Construction Fire Mitigation by:

Improving Fire Resistance of Wood Products

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Executive Summary

Buildings face the greatest risk from fires during the construction phase. In recent years, there have been several examples across Canada of major construction site fires, including those in Calgary, Alberta in March 2015, Kingston, Ontario in December 2013 and Richmond, British Columbia in 2011.

Many risks exist at construction sites, including: The proximity of combustible materials to ignition sources (e.g. electrical equipment and hot work such as welding); the lack of completion of any built-in fire-safety systems such as sprinklers; the absence of doors, finished walls and other separations that may slow fire spread; and, potential site security issues.

It is estimated that more than 100,000 building projects in Canada each year involve wood-based construction; that is, using wood-frame, post-and-beam, and mill or cross-laminated timber.

With this widespread and growing use of wood–due in part to building code changes permitting taller wood buildings–comes the need for a greater focus on construction fire safety. Although research shows that wood buildings are as safe as those built with steel and concrete when effective fire-safety systems are in place, they are more vulnerable to fires when they lack those systems–as is the case during construction.

There are many articles published concerning the fire safety of wood framed mid-rise buildings under construction (e.g., Garis, Maxim and Mark, 2015). These documents focus on best practices around effective ways to reduce the likelihood of fire incidents. But, even with these best practices in place, catastrophic fires of mid-rise buildings under construction continue to happen. As Paulo Coelho (1993) noted, “Everything that happens once can never happen again. But everything that happens twice will surely happen a third time.”

Financial losses due to construction fires can be significant. Furthermore, fire departments generally take a defensive approach to construction site fires as there is typically little to no need for occupant rescue in buildings under construction. Firefighter safety and preventing fire spread are usually the main focuses.

This paper provides an alternative to consider during the construction stage to mitigate the risks to incomplete buildings and to onsite building material through the potential of practical solutions that can lower the combustibility of wood construction as an addition to fire safety plans which reduce the likelihood of fire incidents.

A focus on construction fire safety makes good business sense. By effectively addressing the fire safety gap of under-construction buildings, wood framed mid-rise construction should become a more attractive option for municipalities and developers.

Forward

Issues relating building materials and flammability are wide ranging and challenging. In isolation, it is relatively easy to identify materials that are fire resistant or, in some instances, "inflammable." Unfortunately, buildings are complex structures that have compromises between form, function, structural components and cost. Consequently, the flammability of an individual element may or may not be relevant depending upon where it fits into the overall structural system. To further add to the complexity of the analysis, we often need to consider the phases of a building life-cycle, including the construction phase, the ageing of the structure, and the final demolition or disposal of the structure. Materials that are optimal in terms of form, function and fire resistance at one phase of a building's life cycle, might not be so at another.

Within this context, one needs to keep in mind that fact that there is no one perfect material or composition but that relative strengths and weaknesses of various products regarding an individual characteristic, such as flammability, must be considered within the broader function they serve within the structure. It is theoretically possible to develop building materials that are completely inflammable but are unusable because of their cost, weight, strength, flexibility or esthetic appeal.

This review will focus on what we currently know about wood products and various coating or treatment products and procedures for increasing the fire-resistance characteristics of those wood products.

Construction Fire Safety

As Garis, Maxim and Mark (2015: 5) note, "buildings face the greatest risk from fires during the construction phase." There are numerous reasons for this, ranging from acts of vandalism to construction accidents. It is also the case that incomplete buildings do not have the various fire-prevention and fire-retarding systems in place that we find in complete structures. Systemic barriers are not completed, sprinkler systems are not installed.

The best fire prevention mechanisms are active as opposed to passive systems (see Garis, Maxim and Mark, 2015). That is, even the most flammable materials can be safely stored and used if proper safety procedures are followed. Keeping a worksite clear and tidy; storing flammable materials in appropriate containers and in proper locations; avoiding smoking on the jobsite; maintaining worksite security; and, providing adequate training in the use of materials and proper construction practices are simple yet effective ways of reducing the likelihood of fire incidents. Legislative actions such as the mandatory requirement for "hot work" permits can also have a significant impact.

Beyond active systems, however, are passive systems where safety mechanisms are designed into equipment and components. A good example here is the standard use of grounding and appropriate circuit breakers when electrical equipment is used. The use of spark arrestors for equipment used near flammable gasses or liquids is another form of passive fire prevention. Regarding material, the use of flame-resistant wood products is another element of passive prevention. While the use of barriers and surface cladding (e.g., gypsum or cement board) may be excellent ways to reduce the likelihood of fire spread in finished structures, they do little to nothing to protect wood components during the construction or demolition phases.

Fire and Wood Structures

To varying degrees, wood and wood composites are flammable materials that can combust and, typically, will support the spread of flames over the surface of the material. These characteristics not only place that component at risk, but also provide a hazard to adjoining materials. While the flammability of structural timber is something that immediately comes to mind, wood panels such as plywood and oriented strand or fibre board raise similar concerns.

In response, the industry has developed several techniques for addressing these issues. One approach has been to use "raw" wood products in conjunction with another material such as gypsum boards or steel panels to coat the surface. Another approach has been to modify the flammability characteristics of the wood product itself.

Increasing the "flame resistance" of wood is not a simple matter. A large part of this is due to the complex way in which wood burns. Wood itself is composed of four types of compounds: cellulose, hemicellulose, lignin and several extractives (Rowell, 2013). The ligno-cellulosic materials do not burn directly, but first decompose when heated into carbon-rich and highly reactive char, tar-like substances and volatile compounds. It is these latter components that, with an adequate supply of oxygen, support combustion.[1]

Initially, fire-resistant lumber and wood panels were pressure treated with fire-retardant chemicals in a manner similar to how pressure treated lumber is processed to reduce the effects of weathering and pest infestation on fences and decks. More recently, however, fire-retardant coatings have been developed to reduce the initial flammability and surface spread of flames on wood products. At this point, the most common products are intumescent coatings that swell when a surface is heated.

The flame-spread performance of construction products is rated by various agencies. In Canada, wood products—both raw and with various coatings—are rated and approved by the Underwriter's Laboratories of Canada. One key measure to compare the performance of various products is the Flame Spread Rating (FSR). These Fire Hazard Classification of Building Materials testing standards are known as UL 723 in the US and CAN/ULC S-102 in Canada (Underwriters Laboratories Canada, nd).

Roughly, the Flame Spread Rating (FSR) is an indication of how quickly a flame can spread over a specified surface area within a given period. The FSR is not an actual measure of the rate at which a flame will spread, nor is it a measure of the "fire resistance" of the material; rather, it is a useful indicator or proxy value. To anchor the scale, the flame spread on a particular material is compared

[1] A detailed description of the process of the "pyrolysis" of wood is available in Rowell (2013: 129).

with that of asbestos-cement board, which is rated zero, and on red oak lumber which is rated at 100.[2]

Overall, Class A fire retardants have a flame spread rating of between zero and 25 which indicates that these materials are effective against severe fire exposure. Class B fire retardants have a flame spread rating of between 26 and 75 which is considered effective against moderate fire exposure. Class C fire retardants have a flame spread rating of between 76 and 200. These materials are effective against light fire exposure. Class D materials have a flame spread rating of between 201 and 500 while Class E materials have a flame spread rating of over 500. Class D and E materials are not considered effective against any fire exposure.

In conjunction with the FSR is the Smoke Development Index or SDI. The SDI provides an indication of the concentration of smoke a material emits as it burns. As with the FSR, the Smoke Development Index is anchored at zero for asbestos-cement board, and a value of 100 based on the amount of smoke emitted by red oak lumber. Typically, as SDI of less than 450 is required by interior surface materials.[3]

Background

"Raw" Wood Products

Despite conventional wisdom, most wood products are reasonably fire resistant even in their raw form. Due to its intrinsic cellulose composition and depending upon its mass, surface finish, exposure period and moisture content, wood has a moderately high ignition point. This is obvious to anyone who has attempted to start a log fire without kindling or "fire-starter." Another reason for wood's intrinsic fire resistance is that, even when exposed to a continuous source of ignition, wood "chars" and that char acts as an insulating layer. How well the char performs is typically dependent on the thickness of both the char and the wood itself.

As suggested, the ignition point of wood depends upon numerous factors, including temperature (USDA, 2010: 18-9). At temperatures below 100C, wood can degrade but that degradation largely affects the strength of the material and not its combustibility. Between 100 and 200C, porous char residue can develop. The extent of that charring depends primarily upon the length of exposure. Between 200 and 300C significant charring takes place and various gasses are emitted from the material. Again, depending upon the type of the material and the duration of exposure, the wood may flame (pyrolysis). Between 300 and 450C, flammable gasses are actively emitted and the wood tends to ignite. Intense pyrolysis occurs beyond 450C. Under normal conditions where there is an

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[2] Fire spread analysis is conducted using several approaches, the most common of which is Underwriters Laboratories' Steiner Tunnel Test. See: https://industries.ul.com/blog/uls-iconic-steiner-tunnel-withstands-the-test-of-time. For a more detailed and accessible explanation of the system, see: Hirshler, M.M. (2004) and the accompanying article by R. Laymon ("Standard test method for surface-burning characteristics of building materials ASTM E-84/UL 723" pp. 29-31).

[3] Classifications for the SDI are known as UL 723 or ASTM classification E-84. Building safety codes currently require an SDI of less than 450 for each of Class A, B and C ratings.

adequate source of oxygen and a sufficient duration of exposure to heat, the visual pyrolysis of wood (smouldering, glowing or flame) takes place between 400C and 500C. It is possible to induce pyrolysis in laboratory conditions, however, between 300C and 400C.

Fire-retardants attempt to alter the conditions which lead to pyrolysis. One approach is to seal the surface of a wood product to limit the supply of air or oxygen. Another is to find compounds that alter the temperature to which the wood is exposed. One way of doing this is to provide a heat barrier or insulator. This is typically done by providing an insulating coating or heat sink. Another way is to find chemicals or processes that change the chemical decomposition of wood to either increase the amount or char (an insulator) or to reduce the production and emission of volatile compounds. A third approach is to develop products that either dilute or extinguish the flame.

TABLE 1: ASTM E 84 FLAME SPREAD INDEXES FOR 19-MM-THICK SOLID LUMBER OF VARIOUS WOOD SPECIES*

Species	Flame Spread Index
Softwoods	
Yellow-cedar (Pacific Coast yellow cedar)	78
Bald cypress (cypress)	145–150
Douglas-fir	70–100
Fir, Pacific silver	69
Hemlock, western (West Coast)	60–75
Pine, eastern white (eastern white, northern white)	85, 120–215
Pine, lodgepole	93
Pine, ponderosa	105–230
Pine, red	142
Pine, Southern (southern)	130–195
Pine, western white	75
Red cedar, western	70
Redwood	70
Spruce, eastern (northern, white)	65
Spruce, Sitka (western, Sitka)	100, 74
Hardwoods	
Birch, yellow	105–110
Cottonwood	115
Maple (maple flooring)	104
Oak (red, white)	100
Walnut	130–140
Yellow-poplar (poplar)	170–185

*Adapted from White and Dietenberger (2010: 18-4)

Table 1 is excerpted from the USDA's Wood Handbook (Ross, 2010) and presents the FSI for a variety of commonly used species of wood. Most of the timber is rated as Class C with some species rating toward the upper level of Class B.

Characteristics of Fire Retardants

As noted, treating wood products with fire-retardants changes their fire performance characteristics. While no known retardant or procedure results in a totally inflammable product, retardants delay ignition and slow the spread of flames. This improves the safety performance characteristics of completed structures and reduces the likelihood of pyrolysis during the storage and construction phases of the product. Typically, fire retardants work by reducing the volatile compounds emitted by the wood at a given temperature or by increasing the effective point of combustion.

Historically, two approaches to treating wood and wood products have been used. One approach is to use pressure impregnation to inject solutions into the wood itself. This process is likely familiar to anyone who has used "pressure treated" lumber to construct a fence or wooden deck. In that instance, the treatment is intended to reduce the susceptibility of the wood to rot or insect infestation. These preservative treatments are easy to use since the solution need only reside near the surface of the wood.

Pressure treating wood for fire resistance is much more difficult than treating it for preservation since injecting a solution beyond the wood's surface layer is extremely difficult. In Canada, this type of wood is identified under the National Building Code as falling under the CAN/CSA-080 set of standards. Essentially, this type of wood must have a FSR of less than 25. The success of pressure treatment varies according to the compounds used and the species of wood. For interior applications, inorganic salts have most often been used. These salts include monoammonium and diammonium phosphate, ammonium sulfate, zinc chloride, sodium tetraborate, and boric acid among others. The use of some of these compounds has changed with time as unanticipated side effects are exposed. For example, boric acid, which was commonly used, is now considered a toxic chemical and is highly regulated. It should be noted that wood is typically treated either for preservation or fire-retardation but not both characteristics.

Needless to say, pressure treatment requires specialized equipment and is not something that is currently addressed on-site. Due to the equipment and chemicals required, pressure treating can also be expensive. Furthermore, the inorganic salts used in the process are generally water soluble and can often leach from the substrate when either stored outside or used in external applications. Recently, organic and polymer resins have been introduced that address the leaching issue. Many of those compounds are proprietary, however.

As significant advantage of impregnated wood products is that they can offer enhanced protection throughout the entire construction process. Unlike products that are applied either on-site or after construction, impregnated wood offers fire resistance while being stored as well as through the full construction phase. This is important since much of the fire resistance of either untreated or surface-treated wood requires the product be installed within a system incorporating various forms of complementary barriers that serve to inhibit the spread of flames.

Fire Resistant Coatings

A second approach to developing a fire-resistant product is to coat the surface of the wood. According to the National Building Code, the FSR of the final product must be less than either 25 or 75 depending upon the application. Most surface-coated wood is used for indoor applications. The uses of this product are occasionally limited because nontreated surfaces can result from cutting or other forms of physical damage during transport, storage or construction.

More typically, however, the use of surface coated wood will result in nontreated surfaces being exposed due to physical damage during transport, storage or construction, and from cut ends. Fortunately, small areas of untreated surfaces do not significantly impact the fire protective performance of the coating due to the fact that the small areas of untreated surfaces would be surrounded by coated surfaces and not allow the fire to spread.

The coatings offer fire protection through several mechanisms. Perhaps the most common is that known as intumescent insulation. Intumescent products expand or swell under heat (typically when temperatures reach 200C) to form a low-density layer of insulation. This both delays flame spread and resists the transmission of heat to the substrate. Some coatings are not intumescent but simply offer a thick layer of insulation that insulates the substrate against high temperatures. Typically, these coatings are thicker than intumescent ones. Related to insulating coatings are those that absorb heat. By absorbing heat, these products delay the onset of pyrolysis. Another approach is to use a coating that mimics woods natural tendency to char. These compounds tend to melt and form a crust or simulated char on the surface of the wood. This class of coatings forms a physical barrier on the surface of the substrate.

An example of how an intumescent coating reacts when exposed to high temperatures is illustrated in Figure 1. Here the coating has expanded to delay temperature rise and hinder the transport of oxygen to, and pyrolysis gases from, the surface.

A fairly dramatic illustration of how another product system functions when exposed to flame is illustrated in Figures 2 and 3. Figure 2 shows two wood structure exposed to a substantial flame. The structure on the left in each figure is composed of untreated wood while the structure on the right is constructed with coated material. As Figure 3 illustrates the untreated structure is substantially consumed while the structure on the left merely chars.

FIGURE 1: INTUMESCENT CHAR COATING ON LAMINATE VENEER LUMBER (TAKEN FROM: HAKKARAINEN, 2010) [4]

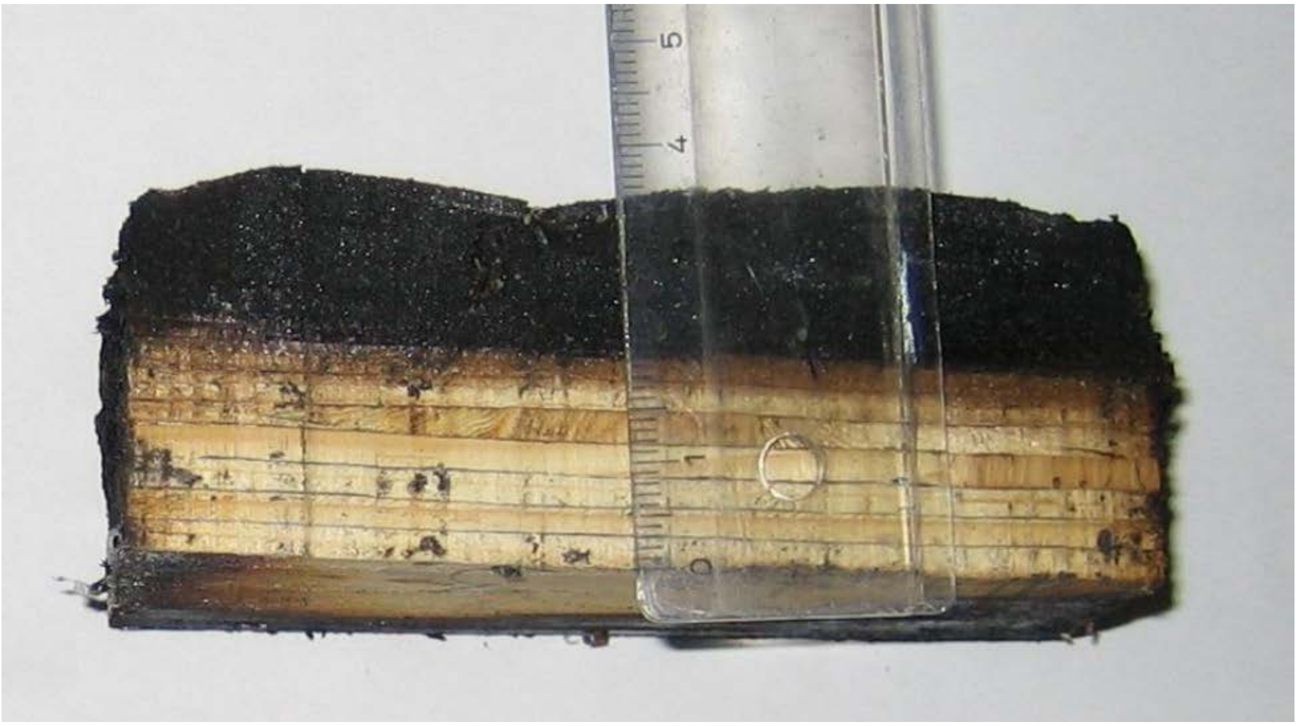

FIGURE 3: INCEPTION

FIGURE 4: RESULTING DAMAGE

[4] Photos courtesy of BarrierTEK Inc., Leduc, Alberta.

It is not uncommon for compounds to complement one another. For example, fire rated paint is often applied over a generic intumescent product to enhance both fire safety and the esthetics of the application.

While there is a significant amount of research being conducted on wood coatings, much is proprietary which means that the actual compounds and proportions are not publicly available. There is, however, a significant amount of university and publicly funded research that forms the basis of our understanding of how various compounds work. We do need to note, however, that much basic research is conducted at the micro or molecular level and how those processes work at that level is often not transferrable to large scale applications that are required in construction applications.

As White and Dietenberger (2010: 18-17) point out in summary, "Intumescent formulations include a dehydrating agent, a char former, and a blowing agent. Potential dehydrating agents include polyammonium phosphate. Ingredients for the char former include starch, glucose, and dipentaerythritol. Potential blowing agents for the intumescent coatings include urea, melamine, and chlorinate parafins. Nonintumescent coating products include formulations of the water-soluble salts such as diammonium phosphate, ammonium sulfate, and borax." Needless to say, other compounds are often used or substituted based on performance or cost characteristics. For example, monopentaerythritol might be substituted for dipentaerythritol. A more detailed discussion of the state of the art in coatings (on various surfaces including wood) is found in the excellent review by Weil (2011).

Current research into coatings is active and wide ranging. Promising research that might lead to new or enhanced coatings has focused on a variety of material such as boron-epoxy combinations (Unlu et al., 2017; Wang, Liu and Lv, 2017); silicon (Wu, et al., 2017); expandable graphite (Zheng, et al., 2016); nanotube/graphene coatings (Song, et al., 2017 and Marzi, 2015); algal biomass (Gady, et al., 2016); and multilayer films (Xuan et al. 2017).

Advantages and Disadvantages of Coated Wood Materials

All materials have advantages and limitations, or costs and benefits associated with them. Some of those relate to structural characteristics such as durability, strength and flexibility. Others relate to esthetics or to secondary characteristics such as cost or the propensity to off-gassing or flammability ratings. No single construction material is ideal for all applications and the strengths and limitations of the material need to be considered at all phases of a structures lifecycle, including the design, construction, use, and eventual renovation and demolition phases.

Coated wood materials are no different in this manner. Some of the potential advantages and possible limitations of coated wood are listed below.

Advantages of Coated Wood Materials

- Ability to slow down spread of fire
- Some coatings can reduce production of gases during combustion
- Ability to reduce smoke development

- Coatings can be applied in factory or on the jobsite
- Application is typically simple and straightforward (similar to painting)
- Coatings can be added to existing structures and installations
- Coatings can be applied selectively (as needed)

Limitations of Fire Retardant Coatings

- Additional cost of manufacture
- Not all applications can be used outdoors without losing their effectiveness (susceptible to weathering and water damage)
- Chemicals can leach from the substrate
- Can be susceptible to physical damage (scraping, etc.)
- Single sided treatments may still leave substrate susceptible to fire damage
- Onsite application may create extra expense and time to completion
- May require separate or specialized storage procedures
- Some treatments may result in unacceptable esthetics

The Case for Coated Wood

Given the variety of fire-resistant coatings on the market, it is difficult to conduct a definitive cost-benefit analysis for the class as a whole. We can, however, identify some of the key elements that should be considered for a given application.

Cost Factors

The most obvious cost relating to coatings is the cost of the material itself. This can vary widely depending upon the compounds used. Prices vary considerably across vendors, the amount purchased and the proportion of the market filled by the product being considered.

The issue of application is also another factor that varies widely. Some coatings are applied in the factory which typically results in labour efficiencies. Other coatings are applied onsite. In some cases, application is an additional step in the construction process which generates a separate cost item; in others, it is a marginal cost as when fire-retardant paint is applied since a paint coat is likely to be applied regardless.

More specific issues to consider might include such matters as:

- Coatings applied onsite can make quality controls extremely difficult.
- Coatings applied onsite can still leave the building vulnerable for periods of time until the treatment is complete.
- Coatings applied onsite can be impacted by the environment during application. (treating wet wood substrate may dilute coating and impact ability to adhere to substrate. Treating frozen wood substrates or coating in freezing weather can impact coatings' ability to cure and dry).
- Factory applied coatings with certified listings ensure quality control and performance.
- Factory applied coatings ensure building is protected from beginning to end.

Benefit Factors

It is easy to see the application of fire-resistant coatings as simply an additional cost factor with little immediate or long-term financial return. However, one company, BarrierTek, has estimated that immediate savings can be had from reduced insurance costs during construction. They note that one major underwriter is willing to provide a 38% discount on their construction-phase coverage premium. Thus, they have determined that under current premium rates, the savings on a $20 million Condominium project with a 15 month build time would be approximately $71,500, which would provide a significant off-set.

While there does not currently appear to be any empirical data available, it is also possible to expect that the incorporation of an additional level of fire safety built into the structure could command a premium in a property's sale price. This would likely be most pronounced at the higher end of the market.

Other benefits to the use of fire-resistant coatings are likely longer-term and not related to the construction phase. For example, the use of fire resistant coatings might be viewed as a benefit in buildings where sprinkler systems are not mandated. This could be a particularly powerful argument as a building ages and modifications or renovations occur. Where unlicensed contractors are used, or the renovation is a DIY project, it is possible that systemic barriers to fire spread are broached. The use of improper materials and inadequacies in construction could leave a previously resistant building susceptible to flashovers and other problems.

Where sprinklers are mandated, the use of fire-resistant coatings could be viewed as a partial "back-up" or redundancy should the sprinkler system fail. In fact, the notion of redundancy should be a key consideration in all safety-related applications. The National Fire Protection Association states:

> *". . . fire protection requires the development of an integrated system of balanced protection that uses many different design features and systems to reinforce one another and to cover for one another in case of the failure of any one. Defense in depth and engineered redundancy are concepts that also are relevant here."*

Besides potentially reducing insurance and replacement costs, redundancies offer a longer-term "peace-of-mind" benefit for both safety-conscious tenants and conservative regulators.

Conclusion

Wood and wood products have been used in construction applications for centuries. Wood remains a key construction product because of its numerous desirable properties including its flexibility, high strength to weight ratio, relative durability and its esthetic qualities. Many timber frame structures have lifespans that stretch into hundreds of years. Despite these qualities, one of the ongoing concerns of wood products is their potential flammability. Modern building techniques, such as the use of barrier materials and appropriate claddings, and the introduction of systemic fire suppression devices such as sprinkler systems, have reduced the rate and impact of fire incidents across the board.

Still, there are instances where fire hazards remain both in completed structures and in other phases in the construction process, such when the product is transported and stored. Incomplete structures also pose a raised hazard since the various complementary elements that serve as fire barriers in completed buildings are not in place. Consequently, both academic and industrial research and development continue to seek ways to reduce the intrinsic flammability of the product. In this note, the use of fire-retardant coatings has been examined.

While there are many excellent products on the market, there is no ideal fire-resistant coating currently available that is best in *all* applications. Rather, there are various commercial products that prove to be advantageous in different situations. Thus, for example, some products will hit virtually all the requirements for addressing flammability issues for mid-rise wood frame buildings under construction. As in all elements of construction, the selection of an appropriate product is a trade-off between several factors. Allen Zielnik, who is an industrial scientist within the field, provides a best list of nine factors to consider when selecting an appropriate coating (Zielnik, 2011). Those factors suggest that the product:

- Provide long-term thermal and ignition protection from heat and flame;
- Have a low flame spread rate;
- Produce little or reduced amounts of smoke and toxic gases;
- Be durable under normal environmental exposures;
- Have good wear resistance and maintainability;
- Have and retain good aesthetic properties (for exposed surfaces);
- Be easy to apply, maintain and repair;
- Be low in VOCs and odor; and
- Be cost-effective.

How those factors are to be weighted, however, depends upon the specific application.

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