Value Engineering of Passive Fire Protection for Structural Steel

By Arthur Nestor R. Iwankiw, P.E., PhD, J. Parker, P.E. and Jesse J. Beitel

Customary practice in the US is for the project architect to specify the necessary steel fire protection, as required by the prescriptive criteria of the building code. The structural engineer of record typically has no involvement in this process. Sometimes value engineering by a designated fire protection consultant or material supplier can result in substantial project cost savings and benefits.

In some cases, it may not be project economy, but rather the nature of the innovative expressive design itself may motivate an engineered design. In such instances, the published fire resistance ratings and criteria may be too restrictive and more advanced, or alternative, means and methods to comply with the code intent are often necessary. The latter is often referred to as "performance-based design".

Other background information on these topics was excerpted from the AISC publication Facts for Steel Buildings-Fire (2003) written by Iwankiw.

Building Code Requirements for Structural Fire Resistance

Fire resistance requirements are intended to provide for life safety and property protection by preventing fire spread and the collapse of the structure until all the building occupants have had an opportunity to evacuate the premises. Passive structural protection contributes only one part to the building's overall fire safety. Several complementary fire and life safety features are necessary to enable adequate fire response, and the safe exiting of the occupants of a building in the event of a fire emergency. These include:

- Structural fire protection.
- Compartmentation, with both horizontal and vertical fire barriers.
- Fire alarm and detection devices.
- Automatic sprinklers.
- Smoke control.
- Egress provisions, including exits, stairs, elevators, and their locations and distances.
- Standpipes for fire department operations.

The balance of this article will deal exclusively with structural fire protection.

The newer IBC 2003 and NFPA 5000 model building codes are the most prominent model codes for present and future design and construction, though some vestiges of the prior 1997-2000 model codes from ICBO, BOCA and SBCCI remain in effect. These two codes are generally similar in terms of both structural design and fire resistance requirements. The reader should verify the actual fire protection requirements in the governing local building code, the referenced national code and standards for all the actual code requirements in a particular jurisdiction.

The method long used by the building codes is to separate buildings into various occupancy categories and use group subcategories. The IBC lists 10 occupancy categories, while NFPA 5000 has 11, such as assembly, business, educational, and factory/industrial. These categories are further segmented into use groups that are specifically described. For example, the assembly "A" occupancy in the IBC has 5 possible groups: A-1 through A-5.

Types of construction distinguish between combustible or noncombustible construction and the degree of fire resistance of the primary structural framing material. The principal structural elements of the building in Types I and II construction are required to be noncombustible, with some minor exceptions. Steel, concrete and masonry construction are noncombustible, and classified as either Type I or II construction. This IBC code classification system thereby specifies the highest inherent structural fire resistance to Types I and II, and the least to Type V. Accordingly, the more critical building occupancies and uses are prescribed to have the preferred Type I and II construction designations, with accompanying more liberal heights and area limitations. Types III, IV and V are progressively more restrictive in terms of allowable heights and areas. The building size, footprint, and its fire protection are typically determined in conjunction with the occupancy and type of construction allowed by the code.

The allowable heights and areas (see Table 503 in the IBC; Table 7.4.1 in NFPA 5000) contain the detailed information that delineates the various occupancy groups, heights and area limitations, and types of construction. These allowable heights and areas are the baseline reference, from which further increases are possible when provided with such considerations as sprinklers and frontage separation.

The high-rise building is defined by the IBC as one having an occupied floor more than 75 feet above the lowest level of fire department vehicle access. Automatic sprinklers are required for all high-rise buildings, with just a few exceptions in the IBC and no exceptions in NFPA 5000. Where supervised sprinkler control valves for each floor are present, either a reduction of the Type IA Construction to Type IB requirements, or a reduction of Type IB Construction to Type IIA requirements is permitted in the IBC. Similar reductions are allowed in NFPA 5000. These Construction Type reductions are important in determining the minimum required fire resistance ratings for the building elements. The fire resistance ratings for building elements have historically been defined

Table 1: Summary of Fire Resistance Requirements (IBC 2003)

Building Element	Type I		Type II		Type III	
	A	B	A	B	A	B
Structural frame	3	2	1	0	1	0
Bearing Walls						
Exterior	3	2	1	0	2	2
Interior	3	2	1	0	1	0
Floor Construction	2	2	1	0	1	0
Roof Construction	1 1/2	1	1	0	1	0

as a function of the type of construction that is employed. *Table 1* (Based on Table 601 from the IBC) gives these fire resistance rating requirements, which are generally representative of construction practices over the last several decades. Types IA and IB in the IBC, as well as the comparable designations in the NFPA 5000, provide the greatest allowed heights and areas, which in many cases are unlimited by the code.

In high-rise buildings, special requirements for automatic sprinklers allow the Type IB construction requirements to be used for a Type IA building, and Type IIA requirements for a Type IB building. The practical implication of this for a Type IA building is a 1-hour reduction, from 3 hours to 2 hours, in the minimum fire resistance for the frame girders and columns; for a Type IB building, it is a 1-hour reduction for both the columns and floors, from 2 hours to 1 hour. These allowable fire resistance reductions are important, and, along with the available Type IIB Construction provisions for zero rating time (unprotected steel) in low-rise buildings, their implementation can result in meaningful cost savings on a given steel project.

Type of Construction

Type of Construction affects the extent and cost of required structural fire protection, and is the basis on which the building will qualify given its use/occupancy, heights, areas, etc. Type of Construction is usually selected based on the owner's project objectives (floor area, use and height of building), needs and the constraints of the available property location. However, careful early review of the applicable building code in this regard may reveal some reasonable and manageable substitutions or modifications to the original project plans. These may enable a move to a more favorable construction type designation to optimize the required fire resistance ratings for the structure.

For example, the initial project specifications may call for a building that appears to almost fit a preferred construction type or designation, but falls into the more stringent one that requires more fire protection. In small to medium size buildings of about 6 stories or less, if there is some project flexibility allowing for modifications to qualify for the less demanding construction type classification, then the potential for cost savings can be realized, with even possibly the attainment of unprotected Type IIB construction. However, it should be realized that certain mandatory code provisions, such as fire-rated shaft enclosures, including exits, would require similarly rated construction for its supports, thereby potentially limiting the range of use of Type IIB construction. Some trade-offs between floor area and number of stories, frontage area, or the discretionary use of sprinklers, are the primary means through which this favorable reduction of code requirements can be achieved. As with any major decision, agreement on the Type of Construction selection should be reached on the basis of full knowledgeable input from all the project parties and disciplines.

For high-rise buildings with unlimited heights and areas, Type IA or IB will be necessary per the IBC as the baseline, but the mandated use of sprinklers allows for a one category reduction in fire protection requirements, as previously described, which can translate for up to a 1-hour fire resistance difference in both the beams and columns.

Product Selection

The common choices for protected steel construction include gypsum board, sprayed fire-resistive materials (SFRM), and intumescents/ mastic coatings. New fire protection products and listed assemblies are continually being added to the inventory of available choices, as contained in the Underwriters Laboratory Fire Resistance Directory, Volume 1 and other sources. Timely independent and professional advice on this selection are likely to avoid problems or concerns about the appropriateness of a given structural fire protection product for the intended service and performance.

Restrained and Unrestrained Ratings

Gewain and Troup (2001) summarized pertinent facts, past research, and historical experience to reinforce assertions that the restrained classification for fire protection design is most appropriate for steel beams, girders, floor and roof assemblies that support concrete slabs and that are welded or bolted to integral framing members, as given in ASTM E119-00, Appendix X3. The proposed AISC 2005 Specification for Structural Steel Buildings, in a new Appendix on structural design for fire conditions, is expected to explicitly contain this statement on use of restrained ratings for steel construction in fire design.

Member Substitutions

In practice, it is common for floor beams to naturally exceed the minimum steel member sizes shown in the fire resistance designs. A heavier steel beam shape, or one with a greater *W/D* (weight to heated perimeter) ratio, may be conservatively substituted for the lighter members shown in fire-rated designs with the given protection thickness. However, doing so without compensating for the more favorable thermal mass characteristics of the beam with the higher *W/D* ratio is inefficient. This excessive overprotection of all floor members based on the smallest listed beam shape in the fire rated design occurs frequently, and can be costly. The preferred economical approach is to use the analytical relationships developed from fire test to determine the thickness requirements in SFRM requirements for the actual beams, or several size groupings, as a function of their actual *W/D* properties.

The fire resistance listings give the minimum steel column size necessary for the applicable fire rating – the member that was tested – comparable to what was done for steel beams. Again, larger members than the minimum steel size may be conservatively used with the fire protection requirements in a given design. However, if a lighter steel section is to be used for the column, more fire protection will be required. As in beams, the reason for this adjustment is the increased thermal mass capabilities of heavier members with larger *W/D* ratios, which require less insulation than lighter members for the same fire exposure conditions.

Savings Projections With Prescriptive Criteria

The portion of the total project budget that is typically allocated to structural steel framing is less than 10 percent, and the associated structural fire protection typically comprises no more than roughly 10 to 15 percent of this steel package cost. This approximate 1 to 1½ percent of the overall budget for passive steel fire protection is modest, and seemingly would not appear to be a relatively significant cost factor. However, there is still significant potential to reduce cost without sacrifice of safety as shown in *Table 2*.

Fire Engineering

More advanced fire engineering analyses, beyond the given pre-scriptive code requirements, may justify certain building design features or assess factors that are beyond the prescriptive scope of the current codes. These may include, but are not limited to, the need for unprotected or exposed construction due to architectural or other reasons, use of new (or not listed) materials or assemblies, consideration of member load effects and/or of natural (nonstandard) fire exposures. Externally unprotected construction would likewise typically require additional engineering study to verify its fire safety adequacy for the protected, noncombustible Type I or IIA designation of the building. While this work may be also partially motivated by economy, it is probably much more influenced by the non-financial project needs and constraints of the owner or architect, wherein the unique occupancy, appearance, and/or use of the building is expected to be consistent throughout its service life.

Conclusions

Value engineering could identify meaningful direct cost savings and indirect benefits in the structural fire protection for some buildings and typical conditions, just by implementation of the regular prescriptive ratings and criteria of the current building codes. A suitably scoped peer review or code compliance check performed by an experienced structural fire protection engineering consultant could likewise serve the same purpose. The potential streamlining of common conservative design assumptions and excessive protective material applications can provide improved economy without sacrificing the intended safety objectives of the codes. In select cases, dependent on the exact nature of the encountered initial circumstances and size of the project, it is expected that very tangible passive fire protection cost savings or their reallocation can be realized, even reaching hundreds of thousands or several million dollars, as the example projections illustrated.

Table 2: Maximum Estimated Potential Savings in Structural Fire Protection (Passive) Costs (per ft² of floor area) for Steel Buildings

Type of Construction	Low-rise (≤ 6 stories)	High-Rise
Protected (IA, IB, IIA)	\$0.30 - \$0.60/ft²	\$0.30 - \$0.60/ft²
Unprotected (IIB)	\$1.40-\$2.00/ft²	N/A

Additional engineering analyses of structural fire resistance for unique non-routine conditions (load effects, natural fires, or Architecturally Exposed Structural Steel) could likewise result in enhanced value to the project of terms of safely satisfying the owner's and/or architect's special objectives, apart from any economic aspects.

Greater professional engineering attention directed toward structural fire resistance design can safely bring both economic and functional benefits to the completed project.▪

Arthur Parker, P.E. is a Senior Fire Protection Engineer Hughes Associates, Inc.
Jesse Beitel, is a Senior Scientist and Principal with Hughes Associates, Inc.
Nestor Iwankiw, P.E., PhD, is a Senior Engineer and Director of the Chicago Office, Hughes Associates, Inc.

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Fire Protection Materials for Architecturally Exposed Structural Steel (AESS)

By Arthur J. Parker, P.E., Jesse J. Beitel and Nestor R. Iwankiw, P.E., PhD

Current trends in building design include leaving building structural steel elements visually exposed rather than concealed. A number of tested and listed fire protection materials are available to provide required fire resistance ratings. In some cases, building designers may desire to leave the steel members unprotected. In this case, an engineering analysis must show adequate structural fire resistance performance to meet the necessary fire safety objectives given the expected occupancy, fuel contents, structural steel sizes, building configuration, and anticipated fire exposure.

Building Code Requirements

Minimum fire resistance ratings for structural frame members, nonbearing interior and exterior walls and partitions, and floor and roof construction are provided in the building codes. The minimum fire resistance rating is determined by the building construction "Type" and the classification of the structural member as primary or secondary. The height and area of the building and the occupancy classification determines the building Type. Most steel framed, multi-story buildings are constructed as non-combustible Type I or II buildings and are the focus of this article.

A structural member must be classified as either part of the primary structural frame or as a secondary member. Columns and girders, beams, trusses, and spandrels having direct connections to the columns and bracing members designed to carry gravity loads are defined by the building code as the primary structural frame. Structural members of the floor and roof construction, which have no connection to the columns, are considered as secondary members and are not considered part of the structural frame.

Figure 1: Structure Steel Members Protected with a Thin-Film Intumescent (Photo Courtesy of Isolatek International)

The minimum hourly fire resistance ratings can then be determined from the building codes. For example, Table 601 of the International Building Code (IBC) provides the requirements for the various building elements. Similar requirements are provided in NFPA 5000.

Fire Protection Materials

Many products are available to provide fire resistance for protected construction. In general, fire protection materials should:

- Provide the required thermal protection when tested in accordance with the ASTM E 119 test standard (or similar fire resistance test methods);
- Be a listed product or system;
- Be efficient to apply, resulting in a uniform thickness;
- Adequately bond to the underlying steel element;
- Be resistant to corrosion, weathering, and aging (when required);
- Resist abrasion damage resistance (incidental or otherwise) for materials that are applied within the reach or access of the building occupants; and
- Ideally, be a non-combustible material.

Common fire protection materials used for structural steel include sprayed fire-resistive materials (SFRM), thin-film intumescents, epoxy-based intumescents/mastics, board type products (mineral fiber and gypsum wallboard), and intumescent mat wrap materials. This article specifically addresses the application of SFRM and intumescent materials applied to commercial structural steel for AESS applications. Incorporation of unprotected construction beyond the limits of the building code requirements may still be feasible, provided an appropriate analysis is conducted (e.g., performance based design) by a qualified structural fire protection engineering firm.

When properly applied to the structural steel at the listed minimum thickness (and density when using SFRM), fire protection materials will provide the required fire resistance rating. Each type will have a number of manufacturers, product variations, performance characteristics, and requirements, and advantages/disadvantages, all of which can affect project design choices.

Important considerations will include aesthetics, performance (fire safety, durability, maintenance, exposures), and cost. Intumescents are likely the ideal choice for meeting AESS requirements, with thin-film intumescents being more diverse and cost effective than the epoxy-based intumescents. SFRM are less expensive to apply than the thin-film intumescents, but may lack the necessary finished appearance. Board and wrap products are applied in such a manner that the contour of building steel are completely hidden, which may make them undesirable.

Thin-Film Intumescents

Thin-film intumescents (*Figure 1*) are brush or spray-applied directly to the structural steel at relatively thin thicknesses; approximately 0.03 to 0.40 inches (dry film thickness). When exposed to heat, they undergo a chemical change and form an insulating char layer 15 to 30 times thicker than the initial application thickness. Listings in the Underwriters Laboratories, Inc. (UL) Fire Resistance Directory in the D, N, and X design series, are provided for beams and columns with fire resistance ratings ranging from 1 to 4 hours. Approved primers must be applied to the steel prior to the initial application to insure proper adhesion to the structural steel.

Thin-film intumescents can be applied in a single spray pass at the lower thickness ranges. Multiple spray applications are required for greater thicknesses. Drying time must be allowed for multiple coat applications. Adequate ventilation is important during the spraying process, as many thin-film intumescents are solvent based. A paint finish coat may be applied over the dried thin-film intumescent to provide the desired finished appearance. A listed finish coat is not required, though the manufacturer's recommendations for suitable materials should be followed. Thin-film intumescent coatings are arguably the most aesthetically pleasing, though they are more expensive than SFRM.

Current thin-film intumescents most commonly provide 1- and 2-hours of fire resistance. Fire resistance ratings of 3- and 4-hours are available; though limited to massive structural members with a high *W/D* ratio (the thermal mass provided by a steel building element). In the *W/D* ratio, "W" is the weight of the beam, in pounds per linear foot, and "D" is the heated perimeter of the steel element in inches.

Figure 2: Steel Column Protected with Epoxy Based Intumescent (Photo Courtesy of PPG Industries, Inc.)

With few exceptions, thin-film intumescents have not been successfully tested (and/or listed) to provide fire resistance ratings for open web steel joists, light structural members (e.g., angles), or to the underside of fire rated roof deck systems. Use for exterior applications is also currently not recommended.

The next generation of thin-film intumescents are expected to provide more options in steel sizes, increased 3- and 4-hour fire resistance rating thicknesses, water-based formulations to better comply with health and safety regulations, and greater single-pass application thicknesses. The resulting applications will likely be safer and more cost effective.

Epoxy-based Intumescents/Mastics

Epoxy-based intumescents/mastics (*Figure 2*) are heavy-duty intumescents developed primarily for the offshore and petrochemical industries, where severe fire exposures can be encountered. Exposure of the epoxy-based intumescents to the high heat flux environments result in the development of a robust char layer, capable of withstanding highly erosive fire exposure environments. These products have been back-fitted to some extent into other use applications, including protection of structural steel in commercial buildings, clean rooms, and pre-construction applications.

Application thicknesses range from approximately 0.2-inches to over 1 inch thick, depending on the size of the structural member and the fire resistance require-ments (up to 4 hours). Typical char layers are on the order of 50 to 100 times the original thickness, significantly higher than thin-film intumescents. Support for the increased char layer thickness is provided by incorporating internal reinforcement (metal wire, fiberglass, or carbon scrim mesh) in areas vulnerable to damage, such as flange tips. No special surface primers are required for the epoxy-based intumescents to achieve adequate adhesion with the steel surface, only a clean surface free of oil, dirt, grease, or heavy mill scale. The finished texture of the spray applied epoxy-based intumescent is slightly rougher than the thin-film intumescent text-ure, potentially limiting its usage for AESS applications.

Figure 3: Structural Steel Column Protected with SFRM

Listings for epoxy-based intumescents are provided in the X600 and XR600 (hydrocarbon exposure) design series in the UL Fire Resistance Directory. A single, minimum beam size is typically provided in the X600 series listings. Adjustments for alternate beam sizes are more problematic, since calculation methods have not yet been developed for epoxy-based intumescents, as have been developed with SFRM.

Epoxy-based intumescents are extremely durable for exterior applications, provide excellent adhesion qualities, and can have an aesthetically pleasing appearance. Testing has been conducted against various blast loadings to insure that adhesion to the steel substrate (either a structural member or bulkhead) prior to the ensuing fire exposure is maintained. These excellent performance qualities do come at a price, so epoxy-based intumescents are specified predominantly in special applications where severe fire exposures could be encountered.

If the newer threats of terrorist actions, and the resulting abnormal exposures due to combined impact, blast damage and/or fire are deemed a design factor, this class of protective coatings may be a more viable option. The design services of a specialty fire protection consulting firm should be engaged for advice in such applications.

Sprayed Fire-Resistive Materials (SFRM)

SFRM fall into two broad categories: sprayed mineral fiber SFRM (dry-mix) and sprayed cementitious SFRM (wet-mix). All SFRM are composed of varying mixtures of mineral fibers, Portland cement, binders, and water.

The finished appearance resembles a rough sprayed plaster-like texture. *Figure 3* shows a steel column

protected with mineral fiber SFRM with the typical rough texture. Some SFRM products can be trowel applied or trowel finished to produce a smoother finish, but the material thickness (on the order of 1 inch or more) will commonly result in a bulky appearance and non-uniform look given the inevitable local overspray. The thin, architecturally appealing lines of the steel are consequently obscured and overwhelmed by these SFRM features. Therefore, for aesthetic reasons SFRM would not ordinarily be the protection material of choice for use in prominently displayed AESS areas.

Sprayed mineral fiber SFRM contain a mixture of mineral fibers and Portland cement with a density, pounds per cubic foot (pcf), ranging from the mid-teens to the low twenties. Sprayed-fiber SFRM are shipped dry in bags to the job site, poured into a special hopper where they are "carded" or mixed. The dry fibers are conveyed by low pressure air through a hose to a special nozzle attached to the end of the spray head where it is mixed with atomized water prior to application to the structural steel. When set appropriately, the desired SFRM consistency and density is achieved.

Sprayed cementitious SFRM may contain gypsum binders or Portland cement, and have densities ranging from the mid-teens up to approximately 50 pcf. Cementitious SFRM are also shipped dry to the job site, however the SFRM are mixed with water in the hopper to form a slurry. The wet SFRM are then conveyed through a hose to a spray nozzle, where compressed air is typically used to disperse the material into a spray pattern for direct application to the structural steel. Increasing the density of the cementitious SFRM provides a harder, more durable, weather and abrasion resistant cover for longer-term and unusual exposures, but these benefits come at a higher price compared to the sprayed-fiber SFRM. A comparison of the generic usages of sprayed-fiber and cementitious SFRM is provided in *Table 1.*

The minimum thickness of the SFRM depends on the steel size and the hourly fire resistance rating required. UL Fire Resistance Directory provides minimum thickness and density values for columns, beams, trusses, floor/ceilings, and roof deck assemblies in the D, N, S, P, and X design series. The appropriate Listing for the SFRM and the steel sizes being protected on the job site will be calculated by the building designer and contained in the submittal documents. Adjustments to the SFRM thickness, using calculation methods contained in the UL Fire Resistance Directory, can be applied to minimize the SFRM application.

Table 1: Usage Comparison of Sprayed-Fiber and Cementitious SFRM

Installed Density (pcf)	Sprayed-Fiber (Dry-Mix) SFRM	Cementitious (Wet-Mix) SFRM	Common Uses
Mid teens to 20	Portland cement and mineral fiber factory mix	Gypsum plaster with vermiculite or shredded polystyrene	Concealed structural steel
20 - 25	Portland cement and milled mineral fiber factory mix	Portland cement and/or gypsum with vermiculite or shredded polystyrene	Weather-exposed structural steel Loading docks Equipment rooms
40 to 50	None available	Portland cement and vermiculite or Mica and other aggregates	Weather-exposed structural elements such as parking garages, overpass structures

Testing and Listings

UL offers numerous listings for the materials described above. The requirements provided in the listings and the manufacturer's written installation instructions must be followed to insure proper application. Calculation methods derived from testing may be utilized, within appropriate limits, when situations arise which are outside the bounds of the listing. For example, UL provides an equation based on the *W/D* ratio of the steel member being protected such that the required SFRM thickness is reduced as the *W/D* ratio increases.

General calculation methods for the intumescent materials do not currently exist. There is limited performance data over a wide range of structural steel sizes available, and a thorough theoretical understanding of the intumescing process is unknown. A minimum intumescent insulation thickness can be calculated, provided thicknesses for bounding steel members are known. Existing fire test data can also be utilized to predict the performance of intumescent materials. A qualified structural fire protection engineer can utilize the manufacturer's test data and product knowledge, and analytical engineering tools to determine an appropriate insulation thickness. Alternatively, a fire test can be conducted for the assembly being designed.

Inspection Requirements

Specific requirements are included in the building codes to insure that the fire protection materials are applied in accordance with the listing and manufacturer's requirements. Section 1704.11 of the IBC provides specific requirements for the inspection of SFRM materials. Field testing standards are available to verify the SFRM density, field applied insulation thickness, and adhesion/cohesion. A number of American Society for Testing and Materials (ASTM) and Association of the Wall and Ceiling Industries – International (AWCI) standards exist for conducting field testing of SFRM applied to building structural steel.

Inspecting field applied intumescent materials used for structural steel protection is not specifically required in the building codes. AWCI provides inspection criteria for the thickness measurement of applied coatings. The density of the field applied intumescent materials does not vary during installation; therefore, no verification of the installed density is required.

Conclusions

In many applications it is possible to incorporate unprotected AESS, with special engineering analysis to demonstrate compliance with the performance objectives of the code for the encountered project conditions. An appropriate engineering analysis must be conducted by a qualified structural fire protection engineer to justify deviations from the prescriptive building code requirements.

Fire protection of AESS within the building code requirements can be provided by use of a number of commercially available, tested, and listed fire protection materials. Fire protection materials are applied directly to the steel surface at a listed minimum insulation thickness to provide the required fire resistance rating. Limitations for all insulation materials exist, and must be followed to prevent misapplication of the product and to ensure proper fire performance. Building codes, test standards, and industry practices provide specific inspection guidelines for insuring that the fire protection materials are properly applied and will provide the level of safety required. A qualified structural fire protection engineering firm is best suited to advise the project team on the selection, design, application, inspection, and maintenance of the potential fire protection products for protected construction.▪

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