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Fire Behaviour and Fire Safety in the Built Environment: An Analytical Review of Emerging Hazards

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ABSTRACT

Background: Fire behaviour in the built environment results from a coupled sequence of chemical and physical processes that begin at ignition and, depending on fuel, ventilation, and compartment geometry, may culminate in flashover, sustained fully developed burning, or extinction. A sound and up-to-date understanding of these processes provides the scientific basis for fire-safety engineering, regulatory development, and hazard reduction. This need is especially acute in India, where the National Crime Records Bureau (NCRB) recorded 5,888 fire-accident deaths in 2024 alone, and where major fire incidents provide documented examples of interactions among fire dynamics, building conditions, emergency response, and fire-safety implementation. This review situates that Indian experience alongside major international fire disasters, including Grenfell Tower in London and the January 2025 Los Angeles wildfires.

Scope: This analytical review synthesises established and current (2018–2025) literature on fire initiation, compartment fire dynamics, smoke generation and toxicity, fire spread mechanisms, predictive modelling, and two fast-evolving application areas — lithium-ion battery energy storage fires and mass timber construction — where classical fire science is being actively extended. It further incorporates incorporates a dedicated literature review, a tabulated synthesis of the sources examined, statistical analysis of NCRB fire-accident data for India with accompanying bar-graph visualisations, and five real-world case studies (three Indian, two international) selected analytically to examine how established fire-science mechanisms interact with building design, materials, regulation, emergency response, and operational practice. The review also applies a structured qualitative cross-case framework to five incidents to identify recurring fire-safety mechanisms and implementation issues.

Methodology: The review uses a transparent narrative-synthesis approach combined with structured qualitative cross-case analysis. Searches covered Scopus, Web of Science, Google Scholar, major publisher indexes, standards databases, government repositories, and official inquiry/investigation records. Peer-reviewed literature from 2018–2025 was prioritised for rapidly evolving topics, while foundational texts and standards were retained where they provide established technical bases.

Key findings: Flashover in typical compartments is associated with an upper-layer gas temperature of approximately 500–600°C and a floor-level radiant heat flux of approximately 15–20 kW/m²; fire severity is governed primarily by ventilation factor and fuel load rather than fuel chemistry alone; smoke exposure remains a major contributor to fire fatalities; mass timber compartments exhibit nominal char rates on the order of 0.6–0.7 mm/min for structural members (higher, up to approximately 1.2 mm/min, in some full compartment tests); lithium-ion battery thermal runaway, triggered at cell temperatures often in the 150–250°C range, remains a rapidly evolving fire safety research priority; and the cross-case analysis identifies recurring roles for combustible fuel load, smoke and egress constraints, external/cavity spread, battery-specific hazards, and ember-driven wildland-urban interface ignition. For India specifically, NCRB data show fire-accident deaths declining by roughly 35% between 2019 and 2024, yet 60.4% of 2024 fire deaths still occurred in ordinary residential

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buildings and roughly one in six fire deaths nationally is attributed to electrical short-circuits — a conventional and potentially preventable fire hazard.

Conclusion: Continued research integrating experimental, computational (notably NIST's Fire Dynamics Simulator, the FDS 6.10-series releases), and performance-based approaches is essential to keep fire safety engineering aligned with evolving construction materials, energy technologies, and climate-driven hazard patterns. For India specifically, the evidence assembled here suggests that improved implementation and enforcement of existing fire-safety provisions may offer an important near-term opportunity for risk reduction.

KEYWORDS: *fire dynamics; fire behaviour; flashover; heat release rate; smoke movement; compartment fire; fire modelling; lithium-ion battery fire; mass timber fire performance; performance-based design; facade fire spread; wildland-urban interface fire; fire incident case studies; India fire safety; National Building Code of India; NCRB fire statistics.*

1. INTRODUCTION

1.1. Background and Significance

Fire remains one of the most persistent hazards to life, property, and infrastructure despite decades of advancement in fire safety engineering, detection technology, and regulatory control. Structural fires continue to cause substantial annual loss of life and economic damage worldwide, with the majority of fatalities attributable not to direct flame contact but to smoke inhalation and, in a smaller proportion of cases, structural collapse. Effective prevention, detection, and suppression strategies all depend on a rigorous understanding of fire science — the study of how fires ignite, grow, spread, and behave under varying environmental and material conditions.

Fire is a highly nonlinear phenomenon: small changes in fuel geometry, ventilation, or compartment configuration can produce disproportionately large changes in fire severity and growth rate. This nonlinearity is precisely what makes fire science both scientifically demanding and practically essential — building codes, suppression system design, and evacuation strategy all rest on assumptions about fire behaviour that must be grounded in sound, current physical understanding rather than intuition or outdated generalisation. In simple terms, fire safety engineering only works if the science behind it keeps pace with how buildings, materials, and energy systems are actually changing on the ground.

1.2. Why This Study Matters

Three global trends make a consolidated, current review of fire science especially urgent at this point in time. First, cities are building taller and denser, and refurbishment of ageing housing stock increasingly relies on lightweight facade and insulation systems whose fire performance is not always fully understood before installation — a gap that the Grenfell Tower fire exposed in the starkest possible terms. Second, the energy transition has placed lithium-ion batteries in vehicles, homes, and industrial storage facilities at a scale unimaginable a decade ago, introducing a fire hazard — thermal runaway — that behaves nothing like a conventional solid or liquid fuel fire and that most existing codes were not written to address. Third, climate-driven changes in temperature, rainfall, and wind patterns are lengthening wildfire seasons and intensifying wind-driven urban conflagrations in the wildland-urban interface, as seen in the January 2025 Los Angeles firestorms.

Alongside these global shifts, fires such as major fire incidents in India illustrate a recurring interaction between conventional fire dynamics, fuel load, means of escape, and the implementation of fire-safety provisions in ordinary premises. Taken together, these incidents demonstrate that fire science is not a settled, historical discipline; it is a living field that must be continuously re-validated against new materials, new energy technologies, and new climatic conditions. Accordingly, the review distinguishes established principles from areas where recent evidence has refined earlier understanding and uses documented incidents to examine how those principles perform in practice.

1.3. Fire Safety in the Indian Context: Scale of the Problem

India's own accident statistics make the case for this review in the clearest possible terms. The National Crime Records Bureau (NCRB), under the Ministry of Home Affairs, publishes fire-accident data annually as part of its Accidental Deaths and Suicides in India (ADSI) report. Figure 1 plots the reported national fire-accident death toll from 2019 to 2024: deaths fell from 10,915 in 2019 to 5,888 in 2024, a decline of roughly 35% over five years, with the extent to which this decline reflects changes in urban fire response, public awareness, code enforcement, or other factors requiring separate analysis.

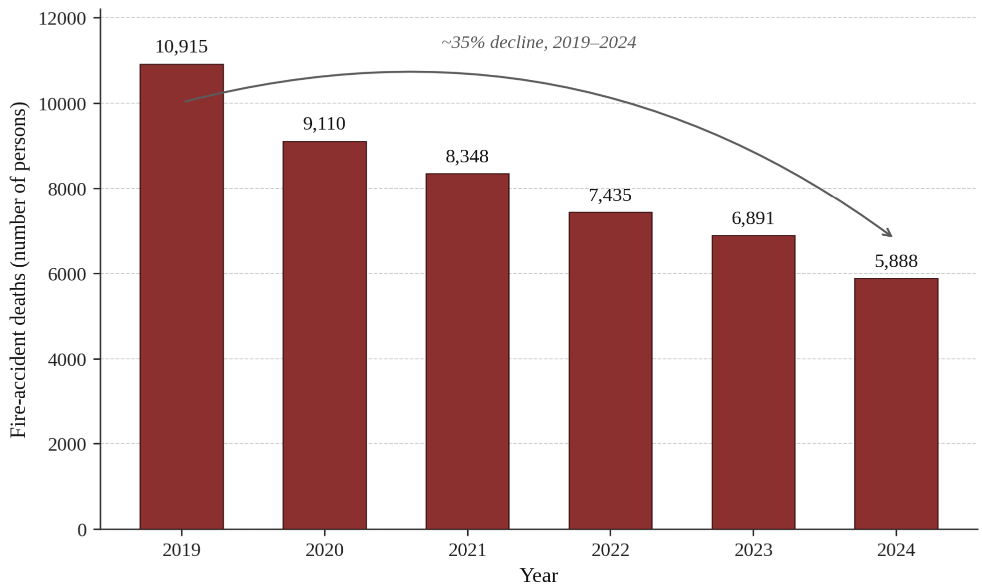

Figure 1. Accidental fire deaths in India, 2019–2024. Source: NCRB, Accidental Deaths & Suicides in India (ADSI), annual reports.

Despite this encouraging downward trend, the composition of the 2024 figures is telling. As Figure 2 shows, 60.4% of all fire-accident deaths in 2024 (3,555 of 5,888) occurred in ordinary residential buildings, not in industrial plants, high-rise towers, or exotic-material facades — underscoring that the everyday domestic environment, not the landmark building, remains India's single largest fire-safety blind spot. Cause-wise data for the same year attribute approximately 17% of fire-accident deaths nationally (1,012 of 5,888) to electrical short-circuits, making faulty wiring and overloaded circuits the single most commonly identified preventable cause. These figures are consistent with the pattern seen across the Indian case studies examined in Section 11, where electrical faults, blocked or absent egress, and unauthorised structural additions recur again and again as causal factors, largely independent of building type or city.

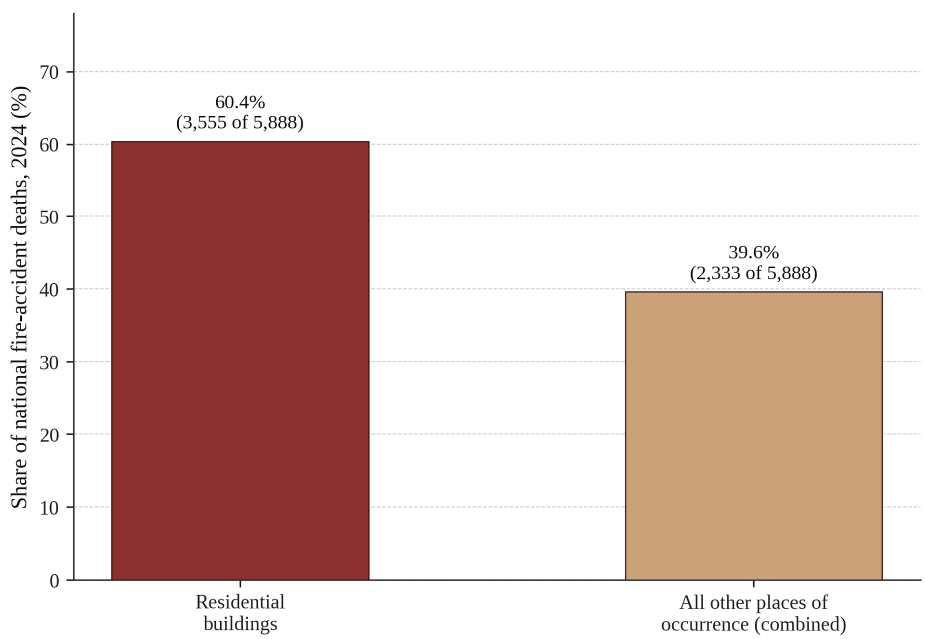

Figure 2. Place of occurrence of fire-accident deaths in India, 2024. Source: NCRB, ADSI 2024, Chapter 1 (Fire Accidents).

India's principal fire-safety instrument is the National Building Code of India (NBC), published by the Bureau of Indian Standards, most recently substantially revised in 2016 with further part-wise amendments through 2023; Part 4 of the NBC specifically addresses fire and life safety. However, the NBC is a model code that individual states and municipal bodies must separately adopt and enforce through local building bylaws and fire NOC (No-Objection Certificate) systems administered by state fire services — and the case studies in Section 11 repeatedly illustrate how differences between prescribed requirements and conditions observed in practice can affect fire outcomes. The selected cases do not establish that this implementation gap is the dominant cause of fire deaths nationally, but they provide a consistent basis for examining it as an important fire-safety systems issue. This distinction between what the code says and what gets built and inspected on the ground is a central theme of this review.

1.4. Scope, Objectives, and Analytical Contribution

This review aims to: (i) consolidate the fundamental chemistry and physics governing fire ignition and growth; (ii) describe the recognised stages of compartment fire development and the parameters governing transitions between them, with verified quantitative criteria; (iii) examine smoke generation, movement, and toxicity as a major contributor to fire fatality; (iv) review fire spread mechanisms within and between compartments and buildings; (v) compare predictive modelling approaches used in current research and design practice, including the current development state of NIST's Fire Dynamics Simulator; (vi) examine two rapidly evolving application areas — lithium-ion battery fire safety and mass timber structural fire performance — in depth, using recent (2022–2025) peer-reviewed findings; (vii) present a structured literature review and tabulated synthesis of the sources examined, together with statistical analysis of Indian fire-accident data; (viii) analyse five major real-world fire incidents — three from India and two international — to ground the theoretical material in practical consequence, with particular emphasis on the Indian regulatory and enforcement context; and (ix) identify specific, evidence-based research and policy gaps suitable for original investigation.

Contribution of the Review. The principal contribution of this review is a unified analytical framework that connects fundamental fire dynamics with emerging material and energy hazards and tests those concepts against documented fire incidents through structured qualitative comparison. Rather than treating the incidents as isolated narratives, the review compares them using common dimensions of ignition, fuel/material contribution, spread mechanism, smoke and egress, regulatory or management conditions, fire-science lesson, and evidence strength. This approach is intended to identify recurring mechanisms and implementation issues while preserving the limitations imposed by heterogeneous source quality and non-representative case selection.

1.5. Search Strategy, Selection Criteria, and Analytical Framework

This review is a narrative evidence synthesis rather than a systematic review or meta-analysis. The heterogeneous evidence base includes peer-reviewed research, foundational texts, standards, government statistics, public-inquiry material, and incident records. The search strategy was structured to improve transparency and reproducibility, but the manuscript does not report a formal PRISMA screening count and therefore makes no systematic-review claim.

1.5.1. Databases and Repositories Searched

1. Academic literature: Scopus, Web of Science, Google Scholar, and publisher indices (Elsevier ScienceDirect, Springer, MDPI, Wiley Online Library) for peer-reviewed journal content.
2. Standards and codes: ISO, NFPA, and the Bureau of Indian Standards (BIS) publication catalogues for the National Building Code of India.
3. Government and statistical sources: NCRB publication archive (Accidental Deaths and Suicides in India, 2019–2024 editions); NIST technical publication repository; Grenfell Tower Inquiry published evidence and reports.
4. Investigative and legal records: official state/municipal investigation findings, court judgments, and multiple corroborating contemporaneous news reports for each fire incident examined in Section 11.

1.5.2. Search Terms

Searches combined core terms — ‘flashover criteria’, ‘compartment fire dynamics’, ‘heat release rate’, ‘lithium-ion thermal runaway’, ‘mass timber char rate’, ‘facade fire spread’, ‘fire dynamics simulator’, ‘smoke toxicity’ — with, for the India-specific material, ‘NCRB fire accident statistics’, ‘National Building Code of India fire safety’, and the name of each individual incident examined in Section 11 (e.g., ‘Uphaar Cinema fire’, ‘Grenfell Tower fire’).

1.5.3. Inclusion and Exclusion Criteria

- Included: peer-reviewed journal articles, government statistical publications, and official investigation/inquiry reports published in English; foundational textbooks regardless of publication date, given their role as the field's standard references; peer-reviewed literature and technical reports published between 2018 and 2025 prioritised for currency on rapidly evolving topics (lithium-ion battery safety, mass timber, computational modelling).

- Excluded: non-peer-reviewed blog or opinion content except where used solely to corroborate factual incident details (casualty counts, dates) alongside at least one other independent source; sources unavailable in English; preprints not subsequently published or independently corroborated, except where explicitly flagged as such in the text.

1.5.4. Synthesis and Verification Approach

Sources were grouped thematically across combustion and fire dynamics, smoke and tenability, spread, modelling, performance-based design, emerging hazards, and incident evidence. Quantitative statements were checked against the cited literature where possible. Incident claims were prioritised from official inquiries, government records, court documents, or multiple independent reports; where final technical investigations were unavailable, conclusions are explicitly treated as provisional.

This is a narrative review and does not report new experimental, survey, or simulation data. The final submission should be checked against the selected journal's specific originality and reporting requirements.

1.5.5. Structured analytical framework

To move beyond descriptive case-study narration while preserving the review design, the five incidents were analysed using a common qualitative coding framework. Each incident was examined across six dimensions: (1) primary ignition or initiating hazard; (2) dominant fuel or material contribution; (3) principal fire-spread mechanism; (4) smoke, tenability, and egress conditions; (5) regulatory, design, or management issue; and (6) principal fire-science lesson. A seventh field records the strength and type of evidence supporting the interpretation, distinguishing official inquiry or government findings from court records, preliminary investigations, peer-reviewed studies, and corroborated contemporaneous reporting. The framework is comparative rather than a numerical risk score: it is intended to identify recurring mechanisms and implementation patterns across heterogeneous incidents without implying that the cases form a statistically representative sample.

The analytical unit is the incident, but the interpretation is organised around fire-safety mechanisms rather than casualty ranking. Recurring mechanisms were therefore identified by convergence across cases—for example, compromised egress, smoke spread, uncontrolled fuel load, external or cavity spread, and differences between prescribed and observed safety conditions. Because the evidence bases differ substantially between incidents, the framework does not assign numerical weights or aggregate a composite risk index. This preserves traceability to the source evidence and avoids false precision.

2. Literature Review

This section reviews the body of published work underpinning the technical discussion that follows, organised thematically rather than chronologically so that the reader can see how different strands of research feed into a common picture of fire behaviour. The literature is synthesised thematically to distinguish established knowledge, recent developments, limitations, and implications for the present review.

2.1. Foundational Textbooks and Handbooks

The conceptual backbone of modern fire science rests on a small number of foundational texts. Drysdale's An Introduction to Fire Dynamics remains the standard reference for the physics and chemistry of ignition, plume behaviour, and compartment fire growth, while Karlsson and Quintiere's Enclosure Fire Dynamics and Quintiere's Fundamentals of Fire Phenomena provide the quantitative, equation-based treatment of compartment fires that underlies most engineering calculations used today. The SFPE Handbook of Fire Protection Engineering, edited by Hurley and now in its fifth edition, consolidates contributions from specialists across detection, suppression, structural fire engineering, and human behaviour in fire, and functions as the closest thing the discipline has to a single authoritative reference work. These texts were written and repeatedly revised across several decades of experimental testing, and this review treats their core quantitative criteria — particularly the numerical thresholds associated with flashover — as a reliable baseline against which more recent, narrower studies can be compared.

2.2. Standards and Technical Guidance

International standards translate fire science into testable, enforceable criteria. ISO 5660-1 defines the cone calorimeter method used to measure heat release rate at bench scale, and is the basis for most material-level fire hazard classification used in this review. NFPA 92 sets out design principles for smoke control systems, while

NFPA 921 provides the methodology used by fire investigators to reconstruct fire origin and cause — a methodology implicitly reflected in how the case studies in Section 11 are analysed. These standards matter for this review because they are the mechanism by which laboratory-derived fire science actually reaches buildings; a finding that never makes it into a standard or code has limited practical safety impact, however scientifically interesting it may be.

2.3. Flashover and Compartment Fire Research

A cluster of studies published between 2021 and 2024 has re-examined the classical flashover criteria — approximately 500–600°C upper-layer gas temperature or 15–20 kW/m² floor-level heat flux — under a wider range of ventilation and fuel conditions than the original mid-twentieth-century experiments used to derive them. The consistent finding across this literature is that the classical thresholds hold well as an engineering approximation, but that severely oxygen-limited compartments (below roughly 14–15% ambient oxygen) can suppress or delay flashover even when the thermal criteria would otherwise be satisfied. This is a genuinely important refinement: it means ventilation-controlled dynamics, not temperature alone, ultimately govern whether and when flashover occurs, which has direct implications for firefighting tactics such as controlled ventilation and door control during search-and-rescue operations.

2.4. Smoke, Toxicity, and Human Tenability Research

Research on smoke toxicity consistently identifies carbon monoxide as the dominant asphyxiant in structure fires, with hydrogen cyanide increasingly implicated as synthetic, nitrogen-containing polymers have become more common in furnishings, insulation, and cladding. This literature places greater emphasis on whether occupants can remain tenable and evacuate before smoke exposure becomes incapacitating, which is precisely the logic embedded in available safe egress time (ASET) versus required safe egress time (RSET) calculations used throughout performance-based design.

2.5. Facade and External Fire Spread Research

The period following the Grenfell Tower fire in 2017 produced a substantial and still-growing literature on facade fire spread, ventilated cavity behaviour, and full-scale facade fire testing. This research consistently finds that combustible cladding and insulation materials, combined with unsealed or poorly detailed cavity barriers, allow fire to bypass internal compartmentation entirely and propagate vertically at rates far exceeding those typical of internal compartment-to-compartment spread. The public inquiry into the Grenfell Tower fire, discussed in detail in Section 11.4, is itself treated in this review as a primary evidentiary source precisely because its expert witness hearings generated an unusually detailed, evidence-based account of facade fire dynamics in a real building rather than a test rig.

2.6. Computational and Data-Driven Modelling Research

The modelling literature spans three broad families — empirical correlations, zone models such as CFAST, and computational fluid dynamics tools such as NIST's Fire Dynamics Simulator (FDS) — each validated against different classes of experimental data and each suited to different design contexts. A newer and fast-growing strand applies machine learning, including convolutional neural networks for image-based flame and smoke detection and surrogate models trained on CFD output, to reduce the computational cost of fire growth and smoke movement prediction. This literature is still maturing: most published studies rely on relatively small or synthetic training datasets, and the review treats machine-learning-based fire prediction as a promising but not yet fully validated addition to the modelling toolkit rather than a replacement for physics-based models.

2.7. Lithium-Ion Battery Fire Safety Research

Lithium-ion battery fire safety has become one of the most active research areas in fire science over the past five years, driven by the scale-up of electric vehicles and grid-scale battery energy storage systems. Recent reviews (Jia et al., 2025; Li et al., 2025; Wang et al., 2025; Zhao et al., 2025) converge on several consistent findings: thermal runaway trigger temperatures typically fall in the 150–250°C range depending on cell chemistry and state of charge; propagation from a single failed cell to adjacent cells within a module is the primary mechanism by which a localised failure becomes a large-scale fire; and suppression is complicated by the fact that thermal runaway can continue through internal electrochemical and exothermic processes, so suppression strategies must address heat removal, propagation, gas hazards, and re-ignition rather than relying on oxygen exclusion alone. These consistent findings across independent reviews strengthen confidence that thermal runaway behaviour, once triggered, follows a broadly similar pathway regardless of the specific application (vehicle, consumer electronics, or stationary storage).

2.8. Mass Timber Fire Performance Research

Mitchell et al. (2023) provide a comprehensive review of full-scale mass timber compartment fire experiments, finding that exposed cross-laminated timber and glulam surfaces contribute additional fuel to a compartment fire beyond what non-combustible construction would provide, elevating both charring rate and peak compartment temperature relative to standard fire-resistance test assumptions. A key open question repeatedly flagged in this literature — and one this review treats as a genuine research gap rather than a settled matter — is whether an exposed timber char layer will self-extinguish once the room's other fuel is consumed, or whether it will continue to smoulder and require active firefighting intervention.

2.9. Synthesis and Identified Gaps From the Literature

Reading across these eight strands of literature together, three gaps recur often enough to be treated as priorities for future research: (i) validated, non-standard (realistic, decaying) fire exposure data for mass timber, since almost all current char-rate data comes from standard furnace curves that do not reflect how real compartment fires actually decay; (ii) large, standardised, publicly available datasets for training and validating machine-learning-based fire and smoke detection models, without which comparison between competing published methods remains difficult; and (iii) forensic-quality, fire-science-literate reconstruction of real fire incidents of the kind produced by the Grenfell Tower Inquiry, which remains rare for fires outside the UK and is an important limitation when interpreting incident-level evidence in this review.

3. Summary of Literature Reviewed

Table 2 below consolidates the principal sources examined in preparing this review, indicating the type of source, its thematic focus, the specific observations drawn from it, and how each source was applied within this paper. The table is organised in the same thematic order as Section 2.

Author(s) & Year	Source Type	Focus Area	Key Observations Noted	Relevance to This Review
Drysdale (2011)	Textbook	Fire dynamics fundamentals	Establishes the physical and chemical basis of ignition, plumes, and compartment fire growth; source of core flashover temperature criteria.	Foundation for Sections 3–5 on combustion chemistry and compartment dynamics.
Karlsson & Quintiere (2000)	Textbook	Enclosure fire dynamics	Provides quantitative equations for compartment temperature rise and ventilation-controlled burning.	Basis for HRR and ventilation-factor discussion in Section 5.3 and 6.2.
Quintiere (2006)	Textbook	Fundamentals of fire phenomena	Systematic treatment of ignition, flame spread, and fire growth modelling.	Cross-referenced for t-squared growth model and flame spread theory.
Hurley, ed. (2016)	Handbook	Comprehensive fire protection engineering	Multi-author synthesis spanning detection, suppression, human behaviour, and structural fire engineering.	Referenced throughout Sections 5–10 for engineering practice context.
Kanury (1975)	Textbook	Combustion phenomena	Classical treatment of combustion chemistry and heat of combustion.	Supports Section 3.2 discussion of gas-phase oxidation chemistry.
Babrauskas (2003)	Reference text	Ignition science	Detailed compilation of ignition temperatures, thermal inertia, and material ignition parameters.	Basis for Table 1 (ignition parameters).
Buchanan & Abu (2017)	Textbook	Structural design for fire safety	Links compartment fire severity to structural fire resistance design methods.	Supports Section 10.2 on structural fire resistance.
ISO 5660-1 (2015)	International standard	Bench-scale HRR	Defines cone calorimeter oxygen-consumption	Basis for Section 5.3 heat release rate

		measurement	calorimetry methodology.	measurement discussion.
NFPA 92 (2022)	Standard	Smoke control system design	Codifies pressurisation, venting, and compartmentation requirements for smoke control.	Supports Section 7.4 smoke control strategies.
NFPA 921 (2021)	Standard/guide	Fire and explosion investigation	Establishes systematic methodology for fire origin and cause determination.	Implicit methodological basis for the case-study analyses in Section 11.
Recent flashover re-examinations (2021–2024, various)	Peer-reviewed journal articles	Flashover criteria under varied ventilation	Confirm classical 500–600°C / 15–20 kW/m² criteria but show oxygen-limited compartments can suppress flashover below ~14–15% O_2.	Refines Section 5.2.2 discussion of flashover conditions.
Peacock, Reneke & Forney (2021)	NIST technical report	CFAST zone model documentation	Documents the two-layer zone-model approach and its validated range of applicability.	Basis for Section 9.2 zone model discussion.
McGrattan et al. (2023); UL FSRI (2025)	NIST/UL technical reports	Fire Dynamics Simulator (FDS)	Documents FDS 6.10 release, 3-D heat conduction, and new pyrolysis sub-model improvements.	Basis for Section 9.3 CFD discussion.
Jia et al. (2025)	Peer-reviewed review, eTransportation	Li-ion battery energy storage system fire safety	Proposes layered (cell/module/container) fire safety strategy; reviews suppression agent performance.	Core source for Sections 2.7 and 12.
Li et al. (2025)	Peer-reviewed review, Energy & Environmental Materials	Battery electrolyte and cell design for fire safety	Reviews flame-retardant electrolyte formulations and thermoresponsive design strategies.	Supports Section 12 discussion of suppression and design mitigation.
Wang et al. (2025)	Peer-reviewed journal, World Electric Vehicle Journal	Thermal runaway warning and suppression	Reviews early warning systems based on gas/voltage signatures and suppression agent trials.	Supports Section 12 discussion of early detection.
Zhao et al. (2025)	Peer-reviewed journal, Battery Energy	Puncture-induced thermal runaway	Experimentally links mechanical damage to thermal runaway onset in EV collision scenarios.	Supports Section 12 discussion of trigger mechanisms.
Mitchell et al. (2023)	Peer-reviewed review, Fire and Materials	Mass timber compartment fire experiments	Consolidates char rate data; identifies self-extinction vs smouldering as a key open question.	Core source for Sections 2.8 and 13.
NIST NCSTAR 1A (2008)	NIST investigation report	WTC Building 7 structural fire collapse	Provides a rigorously documented case of structural fire-induced progressive collapse.	Referenced in Section 10.2 as a benchmark structural fire investigation.
Grenfell Tower Inquiry, Phases 1–2 (2019, 2024)	Public inquiry report / expert evidence	Facade and cladding fire causation	The Inquiry identified combustible ACM cladding and cavity-barrier deficiencies as major contributors to vertical fire spread.	Primary source for Section 11.4 case study.

Post-event analysis, Los Angeles Palisades & Eaton wildfires (2025)	Government damage assessment and press investigation	Wildland-urban interface fire spread	Government and fire-agency assessments attribute rapid structure-to-structure spread in part to wind-driven ember transport and elevated antecedent fuel conditions.	Primary source for Section 11.5 case study.
Bureau of Indian Standards, NBC Part 4 (2016, amended)	National model building code	Fire and life safety provisions for Indian buildings	Sets compartmentation, egress, and material requirements; adoption and enforcement is delegated to states/municipalities.	Core source for Section 1.3 and the Indian case studies in Section 11.
NCRB, ADSI annual reports (2019–2024)	Government statistical publication	National fire-accident casualty statistics	Shows a ~35% decline in fire deaths 2019–2024, but 60.4% of 2024 deaths still occur in residential buildings; ~17% attributed to electrical short-circuit.	Basis for Section 1.3 statistical analysis and Figures 6–7.

Table 1. Summary of principal literature and investigative sources reviewed, organised thematically.

4. Fundamentals of Combustion and Fire Chemistry

4.1. The Fire Triangle and Fire Tetrahedron

Combustion requires the simultaneous presence of fuel, an oxidising agent (typically atmospheric oxygen), and an ignition source of sufficient energy — commonly represented as the 'fire triangle' (Drysdale, 2011). Fire science extends this to the 'fire tetrahedron' by adding a fourth element: the self-sustaining chemical chain reaction that propagates combustion once initiated, illustrated schematically in Figure 3 (Drysdale, 2011). This distinction is significant because certain suppression agents act primarily by interrupting the chain reaction rather than by removing fuel, oxygen, or heat — which is why, for example, a clean agent extinguisher can put out a fire without cooling it or physically excluding air in the way water or foam does.

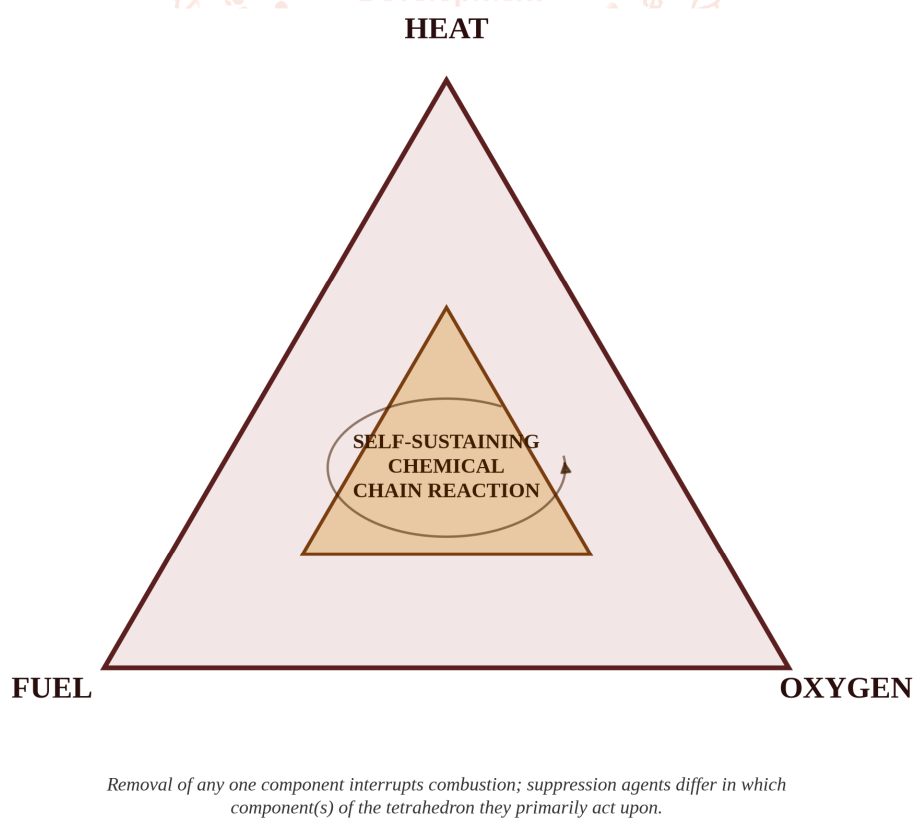

Figure 3. The fire tetrahedron: fuel, oxygen, and heat sustain a self-propagating chemical chain reaction.

4.2. Combustion Chemistry

Flaming combustion is fundamentally a gas-phase oxidation reaction between fuel vapours (or pyrolysis products, for solid fuels) and oxygen, releasing heat and forming products such as carbon dioxide, water vapour, carbon monoxide, soot, and, depending on fuel composition, other species including hydrogen cyanide and hydrogen chloride (Kanury, 1975; Drysdale, 2011). The heat of combustion — energy released per unit mass of fuel consumed — underpins heat release rate estimation and smoke toxicity potency calculations throughout fire hazard analysis. In plain terms, the hotter and more completely a fuel burns, the more heat it releases per kilogram, and this single number drives almost every downstream fire severity calculation.

4.3. Ignition Mechanisms

Ignition may be piloted (a flame, spark, or hot surface provides activation energy to ignite pyrolysis gases) or auto/spontaneous (a fuel-oxidiser mixture self-ignites once it reaches a sufficiently high temperature without an external source). A third pathway, smouldering ignition, involves slow, flameless surface oxidation of a porous fuel and can transition to flaming combustion under favourable conditions; smouldering is a well-documented cause of fires originating in upholstery and stored combustible materials. Key material parameters — flash point, fire point, auto-ignition temperature, critical heat flux, and thermal inertia — are typically measured using standardised bench-scale apparatus such as the cone calorimeter specified in ISO 5660-1 (ISO 5660-1, 2015; Babrauskas, 2003).

Parameter	Definition	Engineering Relevance
Flash point	Lowest temperature at which vapours ignite momentarily given an ignition source	Determines storage and handling classification of liquids
Fire point	Lowest temperature at which vapours sustain continuous combustion	Marginally higher than flash point; relevant to sustained burning risk
Auto-ignition temperature	Temperature at which a fuel ignites without an external ignition source	Governs hot-surface and self-heating hazards
Thermal inertia ($k\rho c$)	Product of thermal conductivity, density, and specific heat	Predicts time-to-ignition under radiant or convective heating
Critical heat flux	Minimum incident heat flux required for sustained ignition	Used in fire spread and separation-distance calculations
Effective heat of combustion	Net energy released per unit mass burned	Input to heat release rate and fire severity calculations

Table 2. Key material ignition parameters and their engineering significance.

5. Compartment Fire Dynamics

5.1. Fire Plumes and Ceiling Jets

Above a burning fuel source, buoyant combustion products rise as a fire plume, entraining surrounding air and forming a rising column of hot, low-density gases. Upon reaching a ceiling, the plume deflects horizontally to form a ceiling jet — a fast-moving layer of hot gases spreading radially outward beneath the ceiling. Ceiling jet characteristics govern the response time of ceiling-mounted heat and smoke detectors and sprinkler heads, which is why detector placement guidance is so specific about distance from walls and ceiling height (Drysdale, 2011; Karlsson & Quintiere, 2000).

5.2. Stages of Compartment Fire Development

Compartment fire development is typically described in four stages: incipient growth, growth, fully developed (post-flashover) burning, and decay, shown schematically in Figure 4. The rate and extent of progression through these stages depends strongly on fuel load, compartment geometry, lining materials, and ventilation.

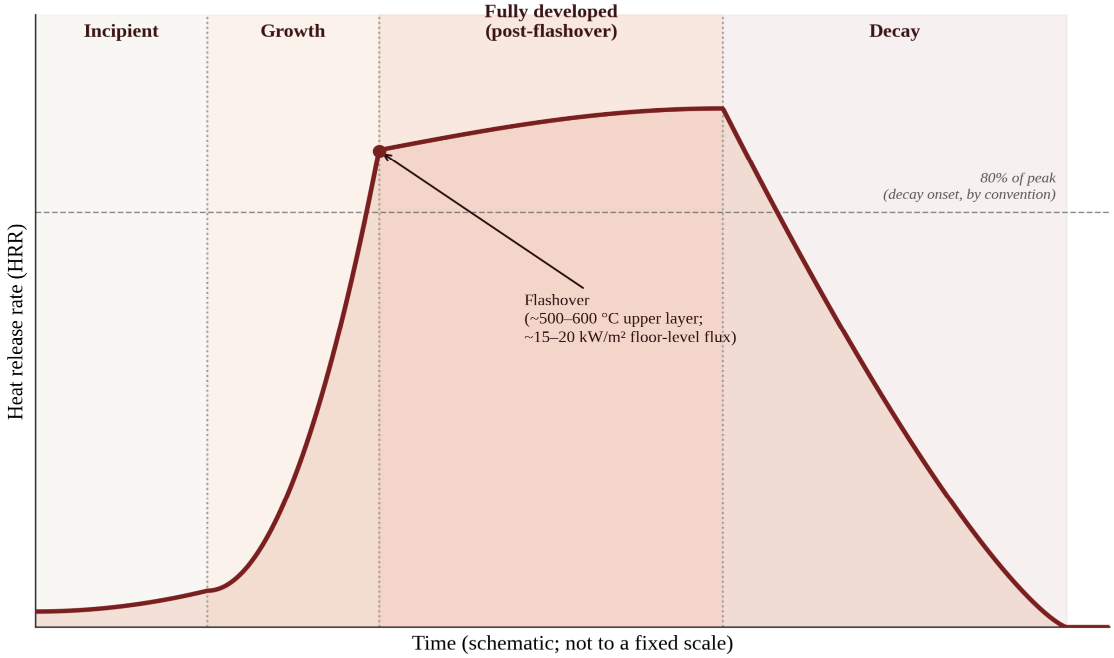

Figure 4. Stages of compartment fire development, showing heat release rate against time and the flashover transition.

5.2.1. Incipient and Growth Stages

During the incipient stage, a localised fire develops from the ignition source, releasing heat and smoke while entraining surrounding air and forming a smoke layer beneath the ceiling. In this stage the fire is generally fuel-controlled: heat release rate (HRR) is governed primarily by fuel burning characteristics and surface area rather than by available oxygen. Growth is frequently approximated using the t-squared fire growth model, in which HRR increases with the square of time from ignition, characterised as slow, medium, fast, or ultra-fast depending on fuel type (Quintiere, 2006; Karlsson & Quintiere, 2000).

5.2.2. Flashover

Flashover denotes a rapid transition from a localised fire to widespread involvement of combustible surfaces within a compartment. Frequently cited engineering indicators include upper-layer gas temperatures of roughly 500–600°C and floor-level radiant heat fluxes on the order of 15–20 kW/m²; these values should be treated as approximate indicators rather than universal physical thresholds because flashover depends on fuel configuration, ventilation, geometry, and thermal feedback. Oxygen limitation can delay or prevent transition to flashover under some conditions (Drysdale, 2011; Karlsson & Quintiere, 2000).

5.2.3. Fully Developed (Post-Flashover) Fire

Following flashover, the fire typically becomes ventilation-controlled: burning rate is limited by the rate at which oxygen enters through openings rather than by fuel surface area. Heat release rates in this phase are commonly estimated using ventilation-based correlations relating mass burning rate to the ventilation factor (opening area multiplied by the square root of opening height). Fully developed fires generate the highest thermal loads on structural elements and form the design basis for structural fire resistance requirements, including standard time-temperature curves used in fire-resistance furnace testing (Karlsson & Quintiere, 2000; Buchanan & Abu, 2017).

5.2.4. Decay

As fuel is consumed, heat release rate declines and compartment temperature falls; the decay phase is often defined as beginning once HRR drops below approximately 80% of its peak value. Structural elements may continue to weaken during decay due to cumulative thermal exposure even as visible fire diminishes, a key consideration for firefighter safety during overhaul operations and for post-fire structural assessment (Buchanan & Abu, 2017).

5.2.5. Backdraft and Ventilation-Limited Hazards

In severely ventilation-limited compartments, combustion may become starved of oxygen while unburned pyrolysis products and carbon monoxide accumulate. Sudden introduction of air — for example, when a door is opened — can result in backdraft: a rapid, sometimes explosive deflagration of accumulated gases. This phenomenon remains a major concern in firefighter safety and continues to inform tactical ventilation research and procedures, including positive-pressure ventilation and controlled entry techniques (Drysdale, 2011).

5.3. Heat Release Rate: Measurement and Significance

Heat release rate (HRR) is a central descriptor of fire size and is closely related to compartment heating, smoke production, and fire growth. Bench-scale HRR is commonly measured using oxygen-consumption calorimetry, including cone-calorimeter methods described in ISO 5660-1. The oxygen-consumption relationship is an engineering approximation whose applicability depends on fuel and measurement conditions; full-scale calorimetry is valuable for model validation and design-fire characterisation (ISO 5660-1, 2015). In plain terms, HRR is simply how much energy a fire is releasing per second — the single number that determines how quickly a room fills with heat and smoke, and it is measured in a laboratory by tracking how much oxygen the fire consumes.

6. Factors Governing Fire Behaviour

6.1. Fuel Load and Fuel Geometry

Fuel load density, arrangement, and surface-to-mass ratio strongly influence both fire growth rate and peak heat release rate. Distributed, high-surface-area fuels (e.g., upholstered furniture, cable insulation, stacked packaging) tend to burn faster and reach flashover more quickly than compact, low-surface-area fuels of the same mass. Fuel load surveys, commonly expressed in MJ/m² of floor area, underpin structural fire engineering design fire scenarios in national and international codes (Buchanan & Abu, 2017). This factor is particularly relevant to temporary or informally constructed structures — such as marquees, pandals, and pop-up commercial venues common at Indian fairs, exhibitions, and festivals — where stored combustible materials and fuel for generators or other equipment can create an unusually high and poorly distributed fuel load relative to the structure's fire-resistance and egress provisions.

6.2. Ventilation

Ventilation conditions determine whether a fire is fuel-controlled or ventilation-controlled and directly affect heat release rate, smoke production, and the likelihood of flashover or backdraft. Ventilation factor is a standard parameter in fire severity calculations, and changes in ventilation — from window failure, door opening, or mechanical smoke control operation — can produce abrupt changes in fire growth rate (Karlsson & Quintiere, 2000).

6.3. Compartment Geometry and Lining Materials

Ceiling height, compartment volume, and the thermal properties of wall and ceiling linings affect heat feedback to the fuel bed. Low ceilings and highly insulating linings promote faster temperature rise and earlier flashover by reducing heat losses from the hot gas layer, while high-volume or well-insulated compartments may delay or prevent flashover for a given fuel load (Drysdale, 2011).

6.4. Modern and Composite Materials

Contemporary construction increasingly uses engineered wood products, composite panels, and synthetic insulation materials whose fire behaviour differs substantially from traditional materials. Some composites exhibit rapid flame spread, high heat release, or the production of especially toxic or corrosive smoke, representing an active area of ongoing research, particularly for polymeric insulation, cored composite panels, and fibre-reinforced polymers used in structural and cladding applications — precisely the category of material implicated in the Grenfell Tower fire discussed in Section 11.4 (Grenfell Tower Inquiry, 2019, 2024).

7. Smoke Dynamics and Toxicity

7.1. Smoke Production and Composition

Smoke is a complex mixture of unburned fuel particulates, combustion gases, and entrained air, whose yield and composition depend on fuel chemistry, temperature, and oxygen availability. Under-ventilated, high-temperature combustion — typical of post-flashover fires — tends to produce higher yields of carbon monoxide and unburned hydrocarbons than well-ventilated flaming combustion (Hurley, 2016).

7.2. Smoke Movement Mechanisms

Smoke movement within buildings is driven by fire-induced buoyancy, the stack effect (temperature-driven pressure differences between a building's interior and exterior, or between floors), wind effects on the building envelope, and mechanical ventilation system operation. In multi-storey and high-rise buildings, smoke can migrate vertically through shafts, stairwells, and service penetrations well beyond the fire compartment, making smoke control system design — pressurisation, smoke venting, and compartmentation — a critical element of overall fire safety strategy (NFPA 92, 2022).

7.3. Toxicity of Combustion Products

Smoke exposure is a major contributor to fire fatalities, although the relative contribution of toxicants, hypoxia, thermal injury, and other mechanisms varies by incident. Carbon monoxide is an important toxicant in structure fires, while hydrogen cyanide may be significant when nitrogen-containing materials are involved. Reduced visibility can also delay or prevent evacuation and therefore forms an important tenability consideration in performance-based design (Hurley, 2016; SFPE, 2019). In plain terms, in most structure fires people are more likely to be harmed by breathing in toxic smoke and losing their way in the dark than by direct contact with flame, which is why smoke control and clear escape routes matter as much as fire suppression itself.

7.4. Smoke Control Strategies

Smoke control approaches include passive compartmentation (fire-resistance-rated walls, doors, and floor assemblies), natural and mechanical smoke venting, and pressurisation of protected escape routes such as stairwells and lift lobbies, as codified in guidance such as NFPA 92 (NFPA 92, 2022). Selection and design of these systems depends on building height, occupancy type, and the performance objectives established under the applicable fire safety design basis.

8. Fire Spread Mechanisms

Fire spread occurs through three principal heat transfer mechanisms, often acting simultaneously and each treated in detail by Drysdale (2011), shown schematically in Figure 5:

1. Conduction — heat transfer through solid materials, which can ignite fuel on the opposite side of a wall or floor assembly, relevant to fire compartmentation performance.
2. Convection — transport of hot gases and flame through openings, corridors, and shafts, often the dominant mechanism for smoke and fire spread between compartments and floors.
3. Radiation — direct thermal radiation from flames or hot surfaces igniting adjacent combustibles, a key mechanism in fire spread between buildings and across external facades.

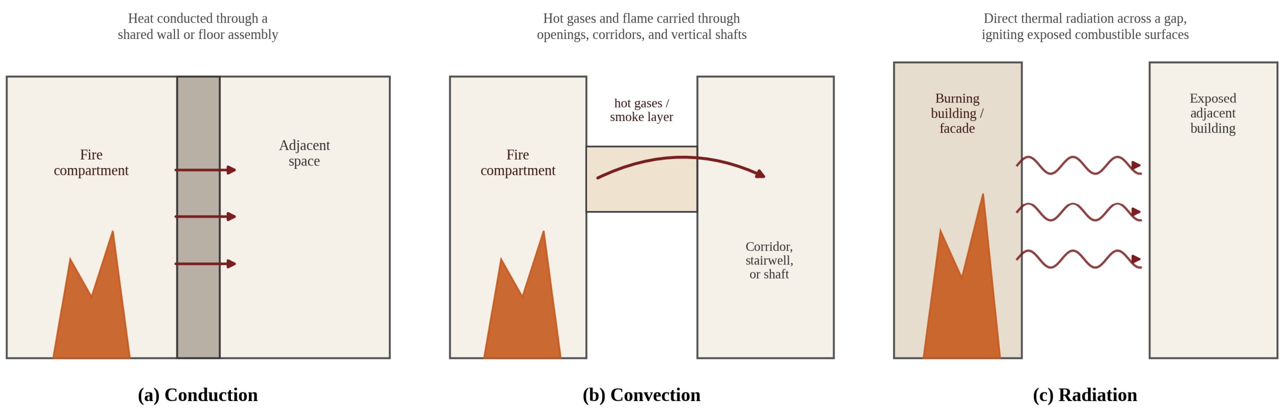

Figure 5. The three principal heat transfer mechanisms governing fire spread within and between buildings.

8.1. Internal Fire Spread

Within buildings, fire spread between compartments occurs primarily through unprotected openings, failure of fire-rated separating elements, and concealed spaces such as ceiling voids and service risers. Compartmentation — the subdivision of a building into fire-resisting cells — remains the primary passive means of limiting internal fire spread and is central to most prescriptive and performance-based building codes (Buchanan & Abu, 2017).

8.2. External and Facade Fire Spread

External fire spread via combustible facade systems and ventilated cavity spaces has drawn substantial regulatory and research attention internationally in the past decade, driving increased use of full-scale facade fire testing, cavity barrier design requirements, and restrictions on combustible cladding materials on tall buildings in multiple jurisdictions. Facade fires can propagate vertically at rates far exceeding internal compartment fire spread, bypassing conventional compartmentation strategies entirely — as demonstrated with tragic clarity by the Grenfell Tower fire, examined in detail in Section 11.4 (Grenfell Tower Inquiry, 2019, 2024).

8.3. Wildland and Wildland-Urban Interface Fire Spread

Fire spread in vegetative fuels is governed by fuel moisture content, wind speed, slope, and fuel bed continuity. In the wildland-urban interface (WUI), ember transport (firebrands) ahead of the main fire front is a dominant mechanism of structure ignition, often occurring well in advance of direct flame contact and driving the need for defensible space and ember-resistant construction detailing. The January 2025 Los Angeles wildfires, examined in Section 11.5, are among the clearest recent illustrations of wind-driven ember transport igniting whole neighbourhoods of structures far ahead of the advancing flame front (Los Angeles County / California, 2025).

9. Fire Behaviour Modelling and Prediction

Predictive modelling supports both research and performance-based fire safety design, with three broad approaches in common use, summarised in Table 3.

Modelling Approach	Description	Typical Application
Empirical / algebraic correlations	Closed-form equations relating HRR, flame height, or temperature to fuel and ventilation parameters	Rapid hand calculations, preliminary design
Zone models	Compartment divided into upper (hot) and lower (cool) gas layers with lumped conservation equations (e.g., CFAST)	Compartment fire hazard analysis, teaching, code-compliance checks
Computational Fluid Dynamics (CFD)	Field models such as Fire Dynamics Simulator (FDS) solving discretised conservation equations across a 3D grid	Complex geometries, smoke movement studies, performance-based design

Table 3. Comparison of common fire behaviour modelling approaches.

9.1. Empirical Correlations

Empirical correlations, derived from experimental data, provide rapid estimates of key fire parameters such as flame height, plume temperature, and flashover heat release rate. Their simplicity makes them valuable for preliminary design and hand-calculation checks, though their validity is generally restricted to the range of conditions under which they were originally derived (Karlsson & Quintiere, 2000; Quintiere, 2006). In plain terms, these are tested rules of thumb — quick to use, but only reliable within the same kind of room, fuel, and fire size they were originally tested on.

9.2. Zone Models

Zone models divide a compartment into a small number of control volumes — typically an upper hot gas layer and a lower cool layer — and solve simplified mass and energy conservation equations for each. Tools such as CFAST (Consolidated Fire and Smoke Transport, maintained by NIST) remain widely used for rapid hazard screening, teaching, and situations where full CFD analysis is not justified by the complexity of the geometry or required precision (Peacock, Reneke & Forney, 2021). In plain terms, a zone model treats a room like two well-mixed layers — hot smoky air on top, cooler clean air below — which runs in seconds on a laptop rather than the hours or days a full CFD simulation can take.

9.3. Computational Fluid Dynamics (CFD)

Field models such as the Fire Dynamics Simulator (FDS), developed by the U.S. National Institute of Standards and Technology with VTT, solve low-speed, thermally driven flow using a large-eddy-simulation framework coupled with combustion, radiation, and heat-transfer submodels. The FDS 6.10 series introduced major updates including three-dimensional heat conduction and revised pyrolysis modelling. Because releases continue to evolve, the exact version used in any study should be reported explicitly and checked against the NIST release record at the time of analysis. Model reliability depends on appropriate input data, mesh resolution, sensitivity analysis, and validation against relevant experimental evidence (McGrattan et al., 2023). In plain terms, CFD tools such as FDS are essentially detailed weather simulators for a building on fire: they divide a room into a fine three-dimensional grid and calculate, cell by cell, how heat, smoke, and gases move over time — powerful, but only as trustworthy as the assumptions and data fed into them.

9.4. Machine Learning and Data-Driven Approaches

An emerging body of research applies machine learning techniques — including regression models, convolutional neural networks for image-based flame and smoke detection, and surrogate models trained on CFD output — to predict fire growth, smoke spread, and detection timing with reduced computational cost relative to full CFD simulation. These approaches show promise for real-time applications such as smart-building fire response systems, though they generally require large, high-quality training datasets and remain an active area of methodological development. In plain terms, machine learning is being used less to replace physics-based fire models and more to get a fast, "good enough" estimate — for example, flagging a likely fire from camera footage in seconds — that can trigger an alarm or evacuation faster than a full simulation ever could.

9.5. Model Validation and Limitations

All fire models, regardless of fidelity, require validation against experimental data before being relied upon for safety-critical design decisions. Known limitations include mesh-dependency in CFD, the restricted applicability range of empirical correlations, and the simplifying assumptions inherent to zone models, all of which must be understood and documented when models support fire safety engineering judgements (McGrattan et al., 2023).

10. Applications in Fire Safety Engineering

10.1. Performance-Based Design

Performance-based fire safety design uses fire behaviour modelling to demonstrate that a specific building design achieves defined life-safety and property-protection objectives, as an alternative or supplement to prescriptive code compliance. This approach requires careful selection of design fire scenarios, appropriate modelling tools, and tenability criteria, as set out in guidance such as the SFPE Engineering Guide to Performance-Based Fire Protection (SFPE, 2019). In plain terms, instead of simply following a fixed rulebook (a set width of corridor, a fixed number of sprinklers), the designer runs fire and evacuation simulations to prove a specific building will actually keep people safe — useful for unusual buildings a standard rulebook was never written for.

10.2. Structural Fire Resistance

Fully developed fire behaviour, particularly time-temperature history and duration, forms the design basis for structural fire resistance requirements, whether based on standard furnace test curves or natural (parametric) fire curves derived from compartment-specific fuel load and ventilation conditions. NIST's investigation into the collapse of World Trade Center Building 7 remains one of the most detailed publicly available case studies of fire-induced progressive structural collapse and continues to inform structural fire engineering practice (NIST NCSTAR 1A, 2008; Buchanan & Abu, 2017). In plain terms, structural members are rated to survive a fire of a certain severity and duration (for example, "two hours") so that occupants have time to escape and firefighters can operate safely, even if the building itself is ultimately a total loss.

10.3. Suppression System Design

Automatic sprinkler and other suppression system design relies on fire growth assumptions — typically t-squared growth curves — to determine detector and sprinkler activation timing, water demand, and system layout, linking fundamental fire behaviour directly to active fire protection engineering (Hurley, 2016). In plain terms, sprinkler and detector spacing is not arbitrary — it is calculated backwards from how fast a specific type of fire is expected to grow, so that the system reacts before the fire outgrows what it was designed to control.

10.4. Evacuation and Human Behaviour in Fire

Egress design integrates fire and smoke behaviour predictions with models of human decision-making, movement speed, and pre-movement (response) time to establish available safe egress time (ASET) versus required safe egress time (RSET), a central performance metric in life-safety-focused fire engineering design (SFPE, 2019). In plain terms, the building is safe on paper only if people can get out (RSET) faster than conditions become untenable (ASET); a design with a comfortable margin between the two is considered safe, one where they converge is not. A single blocked or absent egress route can make even a modest fire catastrophic, regardless of how well the fire itself is understood scientifically.

11. Learning from Catastrophe: Major Fire Incidents and the Case for Rigorous Fire Science

The practical significance of fire-science theory becomes clearer when established principles are examined against evidence from actual buildings and landscapes. This section examines five major, well-documented fire incidents — three from India and two international comparators — selected as analytical exemplars of mechanisms discussed earlier in this review, including smoke and egress, fuel load and occupancy, external fire spread, and wildland–urban interface exposure. The cases are not intended to constitute a representative statistical sample or to establish single-cause explanations. Each case study instead identifies documented fire-safety mechanisms and states the level of evidence supporting the interpretation. Given the India-focused scope of this review, the Indian incidents are presented first, followed by two international comparators retained for comparative context. Figure 6 summarises the reported death toll of the three Indian incidents discussed below.

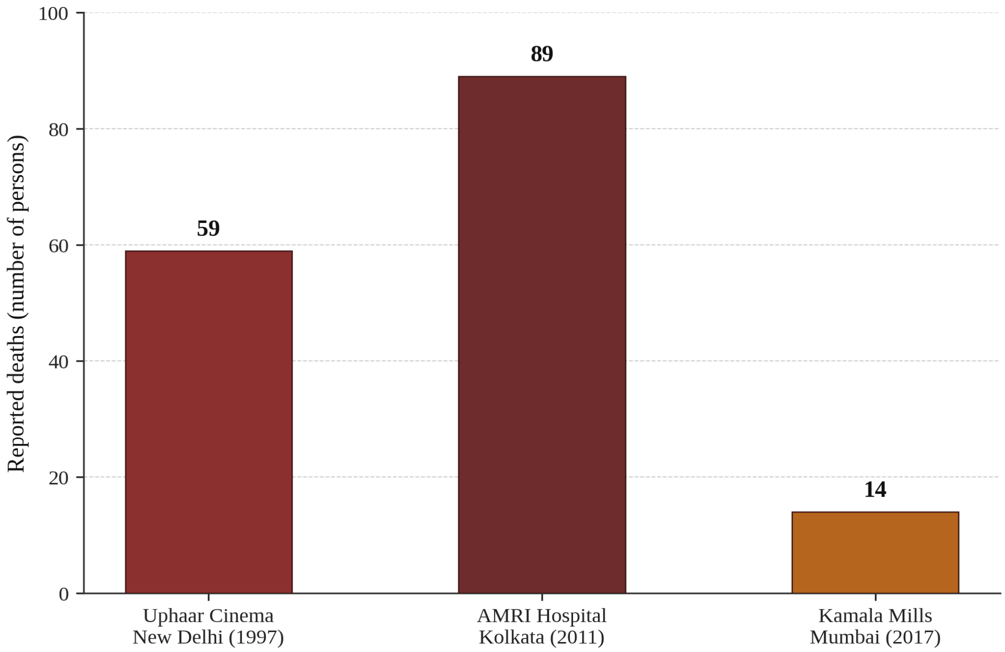

Figure 6. Death toll of selected major Indian fire tragedies, 1997–2024, compiled from official investigation findings and corroborating press reports.

11.1. Uphaar Cinema, New Delhi, India (13 June 1997)

A fire associated with a transformer in the parking area of Uphaar Cinema in Green Park, Delhi, filled the balcony seating area with dense smoke during an afternoon screening. Court and inquiry records document 59 deaths and extensive smoke exposure, with evacuation affected by the configuration and obstruction of available means of egress; 103 others were seriously injured. The incident led to prolonged criminal and civil proceedings concerning the cinema, approvals, and fire-safety arrangements.

Why it matters for fire science: Uphaar illustrates the importance of smoke tenability and effective egress. The case is useful as an engineering example of how building configuration and evacuation conditions can influence life safety.

11.2. AMRI Hospital, Kolkata, West Bengal, India (9 December 2011)

A fire reported to have originated in the basement of AMRI Hospital in Dhakuria, Kolkata, killed 89 people, most of them patients with limited ability to self-evacuate. Investigation and court reporting described combustible materials and waste stored in the basement and smoke movement through building services, including air-conditioning ductwork, as important features of the incident. Subsequent criminal proceedings and regulatory actions formed part of the documented legal history of the case.

Why it matters for fire science: AMRI illustrates the interaction between fuel-load management, smoke movement through building services, and the vulnerability of healthcare occupants. These mechanisms are directly relevant to healthcare-facility fire-safety design, compartmentation, smoke control, and evacuation planning.

11.3. Kamala Mills Compound, Mumbai, Maharashtra, India (29 December 2017)

A fire at a rooftop restaurant and pub in the Kamala Mills compound, a converted mill complex in Lower Parel, Mumbai, killed 14 people. Investigation reporting linked fire development to combustible decorative materials and conditions affecting the available escape route in the rooftop venue. The incident subsequently prompted enforcement and inspection activity concerning similar rooftop establishments.

Why it matters for fire science: Kamala Mills illustrates how changes in occupancy, layout, decorative fuel load, and available egress can alter the fire-safety assumptions associated with an existing structure. It is particularly relevant to assessment of public-assembly spaces and management of changes in use.

11.4. Grenfell Tower, London, United Kingdom (14 June 2017)

A fire that began with an electrical fault in a refrigerator-freezer in a fourth-floor flat of Grenfell Tower escalated into a high-rise external fire that killed 72 people. The Grenfell Tower Inquiry documented the role of the facade system, including ACM cladding with a combustible polyethylene core and combustible insulation, in enabling rapid vertical fire spread. The Inquiry also examined the interaction of facade construction, cavity barriers, testing, regulation, procurement, and the building's evacuation strategy.

Why it matters for fire science, and for India specifically: Grenfell is a well-documented example of external and cavity fire spread and the limits of compartmentation assumptions when facade systems can support rapid propagation. Its lessons are relevant to high-rise fire-safety assessment, while applicability to any specific Indian facade system must be established from the actual materials, detailing, testing, and regulatory context. As of the UK government's first annual progress report on the Inquiry's recommendations, only 12 of 61 recommendations had been fully implemented, illustrating how long substantive regulatory reform can take even after a fire disaster of this scale (Ministry of Housing, Communities & Local Government, 2026).

11.5. Los Angeles Wildfires — Palisades and Eaton Fires, California, USA (7–31 January 2025)

In January 2025, the Palisades and Eaton fires spread through communities in Los Angeles County under severe wind and fuel conditions, causing extensive structure loss and loss of life. Government and fire-agency assessments describe wind-driven ember transport, vegetation and fuel conditions, and rapid structure exposure as important contributors to the scale of the disaster. The two fires also illustrate the interaction between landscape-scale fire behaviour, evacuation, and the vulnerability of buildings at the wildland–urban interface.

Why it matters for fire science, and for India specifically: the Palisades and Eaton fires provide a contemporary illustration of wildland–urban interface fire-spread mechanisms, particularly ember transport and rapid structure ignition. Local conclusions should be based on local fuels, topography, weather, building construction, and emergency-response conditions.

Incident	Primary hazard/ mechanism	Egress/smoke issue	Regulatory/ management issue	Fire-science lesson	Evidence basis
Uphaar Cinema	Transformer/fire in parking area; smoke spread	Smoke-filled balcony; constrained egress	Documented egress and approval issues reported in court / inquiry records	Smoke and egress can dominate life safety	Court/inquiry records; corroborated reporting
AMRI Hospital	Basement fire; combustible storage	Smoke spread through building systems; vulnerable occupants	Fuel-load storage and fire-safety management issues reported in investigation/court records	Smoke control and healthcare egress are critical	Government/ court reporting
Kamala Mills	Ignition of combustible decorative materials	Limited escape route from rooftop venue	Occupancy, layout, decorative fuel load, and egress issues reported in investigations	Occupancy and egress changes can invalidate the safety basis	Municipal / investigative reporting
Grenfell Tower	Flat fire followed by facade/cavity spread	Rapid external spread undermined compartmentation assumptions	Facade-system and cavity-barrier deficiencies identified by the Grenfell Tower Inquiry	External fire spread can bypass compartmentation	Grenfell Tower Inquiry
Palisades/ Eaton	Wind-driven WUI fire and ember transport	Rapid evacuation and structure exposure	Community-scale WUI risk and emergency management	Ember transport can dominate structure ignition	Government assessments; fire-agency reporting

11.6. Analytical Cross-Case Synthesis

The cross-case analysis identifies five recurring fire-safety mechanisms. First, smoke and tenability constraints recur across multiple building types, showing that occupant survival depends on detection, compartmentation, smoke movement, and egress as much as on flame suppression. Second, combustible fuel load and uncontrolled use or storage repeatedly increase fire growth and spread potential. Third, unauthorised alterations or changes in occupancy can invalidate the assumptions on which the original fire-safety design was based. Fourth, external, cavity, battery, and WUI hazards demonstrate that emerging fire behaviour can cross conventional compartment boundaries or involve mechanisms not represented adequately by conventional fuel-fire assumptions. Fifth, the quality of incident evidence strongly influences the confidence with which causal lessons can be generalised. The comparison therefore supports a systems-level interpretation: fire outcomes arise from interactions among ignition, fuel, geometry, ventilation, smoke movement, egress, protection systems, management, and regulatory implementation rather than from a single failure mode.

12. Case Focus: Lithium-Ion Battery Fire Safety

Lithium-ion batteries are widely used in electric vehicles, portable electronics, and stationary energy-storage systems. Their fire behaviour differs from that of conventional bulk fuels because electrochemical reactions, internal heat generation, vent-gas formation, cell-to-cell propagation, and re-ignition can interact during failure. Thermal runaway is a self-accelerating exothermic process within a cell and can be initiated by electrical, thermal, mechanical, or manufacturing-related abuse. Trigger conditions vary substantially with cell chemistry, design, state of charge, and abuse mode; therefore a single temperature range should not be treated as universal (Zhao et al., 2025; Wang et al., 2025).

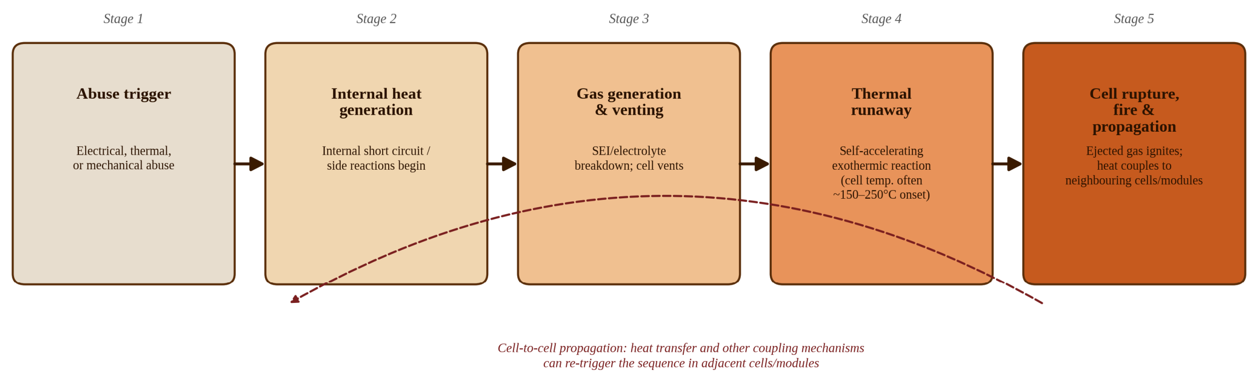

Figure 7. Schematic progression of thermal runaway in a lithium-ion cell, from initial abuse trigger to module/pack-level fire.

Once initiated, thermal runaway may propagate to neighbouring cells or modules through heat transfer and other coupling mechanisms. Fire-safety measures therefore need to address detection, heat removal, propagation control, vent-gas hazards, enclosure design, and re-ignition. The effectiveness of any suppression method depends on the battery architecture and chemistry; water-based cooling is often important for heat removal, while other agents and system-level controls are being investigated. For stationary energy-storage systems, layered protection at cell, module, rack/container, and facility levels is increasingly emphasised (Jia et al., 2025).

13. Case Focus: Mass Timber Fire Performance

Mass timber construction — including cross-laminated timber (CLT), glued-laminated timber (glulam), and related engineered wood products — has grown rapidly in mid- and high-rise construction due to its sustainability, aesthetic, and constructability advantages, but its fire performance remains an active research area because exposed timber, unlike non-combustible materials, contributes fuel to a compartment fire. When exposed to fire, timber forms an insulating outer char layer that protects the underlying cross-section, allowing engineers to predict residual structural capacity from measured or nominal char depth, as illustrated in Figure 8 (Mitchell et al., 2023).

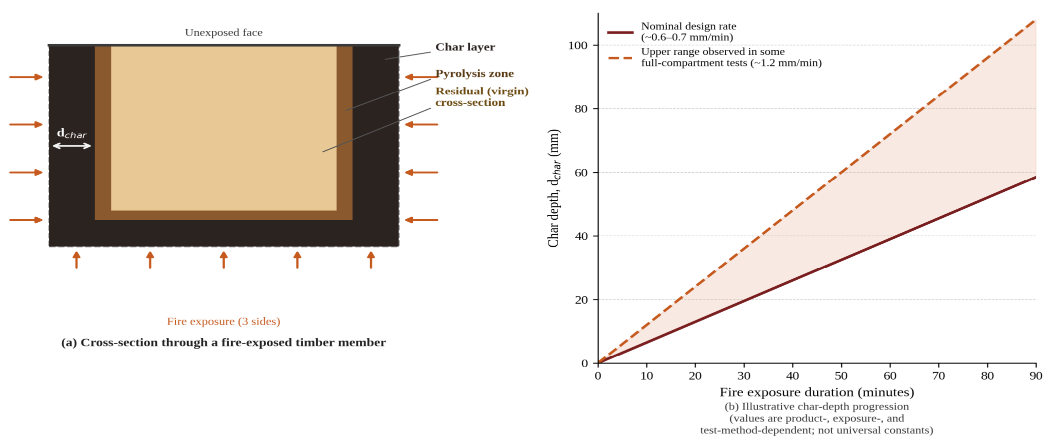

Figure 8. Char-layer formation in a mass timber member under fire exposure, showing the protective relationship between char depth and residual structural cross-section.

Nominal charring rates are useful design parameters, but they are not universal material constants. Values depend on wood product, density, moisture, orientation, exposure, protective layers, and test or design method. The commonly cited order of 0.6–0.7 mm/min applies to particular standard-fire design conditions; full-scale compartment experiments can produce different rates when exposed timber contributes additional fuel and when the fire follows a non-standard, decaying time–temperature history. Consequently, charring values should be reported with their applicable product, exposure, and design basis rather than generalised to all mass-timber construction (Mitchell et al., 2023).

14. Emerging Research Directions

1. Fire behaviour and suppression strategies for lithium-ion battery energy storage systems and electric vehicles, including early warning and non-aqueous suppression agents — an urgency underscored by the documented battery-manufacturing fires.
2. Self-extinction versus continued smouldering of exposed mass timber char layers, and structural fire endurance under realistic (non-standard) fire exposure.
3. Facade and cavity fire spread in buildings with combustible cladding systems, and continued development of full-scale facade fire test standards, directly informed by the Grenfell Tower Inquiry findings.
4. Machine-learning-based prediction of fire growth and smoke movement, and integration with smart-building fire response systems.
5. Wildland-urban interface fire behaviour and ember transport modelling under changing climate and fuel-moisture conditions, informed by the 2025 Los Angeles fires.
6. Toxicity and yield of combustion products from modern synthetic and composite materials, and their integration into tenability criteria.
7. Human behaviour and evacuation dynamics in increasingly complex and tall building typologies, and in complex or changing occupancy conditions in commercial and mixed-use buildings.
8. Enforcement-focused research: how fire safety compliance (NOC issuance, egress audits, cavity barrier inspection) can be made more reliable in practice, not only in design.

15. Discussion

Across the literature and case studies reviewed, a consistent theme emerges: classical fire dynamics theory — developed largely from mid-to-late twentieth century experimentation on conventional building materials and geometries — provides a robust and still-valid foundation (the 500–600°C / 15–20 kW/m² flashover criteria, for instance, are corroborated by both decades-old and very recent studies), but requires continual, active extension as construction materials, building forms, and energy technologies evolve. The growing use of mass timber and lithium-ion battery energy storage introduces fire behaviour characteristics — self-sustained char-layer combustion, and cell-to-cell thermal runaway propagation, respectively — that are not fully captured by fire models and correlations calibrated on traditional fuels, and both remain subjects of active, rapidly-publishing research communities as of 2025.

A second recurring theme is the centrality of ventilation and geometry — rather than fuel chemistry alone — in determining fire severity, reinforcing the importance of compartmentation, smoke control, and structural detailing as much as material selection in overall fire safety outcomes. A third theme, made explicit by the case studies in Section 11, is that the gap between documented fire science and applied practice is an important factor identified across several of the selected incidents, although the heterogeneous evidence base does not support attributing a single cause to the deadliest fires of the last decade. This suggests that future research and code development should continue to treat fire safety as a systems-level problem spanning material science, building design, regulatory enforcement, and human behaviour, rather than a single-variable material or design question.

For India, the selected evidence points to an implementation challenge that warrants further empirical study. The National Building Code provides a model framework for fire and life safety, but the reviewed incidents repeatedly involve deviations from approved use, inadequate egress, combustible fuel loading, or reported deficiencies in inspection and operational control. These cases support the hypothesis that implementation and enforcement are important determinants of fire outcomes; they do not, by themselves, establish that enforcement failure is the dominant cause of Indian fire deaths nationally.

16. Limitations of This Review and Recommendations for Original Research

As a review article, this paper synthesises and verifies established and current literature, national statistics, and secondary reporting on five real-world incidents, rather than presenting new experimental or computational data. The manuscript is an analytical review and should be submitted to a journal whose scope and article types accept evidence-based review and synthesis articles. The principal limitation is the absence of original experimental or computational data; this should be stated transparently rather than framed as a deficiency that must be solved before publication. The incident-level interpretations are also limited by differences in evidence quality across cases; conclusions are therefore framed according to the strength of the available official, inquiry, court, peer-reviewed, and corroborating evidence. Natural extensions of this review into original research include:

1. Bench- or full-scale experimental characterisation of fire behaviour for a specific modern material (e.g., a composite cladding panel or a specific battery cell/module configuration).
2. An FDS 6.10-series parametric study of flashover timing or smoke movement for a specific building typology, validated against published experimental data, for example modelled on a typical Indian mixed-use or residential-industrial building.
3. A quantitative case study analysis of a specific fire incident, with reconstructed timeline, heat release estimates, and lessons for design or code practice — for example, a detailed reconstruction of a major fire incident once a sufficiently complete technical investigation record is available.
4. A state-by-state comparative policy analysis of fire NOC issuance, inspection frequency, and enforcement outcomes across Indian municipal bodies, correlated against NCRB fire-death data by state, building directly on the statistical foundation laid in Section 1.3.
5. Development or validation of a machine-learning model for early fire, smoke, or battery thermal-runaway detection using a specific dataset.

17. Conclusion

Fire behaviour is the product of interacting chemical and physical processes spanning ignition, growth, flashover, and decay, all strongly modulated by fuel characteristics, compartment geometry, and ventilation. A firm grasp of these fundamentals underpins effective fire safety engineering, from passive and active protection system design to structural fire resistance and evacuation planning. As construction materials, building forms, and energy technologies continue to evolve — particularly toward mass timber structures and lithium-ion battery energy storage — fire science must correspondingly advance to ensure that fire safety design keeps pace with the risks these developments introduce. The Uphaar Cinema, AMRI Hospital, Kamala Mills, Grenfell Tower, and Los Angeles wildfire disasters examined in this review illustrate how different initiating hazards can converge on recurring life-safety and fire-spread problems. The structured cross-case analysis shows that smoke and egress, fuel loading and occupancy, compartmentation and external spread, and regulatory or management conditions repeatedly interact to shape outcomes. The cases are not a representative statistical sample; their value is analytical, providing traceable real-world examples through which established fire-science principles can be examined against practice.

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