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(Research Article)

Design and optimization of integrated fire suppression systems for a five-story institutional complex

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Abstract

This study presents the systematic engineering design and technical implementation of an integrated fire suppression system for a 300’ × 100’ five-story mixed-use institutional building. The research addresses a critical gap between the speed of modern fire propagation and the response time of conventional suppression networks in high-occupancy educational and administrative environments. The design process was initiated with a rigorous physical site survey to reconcile actual structural conditions with existing two-dimensional CAD drawings, followed by hydraulic modelling employing the Hazen-Williams formula to determine precise pressure requirements at the most hydraulically remote zone on the fifth floor. The engineering methodology proceeds through five sequential phases: site survey and hazard analysis, hydraulic calculation and system sizing, regulatory documentation and permitting, physical installation, and performance validation. A dedicated pump room was engineered featuring a main fire pump, a standby pump, and a jockey pump operating in a split-configuration redundancy arrangement. A vertical riser of Schedule 40 black steel was installed through the building’s structural shafts, feeding floor distribution networks on each level. The implementation culminated in hydrostatic pressure testing at 200 PSI for a sustained period of 120 minutes and comprehensive functional sequence testing. Full compliance with NFPA 13, NFPA 20, NFPA 72, and the National Building Code of India (Part 4) was maintained throughout. The resulting design constitutes a validated, high-reliability blueprint for modern institutional building resilience, demonstrating that a hydraulically optimized, streamlined system achieves superior safety outcomes compared to conventionally over-engineered installations.

Keywords: Fire suppression system; Institutional building; Hazen-Williams; NFPA 13; Hydraulic modelling; Wet-pipe sprinkler; Fire pump design

1. Introduction

Fire protection engineering in institutional settings has undergone a fundamental transformation over the past three decades, shifting from a collection of reactive, isolated safety devices toward an integrated life-safety ecosystem that operates on the principle of “Defense in Depth.” This philosophy recognizes that multiple protection layers—detection, active suppression, and passive compartmentalization —must operate in coordinated sequence to prevent a localized thermal event from escalating into structural failure and mass casualty [1]. For five-story institutional complexes, this challenge is compounded by three interrelated factors that distinguish them from residential or light commercial occupancies.

First, occupant load density during peak hours frequently exceeds several thousand individuals, many of whom are transitory visitors unfamiliar with exit configurations and manual alarm locations. Second, the vertical geometry of a

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five-story structure introduces the “Stack Effect,” a phenomenon where differential air pressure between floors drives smoke and toxic gases upward through elevator shafts and stairwells at rates that can incapacitate upper-floor occupants before a ground-level fire is even detected [2]. Third, the high concentration of synthetic furnishings, electronic laboratory equipment, and chemical reagents produces Heat Release Rates (HRR) that can exceed 1,000°C within minutes, overwhelming manual suppression efforts entirely.

The present study responds to these challenges by documenting the complete engineering lifecycle of a fire suppression system designed for a 300’ × 100’ five-story institutional facility. The central hypothesis is that a “streamlined” system—one employing advanced hydraulic balancing, precise pipe sizing, and strategic component placement—is measurably safer than a bulkier, conventionally over-designed system, because a leaner configuration minimizes mechanical joints, reduces potential leak points, and delivers suppression water with greater precision. The specific objectives of this research are: (a) to apply the Hazen-Williams hydraulic formula to eliminate dead zones in the piping network and guarantee mandated water density at all remote sprinkler heads; (b) to integrate the suppression network with a Voice Evacuation system and addressable fire alarm panel; (c) to validate the completed installation through hydrostatic pressure testing and functional sequence testing; and (d) to establish a “Zero-Tolerance” maintenance protocol that ensures the system’s reliability across its operational lifecycle.

2. Literature review

A comprehensive survey of the existing literature reveals a convergence of findings that directly inform the design decisions adopted in the present project. The Bureau of Indian Standards’ National Building Code of India (Part 4: Fire and Life Safety, 2016) [1] establishes the baseline regulatory mandate for institutional buildings exceeding 15 meters in height, specifying that an integrated automatic sprinkler system alongside a wet riser is non-negotiable for occupant survival. The code further limits the maximum travel distance to the nearest exit to 30 meters, a constraint that shapes the egress layout across all five floors examined in this study.

On the subject of hydraulic performance, Dhiman and Singh [2] investigated pressure variations in mid-rise fire suppression networks and concluded that gravity-fed supply alone is insufficient for effective suppression on upper floors, necessitating a booster pump with a minimum capacity of 900 LPM and a terminal pressure of 3.5 kg/cm² at the topmost hydrant. This finding directly informs the pump specifications adopted here. Complementing this hydraulic perspective, Rao and Lakshmi [3] demonstrated through fire load analysis in five-story educational complexes that smoke inhalation accounts for over 70% of fatalities in mid-rise institutional fires, reinforcing the decision to priorities early automated smoke detection over reliance on manual alarms.

The hydraulic configuration of the sprinkler network is further refined by work from the International Journal of Civil Engineering and Technology [4], which established that a design density of 5 mm/min per square meter represents the optimal configuration for ordinary-hazard institutional occupancies. Notably, their computer-aided modelling demonstrated a 22% reduction in the Response Time Index (RTI) of sprinkler heads when a precisely calculated grid layout is employed rather than a conventional tree configuration. Sharma and Gupta [5] reinforced the case for redundancy in pumping arrangements, concluding that a Main-Standby-Jockey pump configuration is the most robust arrangement and that the jockey pump is essential for compensating minor pressure leaks that would otherwise trigger premature cycling of the main pump.

Water storage adequacy was examined by Kumar and Mehra [6], who concluded that a minimum underground static storage of 200,000 liters is essential to sustain two hours of firefighting operations before external assistance arrives, while a secondary overhead tank of 20,000 litres provides immediate head pressure for first-response sprinkler activation—a dual-storage strategy adopted in the terrace design of this project. Singh and Nair [13] demonstrated that an Analogue Addressable Fire Alarm System reduces identification time by up to 60% compared to zone-based systems, and the integration of Automatic Voice Evacuation further reduces occupant panic during evacuation. Mehta and Bansal [17] established that a grid piping configuration produces more even pressure distribution across all sprinkler heads compared to a tree configuration, with particular importance for large lecture halls and laboratories. Santosh and Reddy [20] confirmed that the combination of intumescent coatings on structural steel and 2-hour fire-rated doors, when integrated with an active sprinkler network, maintains a building’s load-bearing capacity for at least 120 minutes, allowing full evacuation of all five floors under high-intensity fire conditions.

3. Methodology

The implementation methodology was structured as a five-phase engineering lifecycle, from pre-construction intelligence gathering through to final legal certification and handover. This cradle-to-operational-life approach ensures that system reliability is embedded at every stage rather than verified only at the end.

3.1. Phase I – Site Survey and Hazard Classification

The site survey commenced with a comprehensive architectural mapping exercise to reconcile the 2D CAD drawings with the physical reality of the 300’ × 100’ structure. Particular attention was paid to “dead-end corridors” and common path-of-travel distances in accordance with NFPA 101 Life Safety Code requirements. Utility identification established the entry points of the primary water main and electrical service entrance, while structural constraint analysis located obstructions to discharge—including HVAC ducts and decorative soffits—that would interrupt sprinkler spray patterns. Any obstruction exceeding four feet in width was flagged as requiring a dedicated supplementary sprinkler head.

Hazard classification was conducted in accordance with the NFPA 13 framework. Classrooms, library areas, offices, and hospital-type rooms were classified as Light Hazard (LH), requiring a design density of 0.10 GPM/ft^2 over the most remote 1,500 to 3,000 square feet. Mechanical rooms, laundry facilities, and kitchens were classified as Ordinary Hazard Group 1 or 2, demanding densities of 0.15 to 0.20 GPM/ft^2. Chemical laboratories and high-density storage areas were classified as Extra Hazard and specified for Fast-Response sprinkler heads or foam-water systems where applicable. The site survey was completed with a Hydrant Flow Test to obtain Static Pressure, Residual Pressure, and Pitot Pressure data, which were plotted on $N^{1.85}$ graph paper to generate a Water Supply Curve for hydraulic modelling.

3.2. Phase II – Engineering and Hydraulic Modelling

The hydraulic design was governed by the Hazen-Williams formula, the industry-standard equation for calculating friction loss in pressurized water pipes:

$$\mathbf{p = (4.52 \times Q^{1.85}) / (C^{1.85} \times d^{4.87})}$$

Where p denotes friction loss in PSI per linear foot, Q is the flow rate in gallons per minute, C is the Hazen-Williams friction coefficient (120 for new black steel, 150 for CPVC), and d is the internal pipe diameter in inches. The hydraulic design area—the most demanding zone in terms of water delivery—was identified as the most remote 1,500 square feet on the fifth floor. At the minimum design density of 0.10 GPM/ft^2 for light-hazard classification, this generated a base demand of 150 GPM; however, accounting for sprinkler over-discharge at heads proximal to the riser, the working system demand was modelled at 220 GPM at the design area. Equivalent pipe length tables were applied for all fittings, with a 4-inch 90-degree elbow treated as an equivalent additional 10 feet of straight pipe.

A velocity cap of 20 feet per second was enforced throughout the model to prevent water hammer damage. Pipe schedules were selected accordingly: Schedule 40 black steel (ASTM A53 Grade B) for threaded branch lines and high-pressure risers, and Schedule 10 for large-diameter mains of 4 inches and above using grooved couplings. The K-factor of 5.6 was adopted for standard quick-response pendent heads, applying the relationship $Q = K\sqrt{P}$ to confirm individual head discharge at the design pressure.

3D Building Information Modelling (BIM) was employed during this phase to conduct automated clash detection, identifying conflicts between fire pipes and structural beams or HVAC ducts before physical installation. This allowed pipes to be pre-cut and grooved at an off-site fabrication shop, reducing on-site installation time by an estimated 35%.

3.3. Phase III – Documentation and Regulatory Permitting

Technical documentation was prepared in accordance with the CSI Master Format, specifically Division 21 (Fire Suppression). The drawing suite comprised site and utility plans showing the Point of Connection to the municipal main, floor plans at a scale of 1/8” = 1’-0” with complete symbol legends and pipe sizing annotations, and riser isometric diagrams showing the sequential component arrangement: Fire Pump → Check Valve → Main Riser → Floor Control Valve → Water Flow Switch.

All equipment specifications required UL Listing and FM Approval. The regulatory submission package was prepared for review by the Authority Having Jurisdiction (AHJ), incorporating hydraulic calculation reports with Hazen-Williams results and safety margins, material submittal packages with manufacturer data sheets, and a Sequence of Operations document describing the logic interaction between water flow switches and the Fire Alarm Control Panel. Permit issuance resulted in the drawings being designated as Issued for Construction (IFC), a set of which was maintained on-site throughout the construction phase.

3.4. Phase IV – Physical Installation

Mobilization established a dedicated on-site fabrication shop equipped with grooving and threading machines for pipe preparation. Personnel deployment comprised certified Pipefitters, Fire Alarm Technicians, and Fire Pump Specialists, all of whom completed site-specific safety inductions covering the Risk Assessment and Method Statement (RAMS) for working at heights, hot work, and confined space entry.

The core installation proceeded in the following sequence. The pump room was constructed first, housing a Horizontal Split-Case Main Fire Pump, an identical Standby Fire Pump, and a vertical multi-stage Jockey Pump. The main riser—a 6-inch Schedule 40 black steel pipe—was installed through the building's structural shafts and supported by riser clamps at every floor level. At each floor, a Floor Control Valve Assembly (FCVA) was installed, comprising an OS&Y Gate Valve with a tamper switch, a vane-type water flow switch, a pressure gauge, and an Inspector's Test and Drain connection. Floor distribution networks were installed using a grid piping configuration for open-plan laboratory and auditorium areas and a tree system for cellular office zones.

Sprinkler head selection prioritized Quick Response (QR) Pendent heads with a K-factor of 5.6 for all occupied spaces, rated at 155°F (68°C), and 200°F+ heads for mechanical rooms and kitchens to prevent accidental actuation from ambient heat. Concealed-type heads were specified for public corridors and reception areas to preserve architectural integrity. Seismic bracing was installed at all required intervals in accordance with ASCE 7 and NFPA 13, with flexible grooved couplings at building expansion joints. Automatic air vents were installed at all high points in the piping network to eliminate oxygen pockets and retard internal corrosion.

The water supply system featured an underground static storage tank sized at 54,000 gallons—calculated from a total demand of 600 GPM for 90 minutes—plus a 20,000-litre overhead terrace tank providing immediate gravity-fed head pressure. Backflow prevention was achieved through a Reduced Pressure Zone (RPZ) assembly at the service entrance, accounting for a 12 PSI pressure drop in the hydraulic model.

3.5. Phase V – Testing and Validation

Hydrostatic testing was performed on all installed piping by pressurizing the system to 200 PSI (or 50 PSI above the working pressure, whichever was greater) and maintaining this pressure for a minimum of 120 minutes. A pressure drops exceeding 1 PSI, not attributable to ambient temperature change, constituted a failure requiring leak identification, repair, and full retest from zero.

Functional sequence testing was conducted by activating the Inspector's Test Connection (ITC) at the most remote point of each floor to simulate single-sprinkler discharge. The water flow switch delay was confirmed at 30 to 60 seconds before alarm transmission to the Fire Alarm Control Panel. Fire pump auto-start sequences were verified through controlled pressure bleeding, confirming Jockey Pump start, followed by Main Pump start at the pre-set cut-in pressure. Pump output was measured at 100% and 150% of rated capacity using a Pitot tube and calibrated flow meter; deviations exceeding 5% from factory performance curves were treated as requiring mechanical correction.

The Integrated Life Safety Matrix ("Black Start") test verified simultaneous actions upon flow switch activation: elevator recall to ground floor, HVAC fan shutdown, magnetic fire door release and closure, and continuation of emergency power supply through the Automatic Transfer Switch. The NFPA 25 inspection log was populated with baseline data for all future periodic inspections.

4. Results and discussion

The primary product of this project is a comprehensive, seven-level engineering blueprint—encompassing the Ground Floor, First through Fifth Floors, and Terrace—that successfully integrates a high-density firefighting network into the architectural fabric of the institutional building. Hydraulic flow analysis confirmed that vertical synchronization across all seven levels achieves optimal pressure distribution throughout the riser, effectively managing head loss while maintaining mandatory flow rates in all high-occupancy zones.

4.1. Floor-by-Floor Design Outcomes

On the Ground Floor, the fire suppression overlay introduced a prominent central crosshair distribution point feeding both the open retail area and the administrative waiting zone. Red-line indicator points confirmed the placement of emergency alarm panels and zone-control valves adjacent to the primary staircase, ensuring that first-responder access to isolation controls is unobstructed. The First Floor, housing the auditorium and IT laboratory, required the highest sprinkler density in the building: the auditorium's high ceiling necessitated ESFR (Early Suppression Fast Response) heads with K-factors ranging from 14 to 25, while the IT laboratory was assigned a Pre-Action valve arrangement to prevent accidental water damage to server equipment.

The Second Floor introduced a more complex distribution challenge due to its mixed-use layout combining small retail stalls, a plumber's room, and a makeup room. A perimeter-and-central-corridor main distribution line was implemented, feeding branch pipes into each individual unit to ensure total volumetric coverage without compromising egress route widths. The Third Floor, containing welding laboratories and administrative offices, required particular attention to Extra Hazard classification in the fabrication area, where an elevated design density of 0.20 GPM/ft^2 was applied and CPVC piping was specifically excluded from proximity to open-flame operations.

The Fourth and Fifth Floors, housing the girls' and boys' hostel dormitories respectively, presented the highest occupant load per floor. A parallel branch-pipe grid was implemented across the expansive dormitory areas to ensure uniform pressure distribution during simultaneous sprinkler activation. The terrace design integrated the fire suppression plumbing network with the existing water storage infrastructure—comprising three tanks of 45 kL, 25 kL, and 25 kL respectively—creating a unified hydraulic reserve of 95 kL. This overhead capacity supplements the underground static storage and provides immediate pressure for first-response activation without dependence on pump start-up time.

4.2. Hydraulic Performance

The Hazen-Williams hydraulic model confirmed that the system demand curve at the most remote fifth-floor zone remains safely below the available supply curve at all design flow rates. With the municipal supply providing 65 PSI static pressure and the system demand at maximum flow registering 48 PSI, a safety margin of 17 PSI (approximately 26%) is maintained—well above the minimum 15% buffer specified in NFPA 13. At rated pump capacity (750 GPM), measured pump output during flow testing deviated by only 2.3% from factory performance curve specifications, within the acceptable 5% tolerance. The jockey pump maintained system pressure within ±2 PSI of the set point during all testing periods, confirming that the sensing line and pressure switch calibration were correctly executed.

4.3. Integration and Validation

The Integrated Life Safety Matrix test produced successful outcomes for all six concurrent actions: elevator recall completed within 8 seconds of flow switch alarm; all 23 magnetic fire doors in the building released and latched within 4 seconds; HVAC supply fans shut down and return fans switched to exhaust mode within 6 seconds; the voice evacuation system broadcast floor-specific instructions within 10 seconds; and the emergency generator assumed full pump load within 9 seconds—within the 10-second NFPA 20 requirement. Hydrostatic testing across all five floors recorded zero pressure drop over 120 minutes on four of the five floors; a minor leak identified at a threaded joint on the third floor was repaired and the test rerun to completion.

The Bill of Quantities (BOQ) analysis yielded a total project cost of approximately ₹16.04 lakhs for the base system, inclusive of pump room infrastructure, piping and reticulation, end-point devices, and commissioning. Life-Cycle Cost Analysis (LCCA) projects that insurance premium reductions of 20–40% on the building's annual premium will recover the installation cost within 7 to 10 years, confirming the economic as well as safety justification for the investment.

A critical discussion point that emerged during the design review concerned the tension between hydraulic efficiency and structural obstruction management. In conventional institutional designs, fire pipes are frequently rerouted around obstructions through multiple additional fittings, each introducing friction loss. The BIM-assisted approach adopted in this project identified 14 potential clashes during the design phase, all of which were resolved before physical installation through pipe re-routing or the installation of supplementary heads beneath wide obstructions. This pre-construction resolution eliminated rework costs estimated at 12–15% of total piping labor and ensured that the as-built hydraulic performance matched the design model within the acceptable tolerance range.

5. Conclusion

This study has demonstrated that the comprehensive design and implementation of an integrated fire suppression system for a five-story institutional complex demands a multi-phase engineering approach that extends from initial site intelligence gathering through hydraulic modelling, regulatory compliance, physical installation, and validated performance testing. The following specific conclusions are drawn from the outcomes of this project:

- The application of the Hazen-Williams hydraulic formula, combined with BIM-based clash detection, produced a validated network that maintains a 26% pressure safety margin at the most hydraulically remote zone on the fifth floor, exceeding the minimum NFPA 13 requirement.
- The Main-Standby-Jockey pump configuration, operating in split redundancy, provides reliable system pressure under all tested conditions, including simulated mains failure and full transfer to emergency generator supply.
- The dual-storage strategy—combining a 54,000-gallon underground static tank with a 95 kL overhead terrace reservoir—ensures a minimum of 90 minutes of autonomous firefighting capacity without dependency on municipal supply.
- Integration of the suppression network with an Analogue Addressable Fire Alarm System and Automatic Voice Evacuation system produced first-response alarm notification within 10 seconds of sprinkler activation, significantly reducing the identification time characteristic of conventional zone-based systems.
- The grid piping configuration adopted for large-area occupancies (auditoriums, dormitories, laboratories) demonstrated superior hydraulic balance compared to the tree system used in cellular zones, confirming the literature findings of Mehta and Bansal [17] regarding even pressure distribution.
- Full compliance with NFPA 13, NFPA 20, NFPA 72, and the National Building Code of India (Part 4) was achieved and verified through AHJ inspection and certification.

The “streamlined” engineering philosophy applied in this project—minimizing mechanical joints, optimizing pipe routing, and deploying hydraulic balancing in preference to oversized piping—has been validated as producing a system that is simultaneously leaner in material requirement and more reliable in performance than conventional over-engineered alternatives. This project therefore provides a replicable engineering template for fire protection practitioners engaged in the design of mid-rise institutional buildings across similar regulatory environments.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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