Critical Analysis of Smoke Management System and Strategies in Healthcare Facilities

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Abstract: Hospital facilities are unique environments that require robust fire and life safety measures due to the presence of vulnerable occupants (critical and bedridden patients, majority of them are on life support systems), complex building layouts, vital medical infrastructure, and bona-fide hospital operations, including various procedures in OTs, ICUs, ICCUs, NICUs, PICUs, radiation therapies, etc., where the safety and well-being of patients, medical staff, and visitors are of utmost importance. Therefore, fire incidents in hospitals pose significant risks due to all these vulnerabilities, complexities, and potential for high patient occupancy.

This article presents a systematic study, performance review, and critical analysis of passive measures, protection system, smoke control & smoke management system and strategies in different super-specialty healthcare facilities, both under the public and private sectors. In these endeavours, various healthcare facilities were extensively audited from the fire & life safety point of view and results were drawn on the basis of systematic gap identification and risk analysis. Further, the results of a thorough investigation and critical analysis of each hospital case with regard to the effectiveness & efficient operation of the smoke management system and integration of various smoke management strategies, emphasizing their mutually significant interactions were also outlined in this paper. It also identifies the ways in which these systems interact with one another, which is important for coordinating efforts to improve fire and life safety as well as the overall resilience of healthcare facilities.

Keywords: **Smoke management system, passive measures, protection system, smoke management strategies, healthcare facilities, fire protection & life safety.**

I. INTRODUCTION

Healthcare facilities are always safe and secure places to get treatment for the general public. In general, healthcare facilities are well-equipped to deal with external disasters, but situations caused by internal risks are more serious and frequently necessitate an emergency evacuation of the facility. Fire incidents are one of the most significant potential risks in healthcare settings out of all hazards. There had been significant death tolls in many incessant hospital fires over the past few decades, and the modern building design components, internal furnishings, and finishings have put forth heightened fire & life safety risks, primarily owing to smoke & toxic products of combustion. Fire & life safety code compliances and building regulations are usually given less attention, primarily during the building design process, the goal being to meet the bare minimum criteria based upon the prescriptive codes in practice, merely to meet the building occupation requirements.

Smoke is known to be the main cause of death in fire scenarios. In hospital buildings, smoke often migrates to locations remote from the fire space, threatening life and damaging hospital infrastructure. Stairwells and elevator shafts frequently become smoke-logged, thereby blocking evacuation and inhibiting rescue and firefighting. The concepts of smoke control and smoke management were developed to address these problems caused by smoke and toxic products of combustion. New concepts addressed system reliability, smoke obscuration, smoke toxicity, driving forces of smoke movement, and various smoke management strategies to mitigate the smoke-related hazards in healthcare facilities.

Taking into consideration the provisions for fire protection & life safety made under Part-IV of the National Building Codes of India-2016, the parameters pertaining to only ‘smoke control/management system and strategies’ have been thoroughly evaluated through a framework already in place. Towards these endeavours, six super-speciality healthcare facilities—four in the government sector and two in the private sector—spread throughout the country have undergone a comprehensive audit from the perspective of fire and life safety in order to assess the current state of the effectiveness and reliability of the smoke management systems in those healthcare facilities

1.2. Historical context and evolution of Smoke Management strategies in healthcare sectors

Smoke management systems evolved significantly after high-rise fires in the 1960s highlighted the dangers of smoke spread through the stack effect and HVAC systems. Early strategies included: Stairwell pressurization to maintain tenable evacuation routes. HVAC shutdown to prevent smoke circulation. Fire floor exhaust systems to limit horizontal smoke movement. These methods were later adapted for large-volume spaces like atria, emphasizing smoke exhaustion and buoyancy-driven venting.

As per the provisions made in the ‘National Building Codes of India, 2016’- (Part-IV), Passive measures in healthcare facilities include 2 hrs fire rated doors & assemblies; integrity of fire/smoke check doors; smoke seals, corner seals, compartmentation; fire resistive construction/fire rated walls, barriers, smoke vents, shafts, sealing of horizontal & vertical openings; whereas, the Protection systems includes fire hydrant, hose reel & wet riser; sprinkler system; smoke detection and alarm system; public address system; clean agent-based fire suppression system; exit signage, provision of smoke curtains/barriers; overall upkeep and operation & maintenance of these systems and training of healthcare professionals, staff and other key stakeholders in operation of the above systems and emergency evacuation procedures.

During a fire emergency in healthcare buildings, the most lethal factor affecting the occupants is the spread of smoke and toxic gas movements in the compartment, adjacent spaces, and the egress corridors. It is a well-established fact that most casualties are attributed to the smoke & toxic fumes.

Initially, pressurization was the main focus of smoke control measures. However, in order to ensure life and fire safety in healthcare facilities or any other high-rise occupancy, the mechanisms of compartmentation, dilution, air flow, and buoyancy have been implemented, either separately or in combination, as a part of a smoke management strategy. Effective smoke ventilation and preventing the spread of smoke through various methods help to reduce smoke-related fatalities. General awareness, training programs, and mock drills provide stakeholders with the necessary knowledge, skills, and practice to protect patients and employees.

Besides these strategies, efficient and effective operation of the fire protection system and integrity of passive measures have a significant impact on the smoke control & management systems in healthcare facilities.

Further, the effective integration of smoke management systems, passive measures, and protection systems plays a crucial role in ensuring life and fire safety in healthcare environments. Research on how to improve hospital buildings' overall safety by integrating smoke management systems with passive measures and protection systems has been scant.

This research study has identified six different super-specialty healthcare institutions spread across various regions of the country to explore various smoke management system components, their layout and critical gaps in the systems, effective strategies, technologies, and design considerations for the integration of these systems, ensuring efficient management of smoke and toxic products of combustion and protection of occupants during fire events. There had been different smoke management strategies tailored to the specific need and layout of the hospital building and arrangement of various critical and sub-critical facilities, which may include smoke compartmentation, stairwell pressurization, atrium smoke control, smoke exhaust systems, dedicated smoke control zones, integration with fire alarm systems, and computer modelling & analysis.

II. SMOKE MANAGEMENT METHODS

There are different smoke management methods available for buildings that contain large, enclosed spaces. Morgan et al. [1] describe various alternative approaches, one of the approach is `*Smoke and heat exhaust ventilation –*

`Smoke management in buildings with large, enclosed spaces is generally provided by a Smoke and Heat Exhaust Ventilation System (SHEVS). Hot smoky gases are collected at a high level and vented to the outside (see Figure 1). Supply of inlet replacement air below the smoke layer is crucial and must be included in the design along with the sizing of the smoke venting system. Natural or mechanical exhaust ventilators can be used, with the latter required, for example, if external wind effects are likely to reduce the efficacy of smoke exhaust. Some form of physical smoke containment may also be required, for example, using smoke curtains or down-stands to create smoke reservoirs. A critical design parameter for this type of system is the clear layer height between the occupants and the smoke layer interface. Guidance on acceptable clear layer heights varies worldwide [2-5] but is usually of the order of 2 to 3 m above the highest egress route open to the enclosed space.

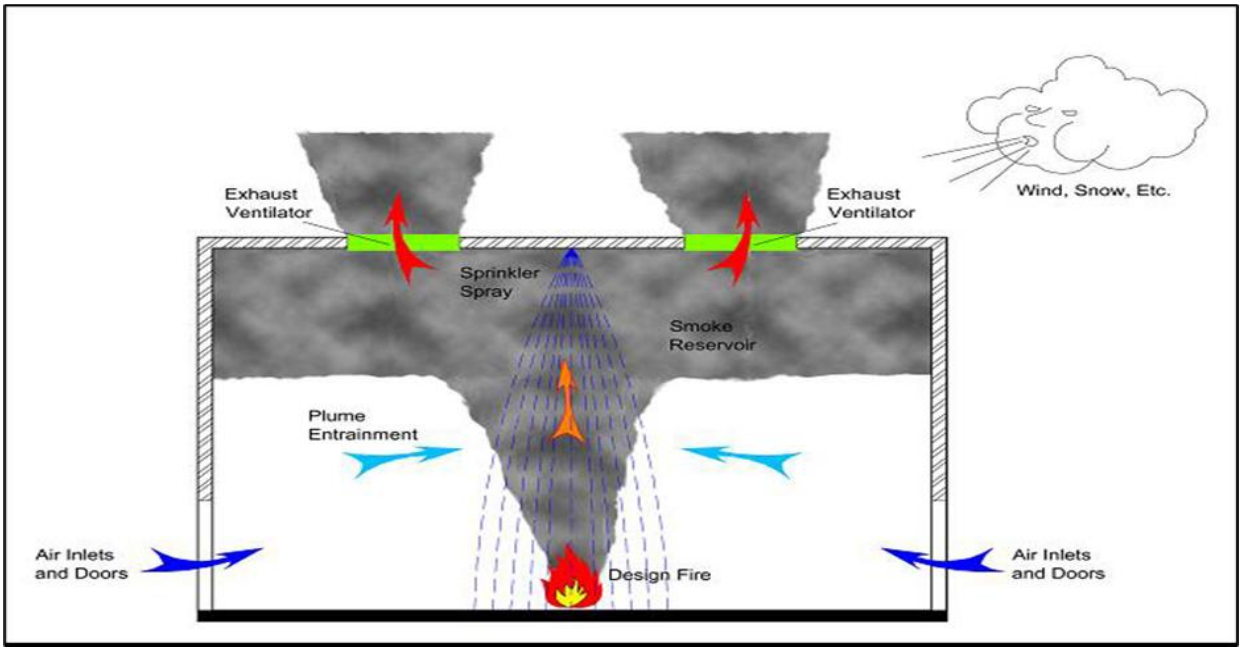

Figure 1: Smoke and Heat Exhaust Ventilation (courtesy of NV IFSET SA)

2.1 Significance of Smoke Control System:

Smoke Control System

A smoke control system is a mechanical or passive system designed to manage and direct smoke in a building during a fire, helping to keep escape routes clear and improve visibility for evacuation. It typically includes the use and maintenance of smoke exhaust fans, pressurization systems, fire dampers, and automatic controls to contain or remove smoke from specific areas. These systems are crucial in high-rise buildings, tunnels, and large structures to enhance fire safety and compliance with building codes.

Passive and Active Smoke Control System:

Passive smoke control systems rely on physical barriers like fire-resistant walls, doors, and smoke curtains to contain smoke. Active systems use mechanical components such as fans, pressurization systems, and exhaust vents to control smoke movement. Both works together to enhance fire safety and evacuation. [2] ([2] Paul, V.K. et al., 2021).

Importance

Smoke control systems play a critical role in fire safety by managing smoke movement to protect building occupants and first responders. By keeping escape routes clear and improving visibility, they reduce the risk of smoke inhalation, which is the leading cause of fire-related deaths.

These systems also help firefighters by controlling heat and smoke, making fire suppression and rescue efforts more efficient. Additionally, they limit property damage and ensure compliance with fire safety regulations, reducing legal and financial risks for building owners.

III. LITERATURE REVIEW

Since 2010, electric short circuits have been the primary cause of fire events in healthcare facilities, reported in the media, with air conditioning equipment accounting for almost 80% of these incidents overall [3]. ([3] SSR IJCMPH 3896-3906, Vol. 7, Issue 10, 2020; Patharla et al). The majority of air conditioners are located in areas with large and variable loads, such as intensive care units (ICUs) and NICUs with ventilator support and OTs, where oxygen-enriched air was the primary cause of nearly all fires [4]. ([4] J Clin Anesth 414-24, 26 2014; K. Chowdhury). The majority of the deaths in these air-conditioned areas were from asphyxia, which is the inhaling of smoke and harmful gases, and they mainly lacked natural ventilation. Significant incapacitation (loss of consciousness) may result from direct exposure to heat and/or harmful combustion products; it may even lead to death in case of severe exposure.

If the fire protection and life safety system, including passive measures, protection systems, and smoke management systems, are not correctly planned, installed, maintained, and monitored for fail-safe operations on a 24x7 basis, even a small fire in the hospital facilities could grow into a catastrophic situation.

In the event of a major fire in any hospital building, the main combustion products are heat, light, infrared radiation, smoke, toxic fumes, and water vapor due to the availability of complex and large-scale inventories, storage, internal furnishings, fixtures, upholstery, etc.

In contrast, smoke and toxic fumes can pose serious health risks to hospital occupants, leading to mass casualties from excessive inhalation of these substances, including carbon monoxide (CO), carbon dioxide (CO_2), hydrogen cyanide (HCN), and acrolein[3] (i.e., propenal (CH_2-CH-CHO)). Heat exposures can also have serious effects on the integrity of building infrastructure. These include hydrogen chloride (HCL), sulphur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), isocyanates (RNCO), phosphorous compounds, and various volatile hydrocarbons (VOCs), such as benzene (C_6H_6), toluene (C_6H_5-CH_3), styrene (C_6H_5-CH=CH_2), naphthalene ($C_{10}H_8$), 1,3-butadiene ((CH_2=CH)$_2$), and others [5]. [5] [Burgess et al. 1979].

Dilution, ventilation, and/or smoke containment are typically three-dimensional approaches that take into account the type and potential of fire and smoke produced, fuel density and geometry, intensity, and rate of fire and smoke spread in order to keep the indoor environment of healthcare facilities within tenability limits and to mitigate the potential hazards of smoke and other toxic products of combustion as explained in the preceding paragraphs. This allows for the safe, timely, and orderly evacuation of occupants while also achieving the goals of life and fire safety.

Additional crucial elements, such as ASET (Available Safe Egress Time) and RSET (Required Safe Egress Time), are significant factors from the emergency evacuation point of view. The efficacy of containing fire and smoke in the zone of origin is mostly influenced by the degree of difficulties faced by fire and rescue personnel as well as the intensity of the fire [6] ([6] Silcock & Shields, 2000). Smoke can move at nearly 2 meters per second, or 5 miles per hour [7] ([7] EN 12101-6), which is faster than the occupant's fastest escape speed, which is 1.75 m/sec [8] ([8] Redoje B. Jevtic, 2020); however, in the event of extremely poor visibility, it drops to 0.2 m/sec, and further escape is impossible beyond the point of incapacitation, or the loss of the ability to evacuate oneself [9] ([9] ISO/TS-21602).

A super-specialty high-rise hospital building's residents can evacuate safely and quickly using a variety of methods, such as simultaneous evacuation, phased evacuation, relocation, and defend-in-place. The safe egress time for occupants varies between 3 and 10 minutes according to various prescriptive national and international building codes and standards. These can vary significantly depending on the actual fire conditions, such as performance-based criteria, codes and standards that cover the nature and geometry of combustible materials, fire load and fuel density, the layout, integrity, and behaviour of building components and passive measures (such as fire retardant coatings or paints, unexposed/cement coated steel frames or structures), the rate of rise and spread of fire and smoke on a specific floor, and the protection system that would activate in the event of a fire or smoke logged conditions and a shift in the residents' ethological characteristics in such an event. Prescriptive and performance-based rules may differ significantly in how they calculate the safe egress time, which may not be precisely known. A performance-based code establishes "how a building is to perform" in the event of fire or other extremes, while a prescriptive code specifies "how a building is to be constructed" [10]. ([10] (Buchanan & Abu, 2017).

IV. METHODOLOGY

The following approaches have been used to conduct and advance the research study:

i) Extensive literature reviews on the subject have been studied, systematically analyzed, and reviewed with respect to smoke control and management in different building typologies, with specific emphasis on healthcare facilities and codes of practice & standards, nationally and internationally.
ii) Analyzed previous research studies in the relevant domain and available results and identified gaps to further this study.
iii) Analytical and descriptive analysis of building plans, different building codes, and pertinent fire prevention, life, and fire safety laws and regulations in different countries.
iv) Evaluation of the case in relation to the availability and proper operation of different life and fire safety features in the relevant hospital building and performance assessment of the smoke control/management system and thorough typical system functional tests during the fire and life safety audit.
v) Analysing each hospital building case viz-a-viz the standard protocols and codes of practices with regard to the efficacy of the smoke management system, its reliability and status of integration with passive measures and protection system through the Building Management System, and identification of critical gaps in each case.
vi) Inferences drawn for future research focused on enhancing the general fire and life safety elements of hospital facilities with the ultimate goal of empowering hospital administrators to offer a secure and reliable healthcare environment worldwide.
vii) The research project is methodically moving forward to concentrate on the following areas:

➢ Examination of six hospitals' smoke control and management systems and its effectiveness through-

- Using dampers to control smoke infiltration in unaffected regions and their integration with the smoke detection and alarm system.
- Integrity of supply and return air ducts/paths from/to AHU.
- Sealing of horizontal and vertical services openings, shaft openings, etc.
- Pressurization of fire towers, stairwell shafts, elevator shafts, lift lobbies, connecting pathways to exit routes, and passages to areas of refuge.
- Provisions of smoke detectors in return air ducts/paths and AHU rooms.
- Integrity of fire/smoke check doors and their ability to provide effective compartmentation.
- Availability, status, and functionality of the integration of the building management system with passive measures, the protection system, and the HVAC system.
- Overall system upkeep, O&M, and general management.
- Level of awareness, knowledge, training, and mock drill rehearsals of hospital staff and scenarios and frequency of such drills and record upkeeping.

viii) Additionally, a number of case studies of deaths brought on by ongoing smoke and fire in hospital facilities, an analysis of the causes of death, deductions, the identification of any gaps, and recommendations for corrective measures to fill them.

V. ASSESSMENT OF FUNCTIONAL RELIABILITY OF SMOKE MANAGEMENT SYSTEM & INTEGRATION STRATEGIES

5.1 Key components of effective smoke management systems in healthcare facilities

Effective smoke management systems in healthcare environments are engineered to limit smoke movement, maintain tenable conditions for evacuation or relocation, and protect vulnerable occupants and critical infrastructure. The following are the primary components and strategies identified in the course of study:

I. Compartmentation and Pressure Differentials

i) The building's inherent compartmentation, such as fire-rated walls and floors, is fundamental. Pressure differentials across these boundaries, achieved by mechanical systems, control air and smoke movement between zones.
ii) "Building pressurization," or the "pressure sandwich" method—exhausting the fire floor while pressurizing adjacent floors—remains a common approach to prevent smoke spread beyond the area of origin.

II. Stairwell and Elevator Shaft Pressurization

Pressurizing stairwells and elevator shafts is critical in keeping evacuation routes free of smoke. This can be achieved via:
i) Top or bottom pressurization of stair shafts.
ii) Pressurized vestibules adjacent to stairwells.
iii) Multi-level pressurization using several smaller fans for optimal pressure distribution.

The design must ensure that door opening forces remain manageable for occupants and staff, even under pressurization.

III. HVAC System Controls
i) Automatic shutdown or modification of HVAC systems during a fire event is necessary to prevent smoke from circulating through air ducts and spreading to unaffected areas.
ii) Smoke dampers and automatic controls are integrated to isolate sections of the building as needed.

IV. Smoke Exhaust and Venting Systems
i) Direct venting of the fire floor through dedicated smoke shafts or automatic dampers is considered highly reliable.
ii) Natural venting via vertical shafts (e.g., elevator or stair shafts) and smoke vestibules with direct access to the exterior can be used, though their effectiveness may vary with weather and building configuration.

V. Atrium and Large-Volume Space Management
i) For spaces such as hospital atria, smoke management relies on chimney and venting principles, using mechanical or natural exhaust to remove smoke and maintain a smoke-free layer above occupants.
ii) Design criteria for such spaces are guided by standards like NFPA 92B, which prescribe exhaust rates and makeup air provisions based on expected fire size and smoke production.

VI. Automatic Sprinkler Integration
i) While primarily for fire suppression, sprinklers also influence smoke production and movement. Their integration with smoke management strategies is essential for comprehensive protection.

VII. System Testing, Maintenance, and Redundancy
i) Regular testing and commissioning of smoke management systems are critical to ensure functionality during an emergency.
ii) Redundancy in fans, controls, and power supplies enhances system reliability.

VIII. Code Compliance and Performance-Based Design
i) Systems must be designed, installed, and tested per relevant codes (e.g., NFPA 92 A/B, BOCA, ICBO) [11], with performance objectives focused on maintaining tenable conditions for the duration required for safe evacuation or relocation.

5.2 Critical Review and Analysis of Different Hospital cases with respect to Smoke Management System

Table-1 Analysis of functional reliability of smoke management system

System Components	Analysis					
Hospital Buildings (Govt./Private) / Parameters	GHB1	GHB2	GHB3	GHB4	PHB5	PHB6
Heating, Ventilation & Air Conditioning (HVAC) System	y	y	y	y	y	y
Integrity/Insulation of AHU Ducts	y	x	y	y	y	y
Availability of Return Air ducts	x	x	x	x	x	x

Provision of Smoke Detectors in Return Air ducts & AHU	y	y	x	x	x	x
Provision and functioning of Dampers in Supply and Return Air ducts in AHU	y	y	x	x	x	y
Fire Stops/Sealing of Openings around AHU ducts	x	x	x	x	x	y
Mechanical Ventilation System/Natural vents	x	x	x	x	x	y
Pressurization of Means of Escape	x	x	x	x	x	y
Pressurization of Lift and Staircase lobbies	x	x	x	x	x	y
Floor Openings in Service Shafts	x	x	x	x	x	y
Atrium Smoke Extraction System	x	x	x	x	x	x
Building Envelope/Façade Fire Safety	x	x	x	x	x	x
Integration of Smoke Management System with Passive measures and Protection systems	y	x	x	x	x	y
Integrated Building Management System (IBMS)	y	x	x	x	x	y
Overall Upkeep and O&M	x	x	x	x	x	y
Training & Rehearsal of Periodic Mock Fire/Evacuation Drills	x	x	x	y	x	x

Legend:

x - Non-functional	GHB—Govt. Hospital Building
y- Functional	PHB- Private Hospital Building
0- Not Required/Not Available	

Table-2

5.3 Related functions of smoke management system components

Following are various system components which renders specific smoke management functions in buildings-

Component	Function in Smoke Management
Compartmentalization & Pressurization	Isolates smoke; prevents cross-zone spread
Stairwell/Elevator Pressurization	Maintains clear evacuation routes
HVAC Controls & Dampers	Stops smoke recirculation via ducts
Smoke Exhaust/Venting	Removes smoke from affected zones
Atrium Management	Maintains smoke-free layers in large spaces
Sprinkler Integration	Suppresses fire, limits smoke generation
Testing & Redundancy	Ensures system reliability and readiness
Code Compliance	Aligns system with best practices

These components, when integrated and maintained, form the backbone of effective smoke management systems in healthcare settings, ensuring both patient safety and regulatory compliance.

5.4 Core smoke management strategies

A structured review of key smoke management strategies and their synergistic interactions is devised

through this research study, taking into account extensive field studies across various building typologies and occupancies in large metropolitan cities.
The following excerpts are deduced through this study:

Passive Design Measures

i) Compartmentation: Fire-resistant walls and doors to contain smoke spread, with case studies showing 87+ smoke zones in large hospitals.
ii) Pressurization: Stairwells and elevators use pressure differentials to prevent smoke ingress, though conflicts may arise with infection control HVAC requirements.
iii) Exterior vent placement: Strategic venting enhances buoyancy-driven smoke evacuation, reducing toxicity risks.

Active Systems

i) HVAC reconfiguration: Systems switch to 100% exhaust mode during fires, creating negative pressure in affected zones while maintaining positive pressure in adjacent areas.
ii) Dedicated smoke control fans: Either standalone or integrated with building management systems, these achieve airflow rates of 3–6 air changes per hour in smoke zones.
iii) Firefighter control panels: Provide real-time system status without allowing manual overrides to prevent operational errors.

Operational Protocols:

i) Automated sensor networks: Detect smoke density and trigger dampers/fans within seconds, critical in facilities with immobile patients.
ii) Quarterly testing: Mandatory for healthcare facilities to verify pressure differentials (≥ 0.05–0.10 inches of water) and door opening forces (< 30 lbs).
iii) Staff training: Mock drills reduce evacuation time by 40% in hospitals with complex layouts.

5.5 Strategic Integration

The integration strategies for various smoke management system components and their resultant outcomes have further been analysed as described below:

Table-3 Strategic interactions, benefits, and challenges

Component	Interaction Benefit	Challenge
Compartmentation + HVAC	Limits smoke spread to 12,000 SF zones while enabling targeted exhaust	Retrofitting difficulties in aging facilities
Pressurization + Sensors	Maintains stairwell integrity during multi-floor evacuations	Balancing infection control pressures
Training + Ventilation	Enables staff to manually override failed dampers in 67% of simulated emergencies	High turnover requiring frequent drills

5.6 Future Directions

i) Smart HVAC systems: Machine learning algorithms to predict smoke dispersion patterns in real time.
ii) Hybrid pressurization: Dual-mode systems accommodating both smoke control and infection prevention.
iii) NFPA 101 updates: Expected mandates for monthly smoke damper inspections in critical care units by 2026.

VI. RESULTS AND DISCUSSION

i) One smoke detector in the ground-level ward is signalling a false fire alert.
ii) The trauma ward's vertical fire riser shaft apertures from the ground floor to the upper floor lack a cavity barrier.
iii) Due to trauma ward doors being open, return air may not be getting enough thrust through the false ceiling.
iv) The absence of smoke detectors in AHU rooms of trauma center wards could allow smoke-laden air

to pass undetected through the AHU's supply air ducts.

v) ICUs at the Trauma Centre had vertical apertures or cavities along the fire riser shaft and electrical shafts, respectively.

vi) Interaction with the concerned senior nursing officer and nursing officers in the Trauma Center's intensive care units revealed that the emergency preparedness plan of the "Trauma Center" did not include any concept of horizontal/phased evacuation of critical patients.

vii) The aluminum-frame glass panel doors that separate trauma wards lack the structural integrity to withstand a two-hour fire and do not provide effective smoke or fire sealing.

viii) In corridors, fire check doors are kept open and secured with chains on both sides. Opening fire doors in the hallway compromises the width of the passage.

ix) Effective containment and compartmentation measures are not in place in the wards of the Trauma Center. A condition of complete chaos could result from the unfettered movement of toxic smoke and fire in the interconnected wards, hallways, and escape routes.

x) The upper floor's fire hydrant and hose reel hose system were inaccessible. There was a substantial load of flammable materials on the ground floor on the backside.

xi) Most of the time, corridors, the entrances of OTs and ICUs, etc., have glass and plywood panels with aluminum frame doors that don't fit well enough to adequately seal the space they serve.

xii) There is no air pressurization system in place to stop smoke from entering common spaces or egress routes.

xiii) There are no fire or smoke check doors in the hallways, the approach to the stairs, or the elevator lobby.

xiv) The absence of a smoke control system throughout the hospital building, which was not included in the building design itself, includes mechanical ventilation, air pressurization, and a water curtain for big open spaces to offer effective compartmentation in the event of a fire. ICUs, OTs, common spaces, trauma ICU neurosurgery wards, and ortho surgery wards all include smoke detectors.

VII. RECOMMENDATIONS AND CONCLUSION

According to the checklists, the overall effectiveness of the smoke management system in all four government hospitals and one of the two private hospitals has largely found compromised, which has attributed to multiple-factors, including failure to seal horizontal and vertical services and shaft openings, poor compartmentation, defective closure mechanism & push bar on fire doors, fire doors that remain open in corridors to allow patients and visitors to move freely, a non-functional smoke detection and alarm system, non-availability & compromised integrity of return air ducts/path for HAVC system, failure to integrate the smoke detection and alarm system & HVAC system with the Integrated building management system. These factors put hospital inmates' life safety and fire protection at heightened risk, as well as the possibility of disrupting entire hospital operations in the event of an uncontrolled fire or smoke event.

7.1 Recommendations

The significance of smoke control and management systems, which include passive measures and protection systems, is crucial for maximizing life and fire safety in hospital buildings.

After having evaluated all the extensive field studies across various super-specialty hospitals, following recommendations are drawn out in order to optimize the fire and life safety in healthcare facilities -

i) All corridors and exit pathways, particularly those leading to critical care sections such as intensive care units, and inpatient wards, must have fire/smoke check doors with two-hour fire resistance and smoke curtains installed in order to avoid the rapid and uncontrolled spread of harmful fumes and fires throughout the hospital complex.

ii) In the event of an emergency, the ideas of "progressive/horizontal evacuation" and "defend in place" will be taken into consideration.

iii) It is necessary to have staircase pressurization in order to stop smoke from entering staircase shafts.

iv) Regular testing of stairway pressurization systems and their integrated operation, together with protective systems like sprinkler systems and flow switches and fire detection and alarm, guarantees their efficient and easily accessible functioning to meet any emergency evacuation of inhabitants.

v) To enable a safer and quicker evacuation, common spaces and exit routes must be air-pressurized.

vi) Effective life and fire safety in the hospital building requires the installation of a mechanical ventilation/smoke extraction system and its connection with the building management system.

vii) It is necessary to properly seal both horizontal and vertical apertures or cavities with a two-hour fire-resistant substance to stop smoke and flames from spreading through them.

7. 2 Conclusion

The case study approach outlined in the preceding paragraphs has been found to be of much significant value and further enables the identification and correlation of the ground realities with the majority of the system vulnerabilities, which may otherwise lead to significant impact on the fire and life safety of not only the critical and vulnerable patients and medical and non-medical staff but also the entire hospital operations.

The case study methodology adopted has demonstrated significant utility in systematically identifying and correlating on-site realities with predominant system vulnerabilities, which, if unaddressed, could critically compromise fire and life safety for patients, healthcare personnel, and the continuity of hospital operations.

The following conclusive inferences have been drawn from the case study approach:

1. The fundamental instruments for safer and quicker hospital occupant evacuations are the proper design and efficient implementation of pressurization of escape routes and common spaces (such as lift and stair lobbies) and effective compartmentation through fire/smoke check doors and/or smoke curtains.
2. In order to optimize smoke control and guarantee effective life and fire safety in hospital buildings, it is essential to integrate the concept of passive measures and protection systems into the building design itself.
3. The Integrated Building Management System (IBMS) plays a more crucial part in this endeavor by controlling HVAC operations and preventing smoke from entering unaffected areas through efficient damper control.
4. Defend in place strategy or horizontal/lateral evacuation of vital patients and others to the pre-designated areas/compartments on the same level or other adjacent building blocks.
5. Public address systems play a crucial role in maintaining effective command and control over the situation, directing residents toward a controlled and organized evacuation, and reducing disorder.

8. Declaration of competing interest

The author(s) declare that they have no known competing financial interests that could have influenced the research work reported in this paper.

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