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LITERATURE REVIEW – PATHWAYS AND MITIGATION OF STRUCTURE IGNITION IN THE WILDLAND-URBAN INTERFACE

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April 2019

This report is not restricted.

This literature review contributes to the state-of-practice review of water delivery systems (sprinklers) in the Wildland-Urban Interface (WUI). Funding for this review was provided by the Forest Resource Improvement Association of Alberta (FRIAA).

Sprinklers are used to protect structures from wildfire during wildland-urban interface (WUI) events across Canada. Traditionally, standard forestry equipment has been used in conjunction with impact sprinklers. FPInnovations is reviewing common practices and equipment used during sprinkler deployments, in Canada, to determine if they are the most appropriate for community structure protection, or if alternative approaches should be considered.

This literature review is meant to provide a consolidated understanding of the pathways to structure ignition in the wildland-urban interface. This understanding can guide mitigation strategies including the use of sprinklers.

301012735: FRIAA SPRINKLER PROJECT

LITERATURE REVIEW

ACKNOWLEDGEMENTS
FPInnovations would like to acknowledge the Forest Resource Improvement Association of Alberta (FRIAA) for funding this project.

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1. INTRODUCTION

Wildfire events that affect the wildland-urban interface are becoming increasingly common. Between 2000 and 2012, more than 38 000 homes were lost during wildland-urban interface fires in the United States. On average, 2970 homes were lost per year during this period, which is more than a three-fold increase compared with 932 per year on average between 1990 and 1999 (IAWF 2013). Alberta has sustained significant structure loss from wildfires that affected the communities of Slave Lake in 2011 and Fort McMurray in 2016. In order for wildland and municipal firefighting agencies to develop or select appropriate policies, approaches, techniques, and equipment to effectively protect structures from wildfires it is critical to understand the mechanisms or "pathways" of structure ignition. This review is a synthesis of information from 33 documents and 8 international standards and codes that discuss structure ignition during wildfire events in the wildland-urban interface.

2. STRUCTURE IGNITION PATHWAYS

According to Cohen (2008), "wildland-urban interface fire disasters depend on homes igniting during wildfires". Furthermore, Cohen states that "if homes are sufficiently resistant to ignition and do not ignite during the extreme wildfire exposure, then the homes survive without firefighter protection: we have an extreme wildfire but not a [wildland-urban interface] fire disaster. Thus, [wildland-urban interface] fire disasters principally depend on home ignition potential". Based on this view, we may conclude that managing the susceptibility of a home to an ignition source is a necessary prerequisite for reducing loss. The literature review suggests that structure loss from a wildfire is rarely the result of the ignition of building materials that are directly exposed to a high-intensity wildfire flame-front. The consensus within the wildfire research community points toward windblown firebrands (embers) as a primary source of structure ignition in the wildland-urban interface (Cohen & Stratton 2008).

The pathway of structure ignition is often described as a process where receptive building materials (e.g., non-class A rated roofs) or fuels adjacent to a structure are ignited by firebrands. In the case of firebrands igniting combustible fuels adjacent to a structure; these new small, low-intensity fires, ahead of the fire-front, continue to consume combustible materials, grow in intensity, and eventually ignite adjacent structural materials. This process occurs in the Structure Ignition Zone which is defined as "the area around a specific structure and associated accessory structures, including all vegetation that contains potential ignition sources and fuels" (NFPA 2018a). Combustible materials can include, but are not limited to: vegetation, landscaping materials, construction materials, firewood, and yard debris.

Calkin et al. (2014) discuss the disaster sequence in the wildland-urban interface and conclude that "if the problem is identified as home ignition, mitigation of the [Structure Ignition Zone] is the most cost-effective investment for reducing home destruction, and this can be augmented with other investments".

Other investments can include fuel management treatments as proposed by FireSmart Canada. Fuel management treatments can reduce the intensity of a fire before it impinges a community and can provide a defensive position for firefighting resources and for the establishment of a wet line. During extreme events, these treatments may not be large enough to prevent the deposition of firebrands, which can originate from several kilometers away, into the structural ignition zone. Therefore removing or managing the combustible materials within this zone is also critical to disrupt the ignition pathway and reduce structure loss during a wildland-urban interface event.

The literature suggests that the probability of structure ignition during an extreme wildfire event is determined, not only by the fire resistance of the structure itself (e.g., building materials, design, and condition), but also by the amount, and susceptibility, of the fuels within the Structure Ignition Zone (i.e., the fuels moisture content, horizontal and vertical continuity, and connectivity to a structure).

3. STRUCTURE EXPOSURE

There are three potential sources of exposure that can result in the ignition of structures in the wildland-urban interface. Gollner et al. (2015) and Caton et al. (2017) identify radiation, direct flame contact, and firebrands as heat transfer mechanisms that can lead to the ignition of a structure.

3.1 Exposure to radiant heat

Radiative heat transfer occurs when a structure is exposed to the radiant heat from a wildfire flame-front, from burning fuels within the Structure Ignition Zone, or from burning neighbouring structures, without direct flame contact. Radiant heat exposure significantly decreases as the distance to the flame increases. Calculations made using the Structure Ignition Assessment Model (SIAM) indicate that the exterior wood walls of a structure cannot be ignited by the radiant heat from a crown fire flame-front if the distance between the flame-front and the structure is greater than 40 m (Cohen 1999). However, radiant exposure did not cause instrumented panels to ignite when the distance from a high-intensity wildfire flame-front was greater than 10 m during experimental fires (Cohen 2004). During a post-fire evaluation of the 2016 Horse River wildland-urban interface fire, Westhaver (2016) determined that, even with a high intensity fire-front the “forest [to] home clearances [along] perimeter areas of Fort McMurray were sufficient to [limit] structural ignition from flames and radiant heat of the forest fire”.

The evidence collected from the Structure Ignition Assessment Model, experimental fires, and post-fire evaluations suggests that radiant heat transfer from a wildfire flame-front may not be the primary cause of structure ignition during wildland-urban interface events.

3.2 Exposure to direct flame contact (combined radiant and convective heat)

A combination of radiative and convective heat transfer occurs when flames come in direct contact with a structure. During wildland-urban interface events, flames from a wildfire, a burning neighbouring building, or burning fuels within the Structure Ignition Zone may come into direct contact with a structure.

Combined radiant and convective heat transferred from a wildfire flame-front to a structure can be significantly different than the heat transferred during a structure-to-structure fire based on a number of factors including, but not limited to; the distance of the heat and flame to the structure, the intensity of the flame front, and the duration of exposure.

Cohen (2008) concludes that "the large flames of burning shrubs and tree canopies (crown fires) must be within one hundred feet [30 m] to ignite a home's wood exterior." Recommendations in the FireSmart and Firewise programs attempt to reduce the potential for direct flame contact from a wildfire flame-front by removing or mitigating flammable fuels in priority zones that surround a home. When these recommendations are followed, the probability of a structure being exposed to direct flame contact from a wildfire flame-front is reduced.

In contrast, full-scale laboratory experiments at the National Institute of Standards and Technology (NIST) showed that high-intensity flame exposure from a burning building is able to ignite a neighboring structure at a distance of 1.8 m (Maranghides & Johnsson 2008). Therefore, when the density of structures is high, the probability of structure-to-structure ignition by direct flame contact increases during a wildland-urban interface event. However, if structure ignitions can be eliminated altogether, then the potential for structure-to-structure fire spread is eliminated.

A more likely source of exposure from direct flame contact occurs when smaller, lower intensity, flames from fuels ignited within the Structure Ignition Zone come in direct contact with a structure. These ignitions are usually the result of firebrands, transported from the approaching flame-front or from a burning neighbouring building, igniting the fuels (e.g., smaller vegetation, cured grass, dry foliage, mulch, firewood piles, boards/logs, or other flammable materials) within the Structure Ignition Zone. These smaller flames consume other fuels within the Structure Ignition Zone, grow in intensity, come in contact with a structure, and ignite it.

Literature suggests that direct flame contact is a significant source of structure ignition. Ignition of flammable fuels within the Structure Ignition Zone, that have an uninterrupted pathway to a structure, have been identified as a primary source of loss during wildland-urban interface fires.

3.3 Physical exposure to firebrands

"Burning [firebrands] are the most important cause of home ignitions. When they land near or on a building they can ignite near-by vegetation or accumulated debris on the roof or in the gutter, or enter the building through openings (an open window or vent for example) and ignite furnishings in the building or debris in the attic" (Quarles 2012).

Firebrands can be a direct source of ignition, if they enter a house through eaves, vents, or other exposed openings, or if they land on non-fire resistant building materials. Examples of vulnerable structural materials include, but are not limited to; non-class A rated roofs or highly flammable porches and decks. Firebrands can land on structural components in concentrations up to 700 firebrands per square metre (Rissel & Ridenour 2013; Westhaver 2017).

Maranghides & Mell (2009) discuss the fire behavior observed during the 2007 Guejito fire in California, in which firebrands travelled up to 9 km ahead of the fire front and were responsible for the ignition of three homes. During the California Grass Valley fire in 2007, 193 of 199 homes destroyed were thought to have been ignited by firebrands directly or indirectly by spot fires induced by firebrands in Structure Ignition Zone fuels (Cohen & Stratton 2008). During the Witch Creek and Guejito fires in California, firebrands and resulting convective (smaller flames) exposures were thought to be responsible for two-thirds of the structure losses (Maranghides & Mell 2013). Most of the homes along the perimeter of Fort McMurray, that were lost during the 2016 Horse River fire, were exposed to convective heat transfer from Structure Ignition Zone fuels that were ignited by firebrands (Westhaver 2017).

Post-fire evaluations and laboratory experiments strongly indicate that firebrands are a significant source of direct and indirect structure ignition. Understanding the mechanisms of ignition and fire spread from firebrand deposition can inform strategies and tactics that can interrupt the pathways to structure ignition.

4. STRUCTURE IGNITION ZONE FUELS

The primary sources of structure ignition in the wildland-urban interface, as reported in the literature, are direct flame contact and physical exposure to firebrands, such that: (1) firebrands ignite fuels in the Structure Ignition Zone and these smaller fires result in the ignition of a structure, or (2) firebrands directly ignite the building materials on, or attached to a structure. The probability of structure ignition resulting from these pathways in the wildland-urban interface depends on fire–weather conditions as well as the spatial arrangement and flammability of the fuels within the Structure Ignition Zone. The potential of these fuels to impact adjacent structures, once ignited by firebrands, depends on their amount, vertical and horizontal continuity, and the fuels connectivity to a structure.

4.1 THE INFLUENCE OF STRUCTURE IGNITION ZONE FUELS ON IGNITION PATHWAYS

The ability to accurately predict fire behaviour in the wildland-urban interface depends on our understanding of the pathways of structure ignition. Identifying the most effective ways of interrupting these pathways can help homeowners prepare in advance, or help firefighting resources determine which fuels within the Structure Ignition Zone should be a priority for mitigation during an incident. This requires a better understanding of the flammability of the various fuels found within a Structure Ignition Zone. Literature suggests that the following fuels contribute significantly to the ignition of structures during wildland-urban interface events:

4.1.1 Fine fuels, vegetation, and landscaping materials

Native and ornamental vegetation, cured grass, dry leaves, litter, combustible landscaping materials such as straw, mulch, wood chip or bark, and landscaping logs that are ignited by firebrands are a common cause of structure ignition by smaller flames (Quarles 2012; Zipperer et al. 2007; Westhaver 2017). If these burning fuels are connected to a structure, the risk of structure ignition through direct flame contact increases.

Removal of these fuels within 1.5 m of a structure should be a priority for homeowners or structure protection resources. Management of these fuels within the remainder of the structure ignition zone can help to interrupt the pathway for structure ignition. Management strategies can include but are not limited to; maintaining a healthy lawn, removal of cured grass and leaves, planting more fire-resistant vegetation and selecting fire-resistant landscaping materials.

4.1.2 Combustible fuels attached to a structure

Combustible elements of the structure such as decks, porches, patios, and attached Structure Ignition Zone fuels, such as fences, are one of the most significant sources of structure ignition (Maranghides et al. 2013; Quarles et al. 2013) in the wildland-urban interface.

Using less flammable construction materials will help to interrupt the pathways of structure ignition. As an example, the use of fire-resistant materials could be considered for the section of the fence that is immediately adjacent to a house. In addition, the area under decks should be maintained and free of highly combustible yard debris or cured grass.

4.1.3 Miscellaneous combustibles

Miscellaneous combustibles can include, but are not limited to; machinery, parked vehicles, liquid propane tanks, petroleum products, outbuildings, furniture, stored materials, firewood, and compost.

Best practices would suggest either removing these combustibles from the Structure Ignition Zone or storing them as far from the structure as possible.

4.2 THE INFLUENCE OF BUILDING MATERIALS AND DESIGN ON IGNITION PATHWAYS

Building materials and building design can also influence the susceptibility of a home to ignition during a wildland-urban interface event. Firebrands can be a direct source of ignition if they land on non-fire resistant building materials, or if they enter a house through eaves, vents, or other exposed openings. Non-fire resistant materials used in building construction should be considered as available fuel for ignition pathways. Literature suggests that the following building components can be considered pathways to structure ignition if exposed to firebrand deposition:

4.2.1 Roof materials and design

Roof materials and design can contribute to the susceptibility of a structure to ignition from firebrands. Wood shake and wood shingle roofs are more susceptible to ignitions from direct contact with firebrands compared to Class A-rated roofing materials (i.e., asphalt shingles). Class A-rated roof coverings are "considered the most effective against severe fire test exposures" (Hakes et al. 2016). Experiments, using a firebrand generator, ignited typical debris (e.g., pine needles) in the gutters attached to asphalt shingled roofs. The ignition of the debris caused the roofing material to melt but did not result in the ignition of, or fire spread along the roof surface (Manzello et al. 2008). In contrast, Quarles (2012) determined that debris ignited in gutters contributed to the ignition of, and fire spread along untreated wood shake roofs, and concluded that should debris in rain gutters be ignited, metal gutters stay in place, whereas vinyl gutters melt, become detached from the facia, fall to the ground, and can contribute to the ignition of finer fuels adjacent to a structure.

Roof valleys, inside and re-entrant corners (an internal or inside corner; usually used to describe angles less than 90°), and intersections between a deck and an exterior wall (IBHS 2007; Manzello & Suzuki 2014) are areas where firebrands can accumulate in significant concentrations. These accumulations can and contribute to the ignition of flammable building materials.

Best practices suggest using roofing materials that provide resistance to fire (e.g., metal coverings, or asphalt shingles), using metal rain gutters, and keeping areas prone to firebrand accumulations free of flammable debris, in areas that are at risk from firebrand exposure.

4.2.2 Exposed openings and windows

Eaves and vents are a potential pathway to structure ignition if these openings allow firebrands to enter the structure and ignite flammable materials (Manzello et al. 2012). The installation of screens over exposed openings can help reduce the size of firebrands that can enter the structure and thus could reduce the probability of ignition.

If glass windows break during flame impingement or if the window falls out due to framing material ignition, the window opening will provide another pathway to structure ignition. Double-paned windows are less vulnerable to flame impingement (Quarles 2012).

5. REDUCING THE RISK IN THE STRUCTURE IGNITION ZONE

At the community scale, the layout of structures and the characteristics of the spaces between them have been shown to be very important in mitigating wildfire risk. Structures on the perimeter of the community need more protection because they are more likely to be destroyed during a wildland-urban interface fire (Maranghides et al. 2013) and once ignited, these structures provide new pathways to structure ignition through additional firebrand generation and structure-to-structure fire spread (Quarles et al. 2013).

FireSmart Canada identifies seven disciplines that can help communities address the threat of wildfire including; Education, Vegetation management, Legislation and planning, development considerations, interagency cooperation, Emergency planning and cross training (Partners in Protection 2003).

At the local scale, creating defensible spaces by managing or removing fuels around homes can be effective in reducing exposure to radiant heat, direct flame contact, and firebrands. Management or removal of combustible material from the Structure Ignition Zone is a fundamental goal of the FireSmart program in Canada and the Firewise program in the United States.

FireSmart Canada has published the "*FireSmart Begins at Home*" manual, which is designed to inform home owners on steps that they can take in the Structure Ignition Zone to help reduce the risk of loss during a wildland-urban interface event. This manual identifies the following priority zones (Figure 1) and associated fuel management strategies:

- Priority Zone 1a (0-1.5 m from the structure): identified as the non-combustible zone or an area surrounding the building where all combustible materials should be removed.
- Priority Zone 1 (1.5–10 m from the structure): identified as a zone that should be fire resistant and suggests the removal of highly combustible fuels, and the presence of fire-resistant lawns and plants
- Priority Zone 2 (10–30 m from the structure): Identified as a zone where thinning and pruning of trees and the elimination of surface fuels should be carried out. The manual recommends a tree spacing (distance between the outer branches) of at least 3 m.
- Priority Zone 3 (30–100 m from the structure): identified as a zone that, if managed, can help to reduce the intensity and the rate of spread of a wildfire by increasing the spacing between trees and shrubs, pruning, and removing ladder and surface fuels.

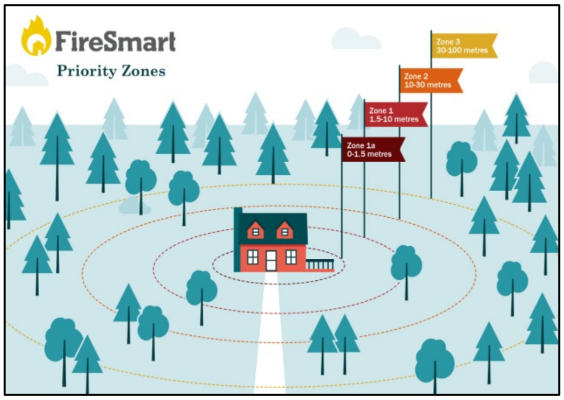

Figure 1. The FireSmart Canada Priority Zones.

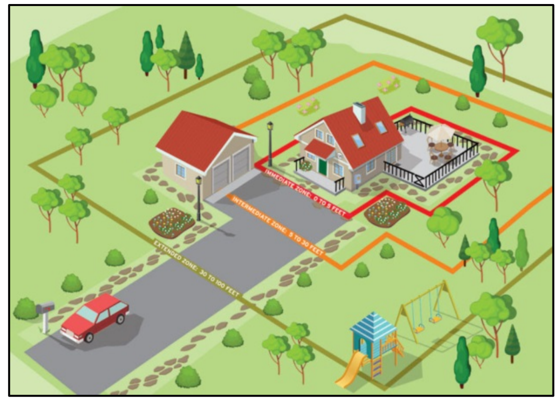

Figure 2. The Firewise Home Ignition Zones (HIZ).

Similarly, Firewise USA uses the concept of the Home Ignition Zone and identifies three zones (Figure 2) surrounding a home that can be managed to reduce the effects of radiant heat from a wildfire (NFPA 2018b). These zones include the Immediate (0–5 ft.), Intermediate (5–30 ft.), and Extended Zone (30–100 ft.).

Other mitigation strategies found in the literature review that could help to reduce the risk of structure ignitions during wildland-urban interface events include, but are not limited to; the creation of defensible spaces, fire service intervention, engineered building solutions, and hardening of structures by applying wetting and covering agents, such as water enhancers and building wraps.

Hardening (reducing the flammability) of a structure by engineering them to resist wildfire exposure (Manzello et al. 2008) is a logical approach. Temporary hardening of structures can be achieved by applying wetting and covering agents: water, foams, gels, material coatings, and blanket materials (Glenn et al. 2012; Takahashi et al. 2013; Urbas 2013). While firebrands still remain a challenge and many design recommendations have been proposed to harden structures against firebrand exposure by using ignition-resistant building materials, the use of “temporary hardening” by wetting and external sprinkler systems should be considered one of the most effective ways to enhance the fire-resistance of structures and reduce the flammability or the receptivity of fuels, within the Structure Ignition Zone, during firebrand exposure.

6. EFFECTIVNESS OF SPRINKLER SYSTEMS

The ability of firebrands to initiate ignition strongly depends on fuel moisture content (Yin et al. 2012). This supports temporarily hardening a structure and Structure Ignition Zone fuels by wetting using external sprinkler systems. The literature review provided only a few documented examples of structure protection operations that used sprinklers.

Experimental crown fires were ignited at the Canadian Boreal Community FireSmart Site in the Northwest Territories, Canada in 2005, to evaluate the effectiveness of sprinklers and an aqueous gel product for structure protection. The experiment showed that “water application from sprinklers reduced the combustibility of the structural fuels and reduced the fire intensity in the wildland fuels immediately adjacent to the cabin. As a result, the structure survived and surface fuels were unburned for 2 m surrounding the cabin within the sprinkler arc” (Walkinshaw & Ault 2008). During a second experimental fire conducted the same year, “sprinklers were operated for 10 minutes prior to wildfire impingement…and continued to operate for an additional 6 minutes after the initial wildfire passage”. Again, the structure survived and “the post-fire investigation indicated that water application from the sprinklers reduced the combustibility of the structure and the wildland fuels immediately adjacent to the cabin” (Walkinshaw & Ault 2009).

During the 2007 Ham Lake fire in Minnesota, USA, 72% of the threatened structures that survived had working sprinklers (Johnson et al. 2008). The Ham Lake case study provides anecdotal evidence, during an actual wildland-urban interface event, of the effectiveness of sprinklers. The Wind-Enabled Ember Dousing System (WEEDS) has been used to extinguish firebrands deposited on a structure and to prevent burning firebrands from entering a structure through exposed openings. Although this system has been shown to be effective during the 2003 Cedar fire in California, USA (Mitchell 2006), its applicability during large-scale events and in different fire exposure conditions has yet to be investigated.

A scan of the following international standards and codes related to the Wildland-urban interface was conducted to determine if there were any standards specific to sprinkler use that would be beneficial to Canadian agencies:

- International Wildland-Urban Interface Code – The objective of this code is to establish minimum regulations for safeguarding life and property from the fire intrusion due to wildland fire exposures and fire exposures from adjacent structures. The code is to be adopted and used supplemental to the adopted building and fire codes for a jurisdiction.
- California Fire Code (Chapter 49: Requirements for Wildland-Urban Interface Fire Areas (California) – This code provides minimum standards for increasing the ability of a building to resist the intrusion of flame or burning firebrands projected by a vegetation fire, and it contributes to a systematic reduction in conflagration losses through the use of performance and prescriptive requirements.
- Australia AS 5414 – 2012 Bushfire Water Spray Systems – This is a standard for the installation of permanent sprinkler systems on homes. The standard calls for a minimum reservoir of 22 000 L (4830 imperial gallons) and a 30-minute to 2-hour continuous run time for the pump.
- Canada, National Research Council – Wildland Urban Interface Fires: regulations and guidelines - A national wildland urban interface guide for Canada was under development in May 2018.

The following National Fire Protection Association (NFPA) standards guide operations in the WUI:

- NFPA 1141: Standard for Fire Protection Infrastructure for Land Development in Wildland, Rural, and Suburban Areas
- NFPA 1142: Standard on Water Supplies for Suburban and Rural Fire Fighting
- NFPA 1143: Standard for Wildland Fire Management
- NFPA 1144: Standard for Reducing Structure Ignition Hazards from Wildland Fire

Most available standards focus on mitigation practices in the wildland-urban interface. No standards were identified that were applicable to sprinkler deployments from a Canadian perspective. If standards for sprinkler use in the wildland-urban interface are to be developed a logical, structured approach is required that needs to be supported by science.

7. SUMMARY

Significant progress has been made in understanding how structures ignite during wildland-urban interface events. The literature review suggests that interrupting the pathways to structure ignition is critical to prevent structure loss. This can be achieved through the removal and mitigation of flammable fuels as recommended in the FireSmart and Firewise programs, by planting less flammable vegetation, and by the use of landscaping and building materials that are resistant to ignition from firebrands. Explorations into structure ignition conditions and the relative flammability of different fuels that contribute to ignition pathways in the Structure Ignition Zone should continue.

Sprinklers can be an effective tool to wet vulnerable structural components and increase the moisture content of surrounding fuels to reduce their receptivity to ignition from firebrands. There are very few documented case studies regarding the effectiveness and best practices for the deployment of sprinklers during wildland-urban interface events. However, the case studies that are available show that sprinklers are effective in preventing structure loss. Further research into effective technologies and practices should include the evaluation of wildfire chemicals to determine if, or how, these can be incorporated into existing strategies and tactics to reduce loss.

Further study in these areas will enhance our understanding of how structure engineering, fuel management, and strategic application of water within the Structure Ignition Zone can increase the chances of structure survival during wildland-urban interface events.

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