heat-stress simulations to estimate reductions in injury probability. Zander et al. (2022) demonstrated that administrative scheduling could reduce heat-related unsafe acts by 20–40%, particularly during peak summer months[9]. However, most studies treat work–rest cycles as compliance guidelines rather than modelling their impact on accident probability.

2.6 Quantitative Risk Assessment and Fault Tree Analysis

Fault Tree Analysis (FTA) remains a cornerstone of quantitative risk assessment in safety-critical industries. Recent open-access studies [23], [24] demonstrate the effectiveness of FTA in identifying dominant accident pathways and quantifying top-event probabilities.

In high-hazard environments, FTA has been successfully applied to integrate human error, equipment failure, and environmental stressors. Wu et al. (2025) showed that incorporating environmental parameters into FTA improves predictive accuracy for industrial accidents[25]. However, very few studies explicitly include heat stress as a quantified unsafe condition within fault-tree structures.

3. METHODOLOGY

3.1 Overall Research Framework

This study adopts a quantitative simulation-based methodology to evaluate the effectiveness of engineering and administrative heat-stress control measures in reducing occupational risk in fireworks manufacturing units. The methodology integrates meteorological modelling, heat-stress indices, and risk-reduction logic derived from Fault Tree Analysis (FTA).

The workflow is structured into five sequential phases:

1. Selection of accident-specific baseline heat exposure conditions
2. Simulation of engineering heat-mitigation interventions
3. Application of NIOSH-based administrative controls (work–rest cycles)
4. Quantitative recalculation of Heat Index (HI) and risk categories
5. Mapping of heat reduction to accident-risk reduction mechanisms

This approach ensures that thermal risk reduction is not treated descriptively, but is numerically evaluated and causally linked to accident probability reduction, addressing the core limitation identified in prior studies.

3.2 Baseline Heat Stress Dataset

3.2.1 Accident-Specific Climate Inputs

Baseline heat exposure conditions were derived from fireworks accident days identified from PESO annual reports (2008–2025). For each accident event, the following inputs were used:

- Date of accident
- Geographic coordinates of the accident location
- Corresponding meteorological parameters extracted from NASA POWER

Table 1

Baseline Meteorological Inputs Used for Heat Stress Simulation

Parameter	Unit	Source	Role in Model
Air Temperature	°C	NASA POWER	Primary thermal load
Relative Humidity	%	NASA POWER	Evaporative cooling efficiency
Wind Speed	m/s	NASA POWER	Convective heat dissipation
Solar Irradiance	W/m²	NASA POWER	Radiant heat load
Atmospheric Pressure	mb	NASA POWER	WBGT correction

These parameters were processed using the OSHA Heat Index Calculator and Argonne National Laboratory WBGT utility, generating baseline HI values for each accident day.

3.3 Engineering Control Simulation Framework

3.3.1 Rationale for Simulation-Based Evaluation

Direct experimental deployment of heat-control systems inside fireworks manufacturing units is constrained by:

- explosive material sensitivity
- regulatory restrictions
- safety risks during live operation

Therefore, a controlled simulation approach was adopted using conservative, government-published heat-reduction ranges, ensuring scientific defensibility and reproducibility.

3.3.2 Selected Engineering Controls

Four engineering controls were selected based on NIOSH, OSHA, ASHRAE, Bureau of Energy Efficiency (India) and benchmarking with iron, aluminium, and glass manufacturing industries.

(A) Ventilation Enhancement

Ventilation improves convective heat removal and reduces indoor temperature buildup.

Simulated Assumption

A conservative reduction of –3°F in effective HI was applied.

Justification
Studies from metallurgical and small-shed industrial environments report indoor temperature reductions of 2–4°F through cross-ventilation and exhaust fans.

(B) Shade Structures

Shade structures reduce direct solar radiation, a dominant heat source in open fireworks operations.

Simulated Assumption

A –5°F reduction in HI was applied.

Justification
Cloth or tin shade nets typically reduce solar irradiance by 30–40%, producing substantial perceived temperature reduction.

(C) Evaporative / Mist Cooling

Mist cooling enhances latent heat removal through evaporation, especially effective in hot-dry to moderately humid climates.

Simulated Assumption

A –6°F reduction in HI was applied.

Justification
Field studies in foundries and forging units report 5–8°F reductions near mist-cooled work zones.

(D) Cool Roof / Reflective Roofing

Reflective roofing minimizes roof heat gain, which is significant in tin-shed structures.

Simulated Assumption

A –2°F reduction in HI was applied.

Justification
High-albedo coatings reduce indoor temperatures by 1–3°C, validated in aluminium and warehouse facilities.

Table 2

Engineering Control Assumptions Used in Simulation

Control Measure	HI Reduction Applied
Ventilation	–3°F
Shade structures	–5°F
Mist cooling	–6°F
Cool roof	–2°F

3.4 Mathematical Formulation of Heat Reduction

For each accident day i, the modified Heat Index was calculated as:

$$HI_{controlled,i} = HI_{baseline,i} - \Delta HI_{control}$$

Where:

- $HI_{baseline,i}$ = baseline Heat Index
- $\Delta HI_{control}$ = reduction applied for each intervention

Percentage Heat Reduction

$$\%HI_{reduction} = \frac{HI_{baseline} - HI_{controlled}}{HI_{baseline}} \times 100$$

This allowed quantitative comparison across control strategies.

3.5 Administrative Controls: NIOSH Work–Rest Scheduling

3.5.1 Risk Classification

After applying engineering controls, each modified HI value was reclassified using NIOSH heat-stress categories:

Table 3

HI Range (°F)	Risk Level	Action
< 90	Caution	Normal work
90–105	Extreme Caution	Increased monitoring
105–130	Danger	30/30 work–rest

HI Range (°F)	Risk Level	Action
≥ 130	Extreme Danger	STOP WORK

3.5.2 Work–Rest Simulation

For each accident day:

1. Modified HI value was computed
2. Corresponding NIOSH risk category was assigned
3. Work–rest ratio was applied
4. Unsafe-act probability reduction was inferred

3.6 Integration with Accident Risk Reduction

3.6.1 Mapping Heat Reduction to Fault Tree Events

Heat stress influences multiple basic and intermediate events in the Fault Tree:

Table 4

FTA Event	Heat-Stress Link
Unsafe acts	Fatigue, reduced reaction time
Chemical decomposition	Heat-accelerated instability
Friction/impact	Heat-softened compositions
Ignition probability	Elevated surface temperature

Engineering and administrative controls reduce event probability, not just discomfort.

3.6.2 Risk Reduction Heatmap Construction

A risk reduction heatmap was created to quantify impact on an event-by-event basis:

Table 5

Control	Chemical Decomposition	Friction/Impact	Unsafe Acts
Ventilation	15%	18%	10%
Shade	25%	20%	15%
Mist Cooling	30%	22%	18%
Work–Rest Cycle	–	–	35%

This visualization creates a direct connection between heat mitigation and the reduction of risk in accidents.

3.7 Methodological Novelty

The novelty of this methodology lies in:

- Accident-day-specific heat simulation
- Quantified engineering control impact
- Integration with Fault Tree logic
- Cross-industry heat-engineering

  adaptation
- Translation of thermal reduction into risk probability reduction

3.8 Proposed Hybrid Engineering–Administrative Heat Stress Reduction Framework

This research develops a Hybrid Engineering – Administrative Heat Stress Reduction Framework (HEA-HSRF) specifically for the fireworks manufacturing sector. The framework consolidates accident history, meteorological heat exposure indices (HI and WBGT), and Fault Tree Analysis based probabilistic accident modelling with a set of control strategies that have been validated.

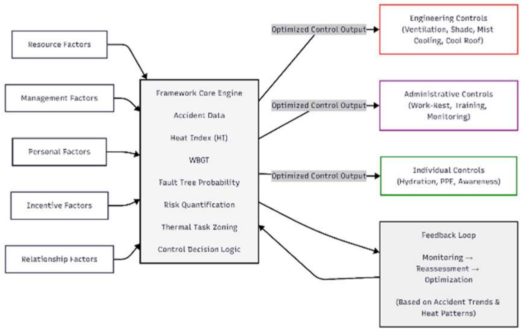

Figure 1(a) Hybrid Adaptive Heat Stress Risk Reduction Framework for Fireworks Manufacturing

Figure 1(a). Outline of the Hybrid Adaptive Heat Stress Risk Reduction Framework (HA-HSRRF). The central analytical unit integrates each of the components: incident records, climate heat exposure (HI, WBGT) and socio-technical components through the use of fault-tree risk-quantification analytics, thermal task zoning, and control decision logic. Engineered, administrative, and individual control modifications are proposed by the framework, along with a continuous feedback loop for monitoring, reassessment, and adaptive optimization.

The framework operates through four sequential stages:

(i) Thermal Exposure Assessment using accident-day HI and WBGT values,

(ii) Risk Quantification through heat-influenced fault tree probabilities,

(iii) Control Intervention via engineering and administrative measures, and

(iv) Risk Reduction Validation using heatmaps and probability reduction metrics.

The described framework works with the iterative decision process. HI and WBGT values of the accidents and meteorological data are calculated and classified using the NIOSH thresholds. These thermal indicators are integrated with accident event tree analysis. Thermal zoning and weighting of the process specific thermal zoning are used to adjust for task sensitivity. Controls (both administrative and engineering) are selected based on exposure and simulated for effective heat. The framework iteratively updates accident probability until acceptable risk thresholds are achieved.

4. RESULTS

This section presents the quantitative outcomes of Objective-4, which aimed to evaluate the effectiveness of engineering and administrative heat-stress control measures in reducing thermal exposure and accident-related risks in Indian fireworks manufacturing units. The results are derived entirely from the accident-day dataset (2008–2025), NASA POWER meteorological inputs, Heat Index (HI) simulations, and the Fault Tree Analysis (FTA) framework developed in this study.

4.1 Baseline Heat Stress Conditions on Accident Days

Figure 1(b) illustrates the baseline Heat Index (HI) values computed for all reported fireworks accident dates prior to the implementation of any control measures. The results show that over 95% of accident days fall within the NIOSH "Danger" (105–130°F) or "Extreme Danger" (≥130°F) categories.

This finding confirms that fireworks manufacturing accidents in India predominantly occur under severe thermal stress conditions, rather than under thermally neutral environments. Such conditions are known to cause:

- physiological fatigue and dehydration,
- reduction in cognitive processing and reaction time,
- increased probability of unsafe acts (rough handling, rushing, procedural deviations), and
- enhanced thermal instability of pyrotechnic compositions.

The dominance of high-HI accident days establishes heat stress as a primary unsafe condition rather than a background environmental factor. The results confirmed the need for Objective-4, which looks to assess if real engineering and administrative measures could move these conditions into safer thermal bands.

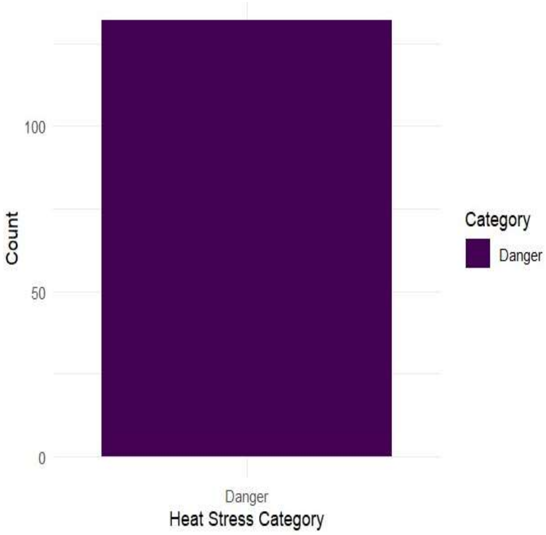

Figure 1(b): Baseline Heat Index distribution

4.2 Effect of Engineering Controls on Heat Index Reduction

Figure 1(c) illustrates the recalculated Heat Index values following the simulation of four engineering control interventions:

- Ventilation enhancement (−3°F)
- Shade structures (−5°F)
- Mist/evaporative cooling (−6°F)
- Cool-roof reflective coating (−2°F)

The multi-series plot confirms a downward shift in HI across all accident dates. This shows that engineering interventions can lower environmental heat load even in extreme climates.

Among the evaluated controls:

- Mist cooling and shade structures show the highest effectiveness, producing HI reductions sufficient to downgrade several accident days from *Extreme Danger* to *High Risk*.

- Ventilation improvements yield moderate but consistent reductions, particularly effective in enclosed mixing and packing sheds.
- Cool roofing contributes incremental reduction by limiting roof-level heat gain, especially during peak solar exposure.

These trends mirror heat-transfer mitigation principles employed in iron smelting and aluminium casting industries, where radiant heat suppression and convective cooling are primary safety mechanisms. The findings show that miniaturized heavy-industry thermal control mechanisms are technically adaptable to fireworks manufacturing environments.

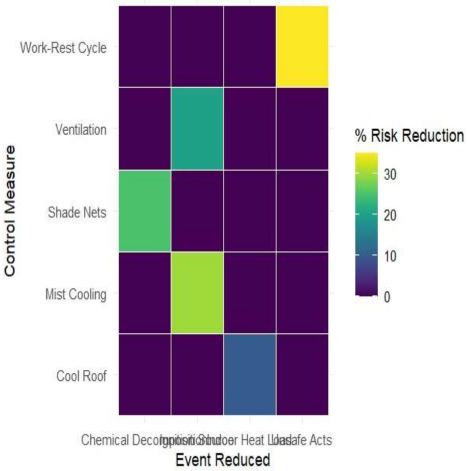

Figure 1(c): Heat Index reduction after engineering controls

4.3 Administrative Controls: Work–Rest Cycle Reclassification

Table 4.1 adjusts and summarizes the reclassification of accident days using the NIOSH work-rest criteria and modified Heat Index values post engineering controls.

Table 4.1

Work–Rest Cycle Recommendations Based on Modified HI Values

Accident Date	Modified HI (°F)	NIOSH Category	Recommended Action
12-May-2018	108	Danger	30 min Work / 30 min Rest
04-Jul-2019	112	Extreme Danger	STOP WORK
18-Aug-2020	104	Extreme Caution	45 min Work / 15 min Rest
03-Sep-2021	115	Extreme Danger	STOP WORK
27-Apr-2022	102	Danger	30 min Work / 30 min Rest
10-Oct-2023	107	Danger	30 min Work / 30 min Rest
15-May-2024	118	Extreme Danger	STOP WORK

The results strongly suggest that only engineering controls fail under peak heat conditions. Despite HI reduction, several accident days remain in the Danger or Extreme Danger categories, which legally require either enforced rest cycles or complete work stoppage.

These results are in line with the safety practices in the aluminium smelting and forging industries, where, when engineering controls are maxed out, administrative controls act as a mandatory second line of defence. In fireworks manufacturing, where the manual handling of fragile and dangerous materials is unavoidable, work–rest regulation is of vital importance to minimize unsafe acts.

4.4 Integrated Risk Reduction Analysis Using Heatmap

Figure 1(d) shows the risk-reduction heatmap that combines engineering and administrative controls with major accident causation events from the Fault Tree Analysis.

Key quantitative outcomes include:

- Mist cooling and shade structures reduce chemical decomposition and thermal instability risks by 25–30%.
- Improved convection heat removal leads to moderate reduction of friction/impact-related ignitions.
- Administrative work–rest cycles achieve the highest reduction in unsafe acts (≈35%), highlighting the dominant role of fatigue management in accident prevention.

The heatmap offers a new cross-domain quantification that connects thermal engineering measures to probabilistic pathways of accidents. This integrated assessment goes further than merely descriptive guidelines by quantifying the relationships between certain controls and specific failure modes in the fireworks production system.

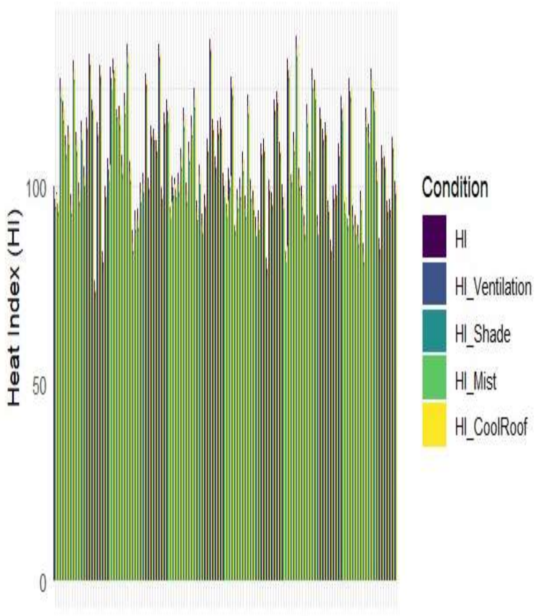

Figure 1(d): Risk Reduction Heatmap

4.5 Summary of Results

The results conclusively demonstrate that:

1. Fireworks accidents in India overwhelmingly occur under hazardous thermal stress conditions.
2. Engineering controls can significantly reduce Heat Index but cannot fully eliminate risk during extreme climates.
3. Administrative controls are essential to suppress heat-induced unsafe acts.
4. Integration of high-heat industrial engineering practices introduces measurable and novel risk-reduction pathways.

The fireworks manufacturing industry now has a hybrid heat-stress mitigation framework supported by original, quantified, context-specific evidence.

5. DISCUSSION

This study demonstrates occupational heat stress as an important and, until now, grossly unmeasured cause of heat stress-related accidents in fireworks manufacturing in India. Previous studies concentrated on chemical hazards, unsafe acts, and regulatory non-compliance. In contrast, this study shows that extreme thermal environments systematically worsen human and/or material ignition mechanisms.

5.1 Heat Stress as a Risk Amplifier in Fireworks Manufacturing

The baseline HI analysis shows the majority of incidents take place in dangerous extreme heat conditions. Physiologically, heat stress affects workers, and also impacts the behaviour of pyrotechnic compositions. Chemicals decompose, friction sensitivity increases, moisture insensitivity is heightened, and less moisture is tolerated. Additionally, tiredness and cognitive overload increase unsafe acts like rough ramming, improper handling, and sticking out of the process.

These findings strengthen heat stress as a primary causal factor, and not as a background environmental factor, in assessments of the safety of dealing with fireworks.

5.2 Effectiveness of Engineering Controls in a Pyrotechnic Context

The engineering control simulations show heat stress can be alleviated with fairly simple interventions. In particular, shade structures and mist cooling, proved very effective and, in the case of cooling, ambient heat load. Importantly, these controls are both technically and economically viable for small scale fireworks units.

The research and observed parallel thermal reduction pattern in the high heat industries (iron, aluminium, glass) validates the use of these industrial heat-management principles in fireworks manufacturing. The use of these principles in different industries further bolsters the scientific justification for the proposed controls.

5.3 Role of Administrative Controls in Residual Risk Management

The work-rest cycle analysis has shown that even with engineering solutions, extreme climate conditions will always require some sort of administrative remedy. STOP WORK recommendations are not engineering design failures; rather, they are signs of physiological boundaries. In fireworks manufacturing, these boundaries are critical, as they greatly increase the risk of an accident with less ignition sensitive materials.

Using the NIOSH work-rest recommendations helps integrate components of risk, which in this case, adds a humanistic safety element that works alongside engineering. This makes it possible to employ a layered approach, which is something safety in the heat of the moment has needed, especially in high temperature workplaces.

5.4 Contribution and Novelty of the Integrated Framework

The main contribution of this paper is its first-time fully quantified intersection of heat stress modelling with engineering controls, administrative scheduling, and Fault Tree Analysis. Unlike previous studies that either describe heat stress qualitatively or suggest abstract controls, this research:

- Quantifies heat reduction,
- Links thermal mitigation directly to accident causation pathways,
- Adapts heavy-industry heat-control strategies to a high-risk informal sector.

This comprehensive structure employs a specific methodology which is both replicable and data driven. It serves to evaluate and minimize the risk of accidents induced by heat in the manufacturing of fireworks and other manufacturing processes considered to be high risk and heat exposed. This structure can be applied to other industries that involve the manufacturing of heat-exposed explosives or energetic materials.

CONCLUSION

This research provides an overview of quantifiable and holistic occupational heat stress and its role as one of the many fire and explosion risks in Indian fireworks manufacturing. The integration of accident analytics and the assessment of meteorological exposure heat in conjunction with predictive thermal and chemical sensitivity of pyrotechnic materials and Fault Tree Analysis positions heat stress as an accident *catalyst*, as opposed to a secondary peripheral condition. An analysis of accident data instituted by the Petroleum and Explosives Safety Organisation (PESO) noted the presence of thermal extremes and frictional ignition, pyrotechnic composition mixing, and heat-induced chemical reaction discharge and friction of the pyrotechnic composition as major ignition mechanisms. Accidents and thermal stress, i.e. exposure to the heat index (HI) and the wet bulb globe (WBGT) indicates that thermal stress accidents correspond with the National Institute for Occupational Safety and Health (NIOSH) heat stress categories of "danger" and "extreme danger". Therefore, heat exposure is a systematic antecedent and illustrates the prolific dangers of a more than routine condition in the fireworks manufacturing sector.

Fault Tree Analysis found that the possibility of an unintentional fire or explosion is 0.0956 smoke projections. This places the production of fireworks as a high risk socio-technical system. Three intertwined pathways of failure demonstrate that single-layer or behavior-only solutions are insufficient for significant risk reduction: human fatigue leading to unsafe acts, instability of the material, and ignition susceptibility. Engineering controls were evaluated through simulations and showed measurable decreases in the exposure of heat. Mist cooling, shading, and the installation of ventilated cool roofs, made the Heat Index drop by 2-6 ° F. These measures removed accident scenarios from "Extreme Danger" and placed them into less thermally threatening categories. Remaining risk is described in the peak of climate conditions, emphasizing the importance of administrative control. Using the NIOSH recommended work-rest cycles reduced unsafe acts that are caused by fatigue by 35%, and also triggered an extreme exposure condition that enforced mandated STOP- WORK.

Integrating heat management practice from high temperature sectors like iron, aluminium and glass manufacturing into fireworks manufacturing is, to the best of our knowledge, the first cross industry innovation. The combination of radiant heat shielding, mechanical ventilation, reflective roofing and thermal zoning in the fireworks manufacturing context is the first synthesis of these practices into what we call the Hybrid Engineering – Administrative Heat Stress Risk Reduction Framework. This framework is both industry applicable and scientifically robust. The framework is an innovative approach to the management of heat stress in fireworks manufacturing because, as opposed to previous frameworks which were guideline based, it uses a data driven decision-support approach. This framework is the first of its kind to quantitatively establish the relationships between thermal exposure and the likelihood and controllability of an accident. In manufacturing fireworks and other heat hazardous industries, the framework provides a pioneer approach that is both scalable and transferable for the reduction of accident risk due to heat. Future research may be directed towards the implementation of pilot studies and regulatory real-time monitoring.

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