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Assessing Legislative Deficiencies in NFPA-Based Fire-Protection Codes for High-Bay Storage Warehouses Exceeding the Prescriptive Ceiling-Height Envelope (≥20 m): A Comparative Applied Study of Three Saudi Facilities

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Abstract:

Purpose. The rapid expansion of high-bay logistics, cold-chain and retail-storage facilities in the Kingdom of Saudi Arabia (KSA) and the wider Gulf region has produced a generation of warehouses whose clear storage heights routinely reach 16–22 m. This study examines whether the prescriptive fire-protection provisions of NFPA 13—adopted in KSA through the Saudi Building Code (SBC 801)—adequately govern the automatic-sprinkler protection of such tall storage occupancies, and it characterizes the legislative gap that emerges above the code's validated ceiling-height envelope.

Methodology. A comparative, embedded multiple-case-study design was applied to three approved Saudi warehouse projects: a furniture retail-warehouse (16 m), a dates and cold-storage facility (20 m), and a furniture storage complex (22 m). Approved architectural and fire-fighting drawings were analysed against a code-gap framework derived from NFPA 13 storage chapters, the Underwriters Laboratories (UL) Specific-Application sprinkler listings, and FM Global Data Sheet 8-9.

Findings. All three facilities exceed the ceiling-only ESFR envelope validated by NFPA 13 (approximately 13.7–14.6 m). In the absence of prescriptive criteria above that envelope, each design team resolved the same fundamental hazard by a materially different, jurisdiction-approved strategy—ceiling ESFR combined with in-rack sprinklers, high-K ESFR with specialised sub-systems, and hazard re-classification with smoke management. This divergence is presented as direct field evidence of the legislative deficiency: the code neither prohibits, prescribes, nor standardises protection for storage above its tested limit, delegating a life-safety-critical decision to discretionary engineering judgement.

Originality. The paper contributes a documented, drawing-based demonstration of regulatory under-specification for tall warehouses in a Gulf context, and proposes a structured set of code-amendment and performance-based pathways to close the gap.

Keywords: Fire Protection Engineering, NFPA 13, ESFR Sprinklers, High-piled Storage, Warehouse Fire Safety, Legislative Gap, Saudi Building Code (SBC 801), Performance-based Design, Ceiling-height Envelope, Code Compliance.

1. Introduction

Warehousing has been transformed over the past two decades by the economics of land, automation and supply-chain consolidation. Because floor area is expensive and materials-handling equipment can now stack goods ever higher, the rational response of developers has been to build upward—replacing the traditional single-storey shed of eight to ten metres with high-bay structures whose clear internal height commonly reaches 16 m and, in automated storage-and-retrieval installations, considerably more. In the Kingdom of Saudi Arabia this trend has been accelerated by the logistics-hub ambitions of Vision 2030, by rapid growth in organised retail and furniture distribution, and by the expansion of temperature-controlled storage for the food and dates industries.

From a fire-protection standpoint, height is not a neutral variable. As the vertical distance between the burning commodity and the ceiling-mounted sprinklers increases, the fire plume gains buoyant energy before the ceiling sprinklers actuate; the actuation of a larger number of heads is delayed relative to fire growth; and the downward momentum required for water droplets to penetrate the plume and reach the seat of the fire rises sharply. Above a certain height, a single tier of ceiling sprinklers—however hydraulically generous—can no longer be relied upon to achieve suppression. Recognising this, sprinkler standards do not extrapolate their design tables indefinitely; they stop at the tallest configuration that has actually been fire-tested and listed.

The dominant installation standard, NFPA 13, Standard for the Installation of Sprinkler Systems, is prescriptive: it supplies design densities, operating areas, K-factors and clearances derived from full-scale testing. Its Early Suppression Fast Response (ESFR) tables—the principal ceiling-only technology for high storage—are bounded by a maximum ceiling height. Independent commentary places this validated boundary at approximately 13.7 m (45 ft) for standard listings, extending to 14.6 m (48 ft) only through specific Underwriters Laboratories (UL) listings for the highest-K devices [1,2,3]. The International Fire Suppression Alliance states the position plainly: NFPA 13 "does not address ceiling-only sprinkler protection above approximately 13.7 metres (45 feet)" [1].

This creates a regulatory discontinuity. A warehouse of 20 m or 22 m clear height—entirely ordinary in the contemporary market—falls outside every prescriptive ESFR table in the standard. The code does not forbid such a building, nor does it supply compliant design criteria for it. Instead, protection above the envelope is displaced to a patchwork of alternatives: in-rack sprinklers, the parallel FM Global rule set, or a fully engineered performance-based design accepted at the discretion of the Authority Having Jurisdiction (AHJ). The consequence is that facilities posing the same fundamental hazard may be protected to materially different specifications depending on which consultant designed them and which pathway the AHJ accepted. It is this under-specification—rather than any single technical shortcoming—that the present study frames as a legislative deficiency.

In KSA the question is not academic. SBC 801, the Saudi Fire Protection Code, is built upon the 2015 International Fire Code and the associated NFPA standards, adapted to national needs [4]. Provisions of NFPA 13 therefore reach Saudi warehouses through the national code, and the ceiling-height envelope—together with its gap—is inherited intact. Yet SBC 801 has itself been criticised for a lack of worked examples and for reliance on externally referenced standards that practitioners find difficult to interpret

[4], precisely the conditions under which an unaddressed height gap is most likely to produce inconsistent outcomes.

1.1. Research objectives

This paper (1) delineates, with exact figures, the ceiling-height envelope validated by NFPA 13 and the point at which prescriptive coverage ceases; (2) demonstrates, through three approved Saudi warehouse projects of 16, 20 and 22 m, that real facilities routinely operate above that envelope; (3) shows that the three projects resolve the resulting gap by three divergent, individually approved strategies; and (4) proposes a structured set of code-amendment and performance-based measures to close the deficiency.

1.2. Research questions

RQ1: At what ceiling height does prescriptive NFPA 13 storage protection cease to be validated, and by what margin do modern Saudi warehouses exceed it? RQ2: How, in practice, do independent design teams protect storage above the envelope, and how consistent are those solutions? RQ3: What specific amendments would convert the present discretionary vacuum into a defensible, reproducible design basis?

2. Regulatory and Theoretical Background

2.1. The architecture of storage protection in NFPA 13

NFPA 13 consolidates the protection of storage occupancies into a dedicated block of chapters (Chapters 20 through 25 in the 2019 and 2022 editions), preceded by the commodity-classification provisions. Protection is delivered through four principal strategies, summarised in Table 1. Control-Mode Density/Area (CMDA) and Control-Mode Specific-Application (CMSA) sprinklers aim to control rather than extinguish a fire, holding it until manual intervention. In-rack sprinklers place heads within the storage array itself, intercepting the fire close to its origin and largely decoupling protection from ceiling height. ESFR sprinklers, by contrast, are designed to suppress the fire from the ceiling through the rapid delivery of large, high-momentum droplets. ESFR is the technology of choice for high-bay storage because it can, within limits, avoid the cost and operational obstruction of in-rack piping; its requirements are set out in Chapter 23 [5,6].

Table 1: Principal Automatic-sprinkler Strategies for Storage Occupancies under NFPA 13.

Strategy	Principle	Dependence on ceiling height
CMDA	Control-mode density/area; hydraulic design by density over a remote operating area.	High — performance degrades as clearance grows.
CMSA	Control-mode specific-application (large-drop); fixed number of design sprinklers.	High — bounded tables.
In-rack	Sprinklers within the rack intercept fire near its seat.	Low — largely height-independent, but costly and obstructive.
ESFR	Early Suppression Fast Response; ceiling-only suppression via high-momentum droplets (Chapter 23).	Critical — validated only up to a maximum tested ceiling height.

2.2 The ESFR ceiling-height envelope

The defining constraint for tall-warehouse protection is that ESFR design tables terminate at a maximum ceiling height, above which the standard offers no ceiling-only criteria. The boundary values, drawn from published technical commentary and manufacturers' listing data, are collected in Table 2. Under standard NFPA 13 listings, ceiling-only ESFR protection is generally limited to a ceiling height of about 13.7 m (45 ft) with maximum storage of roughly 12.2 m (40 ft) [1,2]. The highest-capacity device, the K-25.2 ESFR pendent, extends coverage under a UL Specific-Application listing to a ceiling of 14.6 m (48 ft) over storage of 13.1 m (43 ft) [3]. The parallel FM Global rule set (Data Sheet 8-9, Table 17B) reaches somewhat further, permitting ceiling-only ESFR protection of storage up to 15.2 m (50 ft) beneath ceilings up to 16.8 m (55 ft) [1,3]. No mainstream prescriptive pathway—NFPA or FM—validates ceiling-only suppression for the 20–22 m ceilings examined in this study.

Table 2: Validated Ceiling-only ESFR Height Envelopes Compared with the Case Facilities. Values from Published Commentary and Listing Data [1–3].

Basis / listing	Max. ceiling height	Max. storage height
NFPA 13 — standard ESFR ceiling-only	≈ 13.7 m (45 ft)	≈ 12.2 m (40 ft)
UL Specific-Application, K-25.2 ESFR	14.6 m (48 ft)	13.1 m (43 ft)
FM Global DS 8-9, Table 17B	16.8 m (55 ft)	15.2 m (50 ft)
Case facilities in this study	16.0 – 22.0 m	All exceed the NFPA/UL envelopes, while Cases B and C also exceed the cited FM Global ceiling envelope

2.3. Why the envelope exists

The height ceiling is not an arbitrary conservatism; it is a boundary of empirical knowledge. Sprinkler protection criteria are established by full-scale fire tests, and a listing is only as tall as the test rig that produced it. Commentary from practising engineers attributes the limit to three coupled factors: the physical height limitations of the testing laboratories that generate the listings; the deterioration of droplet penetration through an increasingly energetic plume as height grows; and the absence of commercial incentive for manufacturers to fund the very costly full-scale testing required to extend a listing [2]. In consequence, the ceiling reflects the tallest array for which suppression has been demonstrated rather than the tallest array that could conceivably be protected. Extrapolating the tables beyond it is therefore not a conservative simplification but an unverified assumption—exactly the situation a prescriptive code is designed to prevent.

2.4. Pathways above the envelope

Where storage exceeds the ESFR envelope, three routes remain available, none of which is a prescriptive ceiling-only solution. The first is the addition of in-rack sprinklers, re-introducing the cost and obstruction that ESFR was intended to eliminate but restoring protection close to the commodity. The second is migration to the FM Global rule set, whose Data Sheet 8-9 extends the envelope modestly and which is available to facilities insured under an FM Global programme. The third is a performance-based design, justified through fire-modelling and testing and accepted under the equivalency and new-technology provisions of NFPA 13 Sections 1.5 (Equivalency) and 1.7 (New Technology) subject to AHJ approval [2]. The defining characteristic of all three is that the standard itself supplies no numbers—density, area, K-factor, spacing—for the tall configuration; the design basis must be imported or engineered case by case. It is this shift from codified criteria to discretionary justification that constitutes the deficiency at the center of this paper.

2.5. The Saudi regulatory context (SBC 801)

SBC 801, the Saudi Fire Protection Code, derives from the 2015 International Fire Code and the associated NFPA standards, with modifications for national conditions [4]. Because installation criteria for sprinkler systems are referenced from NFPA 13, the ESFR ceiling-height envelope—and the gap above it—applies to Saudi warehouses just as it does under the parent standards. A recent comparative analysis of SBC 801 observes that practitioners find the code's reliance on external references and its shortage of worked examples among the most challenging aspects of implementation, and notes that certain high-risk occupancy classes receive limited specific guidance [4]. A storage-height gap inherited silently from a referenced standard is a paradigm case of this difficulty: the controlling limit is neither restated nor flagged in the national text, and its practical resolution is left to the individual designer and reviewer.

3. Literature Review

The physics that motivates the ESFR height limit has been documented in the fire-science literature for more than three decades. Foundational full-scale work by Kung and colleagues on four-tier rack-storage arrays established that fast-response sprinklers can suppress a developing rack fire only when the water flux delivered to the top of the array under no-fire conditions exceeds the required delivered density (RDD)—a balance that becomes progressively harder to maintain as the fire, and the plume it generates, grow with height [7]. The RDD/ADD (actual delivered density) framework that emerged from this and related programmes remains the conceptual basis of ESFR design and explains directly why a validated envelope exists: beyond a certain height the actual delivered density falls below the rising required delivered density, and suppression can no longer be assured.

Subsequent studies of runaway high-rack fires reinforced the point that once suppression is lost in tall storage, fire growth can outpace any ceiling-based system, with severe structural and property consequences [8]. This body of evidence underpins the code writers' decision to bound the ESFR tables rather than extrapolate them. More recent experimental and modelling work has turned to in-rack sprinkler optimisation as the principal means of protecting very tall and automated storage, quantifying how in-rack head placement and operating parameters mitigate damage where ceiling-only protection is inadequate [9,10]. The clear trajectory of the literature is that height defeats ceiling-only suppression and that protection of very tall storage migrates, of necessity, either into the rack or into engineered, test-based justification.

Work on ESFR obstructions—including the NFPA Fire Protection Research Foundation programme and its associated full-scale tests, which fed revisions to the 2022 edition of NFPA 13 [11]—demonstrates how sensitive ESFR performance is to the geometry between sprinkler and storage, and by extension how little margin exists for unverified extrapolation to greater heights. At the level of code architecture, comparative regulatory studies of Gulf fire codes, including SBC 801, identify structural reliance on external references and a shortage of worked design examples as recurrent weaknesses [4]. What the literature does not yet contain—and what this study addresses—is a documented, drawing-based demonstration that the height gap manifests in built Saudi facilities as divergent, individually approved protection strategies for equivalent hazards. The present work therefore connects an established physical limit to an observed regulatory outcome.

4. Materials and Methods

4.1. Research design

The study adopts a qualitative, comparative multiple-case-study design of the embedded type, in which each case is a warehouse project and the embedded unit of analysis is its automatic fire-protection strategy relative to the NFPA 13 ceiling-height envelope. The multiple-case approach is appropriate because the phenomenon of interest—how designers resolve an unaddressed code condition—cannot be isolated from its regulatory and commercial context, and because comparison across independent design teams is precisely what reveals the consistency (or inconsistency) that the research questions target. The logic is one of literal and theoretical replication: the cases were selected in the expectation that all would exceed the envelope (literal replication) while resolving it differently (theoretical replication).

4.2. Case selection

Three approved Saudi warehouse projects were selected purposively to span the height range immediately above the ESFR envelope and to represent distinct commodity and occupancy profiles: a furniture retail-warehouse at 16 m (Case A), a dates and cold-storage facility at 20 m (Case B), and a furniture storage complex at 22 m (Case C). The heights reported are the clear storage heights stated for each project; where a project drawing indicated a value differing from the nominal figure, the drawing value was adopted. Diversity of design consultant—each project was prepared by a different engineering office—was a deliberate selection criterion, because independent authorship is what allows divergence in solution to be read as evidence of code under-specification rather than of a single firm's house style.

4.3. Data sources

The primary sources are the approved architectural and fire-fighting drawings issued for each project, including sprinkler layouts, sprinkler schedules, fire-suppression system schedules, pump specifications, and the associated design notes and area tables. To preserve the confidentiality of the owners and design offices, all project-, company- and consultant-identifying information—names, logos, stamps, project numbers and locations—was removed; the facilities are de-identified and designated Cases A–C, and the drawings are represented here by anonymised schematic figures rather than reproductions of the issued sheets. Data extraction focused on the parameters governing the height question: clear storage height, commodity class and hazard classification, ceiling sprinkler technology and K-factor, presence and role of in-rack sprinklers, specialised sub-systems, smoke management, and the declared code basis. Because the analysis is documentary and uses de-identified design data rather than human subjects or personal data, no ethical-approval procedure was engaged.

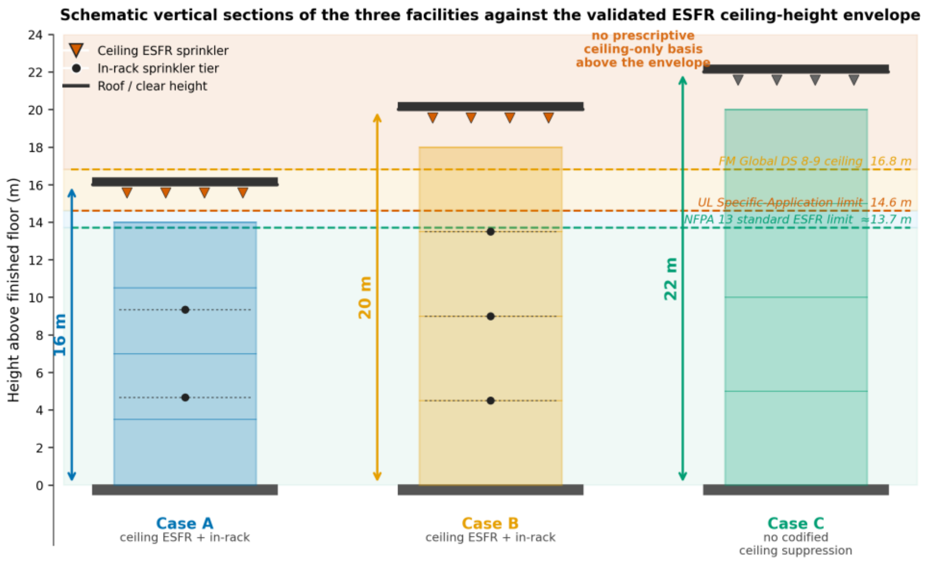
4.4. Analytical framework

Extracted parameters were mapped onto a code-gap framework built from Section 2: for each facility the clear height was compared with the NFPA 13, UL Specific-Application and FM Global envelopes of Table 2 to establish the magnitude of exceedance, and the adopted protection strategy was classified by the pathway (in-rack, FM-based, or engineered) it implicitly followed. The cross-case comparison (Section 6) then tests whether equivalent exceedances produced equivalent solutions. Deficiencies were derived inductively from the points at which the code provided no governing criterion and the design was obliged to substitute discretionary judgment.

5. Case Studies

The three de-identified facilities are described below and summarized, against the ceiling-height envelope of Section 2, in the comparative schematic sections of Figure 1. Each is presented in terms of its clear height, stored commodity, and adopted protection strategy; all identifying information has been removed.

Figure 1: Anonymised Schematic Vertical Sections of the Three Facilities (Cases A–C) Plotted Against the Validated Ceiling-only ESFR Envelope. All three clear heights lie above the NFPA 13 / UL Specific-Application limits (approximately 13.7–14.6 m); Cases B and C also exceed the cited FM Global ceiling of 16.8 m. Schematic and Not to Scale



5.1. Case A — Furniture retail-warehouse, 16 m

Case A is a large furniture retail-and-storage facility prepared to the Saudi Building Code and SASO requirements. The stored commodity—furniture with substantial expanded- and unexpanded-plastic content—falls at the demanding end of the commodity spectrum, approaching Group A plastics, and therefore attracts the most onerous sprinkler criteria. The ceiling protection is provided by ESFR upright sprinklers (K-factor annotated at approximately 15.8, i.e. a high-K ESFR device) supplemented by a dedicated tier of new in-rack sprinklers (K-5.6, with guards). The water supply is substantial: duty and standby fire pumps rated at 2 250 US gpm at 12 bar (one diesel, one electric) with a 225 gpm jockey pump, feeding a network of wet standpipe hose stations, siamese fire-department connections and private hydrants.

The significance of Case A is that, at 16 m—already above the ≈13.7–14.6 m ceiling-only envelope—the design does not rely on ceiling ESFR alone. It re-introduces in-rack sprinklers, precisely the height-independent strategy of Table 1, to compensate for the fact that the ceiling system is operating at or beyond its validated limit for this commodity. Case A thus exemplifies the "in-rack" resolution pathway of Section 2.4.

5.2. Case B — Dates and cold-storage facility, 20 m

Case B is a dates-processing and storage facility incorporating ambient warehouse, staging, cold rooms and freezer rooms, with a mezzanine level. The sprinkler schedule is markedly more elaborate than Case A and is reproduced in Table 3. Ceiling protection over the ambient warehouse and the in/out area is provided by ESFR pendent sprinklers of the highest capacity (K-22.4), while a separate tier of in-rack pendent sprinklers (K-5.6) protects within the racks. The cold and freezer rooms, where wet systems would freeze, are protected by ESFR dry-pendent sprinklers (K-16.4) backed by pre-action arrangements, with FM-200 clean-agent and deluge-foam sub-systems serving special risks.

Table 3: Case B Sprinkler Schedule, Transcribed from the Approved (De-identified) Fire-fighting Drawing. The Facility Combines High-K Ceiling ESFR with an In-Rack Tier and Specialised Low-Temperature and Clean-Agent Systems.

No.	Location	Sprinkler type	K	Size
01	Warehouse — above rack	ESFR pendent	22.4	3/4"
02	Staging area	Upright	5.6	1/2"
03	Cold room — above ceiling	Upright	5.6	1/2"
04	Warehouse in & out area	ESFR pendent	22.4	3/4"
05	Stairs	Side-wall	5.6	1/2"
06	Admin & office areas	Pendent	5.6	1/2"
07	In-rack	Pendent	5.6	1/2"
08	Cold room & freezer (inside)	ESFR dry pendent	16.4	3/4"

At 20 m, Case B lies far above every ceiling-only envelope in Table 2. The design response is a defence-in-depth combination: the highest-K ceiling ESFR available, an in-rack tier, and dedicated systems for the low-temperature and special-hazard zones. Case B represents an engineered, multi-system resolution in which no single element is a prescriptively validated tall-storage solution; the assurance derives from the aggregate of over-provisioned sub-systems rather than from a code table for a 20 m ceiling.

5.3. Case C — Furniture storage complex, 22 m

Case C is the tallest facility in the sample, a large furniture (furnishings) storage complex whose approved architectural plan declares design to the Saudi Building Code, a medium storage-hazard classification, a plot area of approximately 22 232 m² arranged as sixteen units over a very large footprint (of the order of

412 × 525 m), and a declared smoke-venting area of about 1 815 m². The plan foregrounds the architectural and life-safety envelope—occupancy classification, areas and smoke management—rather than a detailed ceiling-suppression schedule of the kind seen in Cases A and B.

Based on the documentation available for this study, Case C illustrates a third apparent resolution of the height gap: the available plan identifies the occupancy as "medium hazard" and foregrounds smoke management, but it does not provide a detailed ceiling-suppression schedule comparable to Cases A and B. Because NFPA 13 sprinkler demand for storage depends on commodity and storage configuration, the available documentation does not establish a prescriptively validated suppression basis for a 22 m array. Case C therefore exposes the documentation and regulatory gap most clearly: the tallest facility in the sample has the least explicit codified tall-storage suppression basis in the records reviewed.

6. Comparative Results

6.1. Cross-case comparison

Table 4 consolidates the three cases against the analytical framework. The first and decisive observation is uniform exceedance: every facility, at 16, 20 and 22 m, stands above the ≈13.7–14.6 m NFPA/UL ceiling-only ESFR envelope, while Cases B and C also exceed the cited 16.8 m FM Global ceiling. The second observation is divergence of solution. Faced with the same unaddressed condition, the three independent design teams adopted three materially different strategies—ceiling ESFR plus in-rack (Case A); high-K ESFR plus in-rack plus specialised sub-systems (Case B); and hazard-classification plus smoke management (Case C). No two facilities are protected on the same design basis, and none of the three bases is a prescriptive NFPA 13 tall-storage table, because no such table exists for these heights.

Table 4: Cross-case Comparison Matrix. Exceedance Is Measured Against the NFPA/UL Ceiling-only Envelope of 13.7–14.6 M.

Parameter	Case A (16 m)	Case B (20 m)	Case C (22 m)
Clear height	16 m	20 m	22 m
Occupancy / commodity	Furniture retail-warehouse (high plastic content)	Dates + cold/freezer storage	Furniture (furnishings) storage
Declared code basis	SBC / SASO	SBC (NFPA-referenced)	Saudi Building Code
Ceiling sprinkler	ESFR upright, K≈15.8	ESFR pendent, K-22.4	Not resolved by ceiling ESFR table
In-rack sprinklers	Yes (K-5.6, guarded)	Yes (K-5.6 pendent)	Not indicated on plan
Specialised systems	Wet standpipe; hydrants	ESFR dry (K-16.4), pre-action, FM-200, deluge foam	Smoke venting ≈1 815 m²
Water supply	2×2 250 gpm @ 12 bar + jockey	Multi-system (per schedule)	Not detailed on architectural plan

Parameter	Case A (16 m)	Case B (20 m)	Case C (22 m)
Exceeds ESFR envelope?	Yes (+1.4 to 2.3 m)	Yes (+5.4 to 6.3 m)	Yes (+7.4 to 8.3 m)
Resolution pathway	In-rack supplement	Engineered multi-system	Hazard-class + smoke mgmt

6.2 Identified deficiencies

Reading the cases against the code yields a set of specific deficiencies, each defined as a point at which NFPA 13 (and, by inheritance, SBC 801) fails to supply a governing criterion for the tall-storage condition and the design is obliged to substitute discretionary judgement:

D1 — Absence of a prescriptive ceiling-only basis above ≈14.6 m. For ceilings of 16–22 m the standard provides no ESFR density, operating area or K-factor. All three cases operate in this vacuum.

D2 — Undefined transition to mandatory in-rack protection. The standard does not state a height at which in-rack sprinklers become obligatory for a given commodity. Cases A and B explicitly indicate in-rack sprinklers, whereas no in-rack system was identified in the available Case C documentation; the code provides no single height rule that resolves this difference.

D3 — Discretionary hazard classification. The available Case C documentation identifies the occupancy as “medium hazard”; however, this designation alone does not establish the commodity- and storage-specific sprinkler design basis required for high-piled storage. The code framework therefore leaves room for interpretation unless the commodity, storage arrangement and height are explicitly tied to the adopted sprinkler design criteria.

D5 — Reliance on smoke management where the suppression basis is not documented. In Case C, the available documentation foregrounds smoke-venting provisions while a prescriptively validated tall-storage suppression basis is not documented. Smoke control can support tenability and property-protection objectives, but it should not be treated as a substitute for a demonstrated suppression basis for tall high-piled storage.

D5 — Reliance on smoke management as a suppression surrogate. Where suppression cannot be codified (Case C), smoke-venting area is foregrounded; smoke control mitigates tenability and property loss but does not suppress a tall high-piled fire, and the code does not prevent this substitution of intent.

D6 — Non-reproducibility of approvals. Because each solution is justified case by case under equivalency/AHJ discretion, two equivalent facilities can be lawfully protected to different standards, undermining the reproducibility that is the purpose of a prescriptive code.

7. Quantitative Gap Analysis

The preceding sections establish the gap qualitatively. This section quantifies it in three complementary ways: as a height-exceedance metric, as a delivered-density (RDD–ADD) argument, and as a prescriptive hydraulic-demand calculation that becomes unclosable above the envelope.

7.1. Height-exceedance metrics

Table 5 expresses each facility's clear height as an absolute and percentage exceedance of the two governing ceiling-only references: the NFPA 13 standard ESFR limit (≈13.7 m) and the highest UL Specific-Application limit (14.6 m). Every facility exceeds both, by between 10 % and 61 %; even against the more permissive FM Global ceiling (16.8 m) two of the three remain above. The exceedance is therefore not marginal—Cases B and C stand 5.4–7.4 m above the tallest validated ceiling-only configuration.

Table 5: Height-exceedance Metrics Against the Validated Ceiling-only ESFR Envelope. *NFPA 13 ESFR Designs Are Evaluated for a Fixed Number of Operating Sprinklers (Typically 12); Case C Is Not Protected by a Ceiling ESFR Table.

Case	Clear height	Exceedance vs 13.7 m	Exceedance vs 14.6 m	Above FM 16.8 m?	Design sprinklers*
A	16 m	+2.3 m (+17%)	+1.4 m (+10%)	No	12 (ESFR)
B	20 m	+6.3 m (+46%)	+5.4 m (+37%)	Yes (+3.2 m)	12 (ESFR)
C	22 m	+8.3 m (+61%)	+7.4 m (+51%)	Yes (+5.2 m)	— (not ESFR)

7.2. The delivered-density (RDD–ADD) criterion

The physical reason the envelope exists can be expressed through the delivered-density balance that underlies ESFR design. Suppression is achieved only when the Actual Delivered Density (ADD)—the water flux reaching the top of the burning array—meets or exceeds the Required Delivered Density (RDD) needed to arrest that fire, i.e. ADD ≥ RDD [7]. Both quantities are height-dependent but in opposite directions: RDD rises with storage height because a taller array develops a larger fire and a more energetic plume before ceiling sprinklers actuate, while ADD falls with height because droplets must penetrate a deeper, more buoyant plume over a greater ceiling-to-storage clearance. Beyond a threshold height the two curves cross and the inequality fails, as illustrated conceptually in Figure 2. The prescriptive tables terminate near this crossover precisely because full-scale tests can no longer demonstrate ADD ≥ RDD; the case heights of 16–22 m sit in the region where a ceiling-only system cannot be shown, from listed data, to satisfy the criterion.

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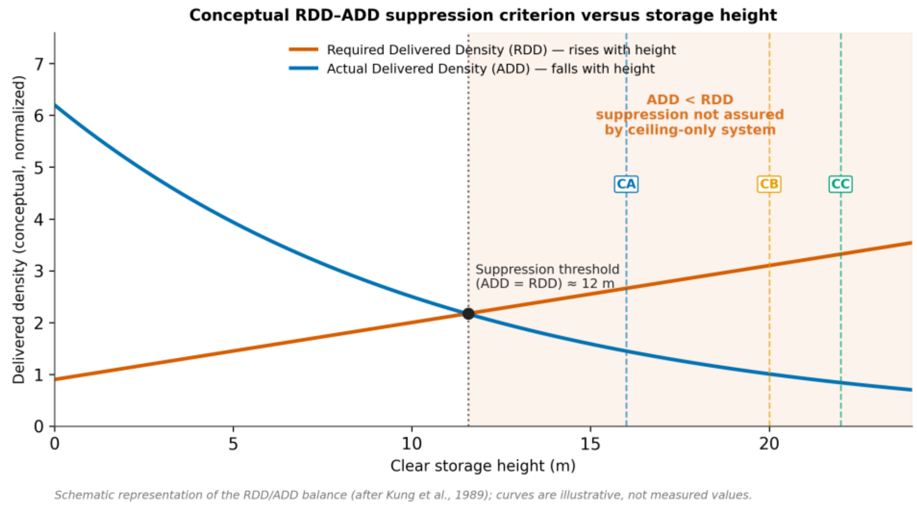
Figure 2: Conceptual RDD–ADD Suppression Criterion Versus Storage Height. Required Density Rises and Actual Delivered Density Falls with Height; Beyond Their Crossover a Ceiling-only System Cannot Be Shown to Satisfy ADD ≥ RDD. Curves Are Schematic (After Kung Et Al., 1989), Not Measured Values; Cases A–C Are Marked.



7.3. Prescriptive hydraulic demand and where it breaks down

The deficiency can also be shown as a concrete failure of the design calculation itself. Under NFPA 13, an ESFR system is sized from the discharge of a fixed number of operating sprinklers (conventionally twelve) using the orifice relation $Q = K\sqrt{P}$, where Q is the per-sprinkler flow (US gpm), K the nominal K-factor, and P the sprinkler operating pressure (psi) fixed by the listing for the specific ceiling/storage height. For the envelope-defining K-25.2 device at a representative listed pressure of the order of 40–50 psi, the per-sprinkler flow is $Q \approx 25.2 \times \sqrt{45} \approx 169$ gpm, giving a twelve-sprinkler system demand of roughly 2 030 gpm, to which a hose allowance of about 250 gpm is added—an order of magnitude fully consistent with the installed 2 × 2 250 gpm pumping capacity observed in Case A.

The decisive point is what happens above the envelope. For ceilings of 20 or 22 m there is no listed operating pressure P for any ESFR K-factor, because no device has been tested and listed at that height. The term P in $Q = K\sqrt{P}$ is therefore undefined, and the demand calculation cannot be closed from prescriptive data at all: the design has no code-supplied basis for flow, pressure, density or operating area. The gap is thus not a matter of insufficient conservatism but of a missing input—an equation that cannot be evaluated—which is why every above-envelope design in this study necessarily substitutes an imported (FM) or engineered (performance-based) basis for a prescriptive one.

This calculation is illustrative only and does not represent a universal listed design point for all K-25.2 applications.

8. Discussion

The three cases, taken together, convert an abstract code boundary into an observable regulatory outcome. The physics is settled: above roughly 14.6 m, ceiling-only ESFR is outside its validated range, and the RDD/ADD balance on which suppression depends can no longer be guaranteed from test data [7,8]. The three cases examined here extend from 16 to 22 m, placing all three above the NFPA/UL envelope and

two above the cited FM Global ceiling. Within this sample, the gap is therefore operationally relevant rather than merely theoretical.
What the cases add is evidence about how the gap is being filled in practice. It is being filled inconsistently. Three competent, independent design teams, each producing an approved design for a comparable fundamental hazard, arrived at three different protection philosophies. This is the predictable result of a code that neither prescribes nor prohibits: in the absence of a shared numerical basis, each designer imports a defensible rationale—in-rack supplementation, multi-system defence-in-depth, or architectural mitigation—and each AHJ, lacking a code table against which to test the submission, accepts a reasonable engineering argument. The outcome is lawful but not reproducible, and reproducibility is precisely what a prescriptive life-safety code is meant to guarantee. Deficiency D6 is thus not a criticism of any individual design but a structural property of the gap itself.

The Saudi dimension sharpens the concern. Because SBC 801 inherits the NFPA 13 envelope by reference without restating it [4], the controlling limit is doubly obscured: it is buried in a referenced standard and unmarked in the national text. A designer working primarily from SBC 801 may not encounter an explicit statement that ceiling ESFR is unvalidated above ≈14.6 m, and a plan reviewer may lack an explicit criterion on which to challenge a tall-storage submission. In this setting the most exposed configuration is the one that leans hardest on discretionary levers, as in Case C, where the available documentation for a 22 m occupancy foregrounds hazard classification and smoke management without documenting a demonstrable prescriptive tall-storage suppression basis.

It is important to state the limits of the claim. None of the three facilities is asserted here to be unsafe; each may well perform adequately, and Cases A and B in particular embody conservative, defence-in-depth provisioning. The argument is narrower and structural: the safety of these buildings rests on engineering judgement that the code neither guides with numbers nor constrains with rules, and equivalent buildings can therefore be protected to non-equivalent standards. That is the legislative deficiency, and it is independent of the outcome in any single case.

9. Recommendations

Closing the gap requires action at both the standard and the national-code level. The following measures map directly onto the deficiencies of Section 6.2 and are ordered from immediate to strategic.

R1. Restate the envelope explicitly in SBC 801 (addresses D4). The national code should state, in its own text, the maximum ceiling and storage heights for which referenced ESFR criteria are valid, and should require an explicit alternative-means submission above that limit—making the constraint visible to every designer and reviewer.

R2. Mandate a height-triggered protection hierarchy (D1, D2). Introduce a rule that, above the validated ceiling-only envelope for a given commodity, protection must include either a compliant in-rack tier or an accepted performance-based design; remove the possibility of relying on an extrapolated ceiling-only system by default.

R3. Constrain hazard classification by commodity × height (D3). Tie the storage-hazard class explicitly to the combination of commodity class and clear storage height, so that tall high-plastic storage cannot be classified downward into a lower design demand.

R4. Adopt a formal performance-based pathway with acceptance criteria (D1, D6). Provide a structured PBD route for above-envelope storage—defined fire scenarios, RDD/ADD or CFD-based demonstration, and documented acceptance criteria—so that engineered solutions are justified against a common, auditable standard rather than ad hoc.

R5. Separate suppression from smoke management in intent (D5). Require that smoke-control provisions be additive to, not a substitute for, a demonstrated suppression basis for tall high-piled storage.
R6. Establish a national tall-warehouse review protocol (D6). Create a specialist review checklist and, for buildings above a defined height, a peer-review requirement, to restore reproducibility to approvals across AHJs.

10. Limitations

The study is based on three purposively selected Saudi facilities and is intended to demonstrate and characterise a phenomenon rather than to establish its statistical prevalence; a larger, systematically sampled survey would be required to quantify how frequently each resolution pathway occurs. The analysis is primarily documentary, relying on approved (de-identified) drawings; the quantitative treatment in Section 7 is illustrative and order-of-magnitude—the RDD–ADD curves of Figure 2 are conceptual rather than measured, and the hydraulic figures use representative listed pressures—so it supports the gap argument without substituting for project-specific fire modelling or full-scale test data. The vertical sections of Figure 1 are anonymised schematics, not to scale, and the clear heights are the design-reported values; some drawing-derived parameters, most notably the K-factor annotation in Case A, carry the uncertainty inherent in reading issued plans. The edition-specific clause numbering of NFPA 13 evolves between the 2019 and 2022 editions, and practitioners should confirm the exact table and section references against the edition adopted in their jurisdiction. Finally, the argument concerns the adequacy of codified criteria, not the safety of any individual building; no conclusion about the actual fire performance of the three facilities is drawn or implied.

11. Conclusion

The three high-bay warehouses examined in this study operate above the ceiling-only ESFR envelope established by NFPA 13 and the cited UL specific-application listing, approximately 13.7–14.6 m. Three approved Saudi facilities of 16, 20 and 22 m were shown to lie above this envelope and, tellingly, to resolve the resulting absence of prescriptive criteria by three different, individually approved strategies. That divergence is the central finding: the code neither prescribes nor prohibits protection above its tested limit, and it thereby delegates a life-safety-critical decision to discretionary judgement that varies from one design team and reviewer to the next. The deficiency is legislative and structural rather than a fault of any single design. It can be remedied—by restating the envelope explicitly in the national code, mandating a height-triggered protection hierarchy, constraining hazard classification, and providing a formal, auditable performance-based pathway. Doing so would convert the identified discretionary gap into a more defensible and reproducible design basis for tall warehouses.

REFERENCES: