iJRASET
International Journal For Research in Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** VIII **Month of publication:** August 2025

DOI: https://doi.org/10.22214/ijraset.2025.73911

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VIII Aug 2025- Available at www.ijraset.com

Modern Coating Approaches to Fire Safety in Wood Structures: A Review of Intumescent and Non-Intumescent Coatings

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Abstract: ***Non-intumescent flame-retardant coatings (NIFRCs) have become effective fire protection solutions for polymeric materials, especially rigid polyurethane foam (RPUF). Unlike intumescent coatings, NIFRCs do not expand when heated; instead, they create stable, inorganic-rich barriers that block heat transfer, delay ignition, and reduce smoke release. This review highlights progress in hydrogel, silica sol, aerogel, and ceramic-based NIFRCs. These developments show remarkable improvements, such as longer time to ignition, lower peak heat release rate, decreased total heat release rate, and less smoke production. The protecting mechanism includes water vapor cooling, char layer formation, and strong barrier effect. A comparison with intumescent coatings highlights the benefits of NIFRCs in durability, thickness, and smoke suppression, making it a promising option for sustainable fire-safe building materials.***

Keywords: Intumescent coating, non-intumescent coating, Fire retardant coating, wood fire protection, flame retardancy.

I. INTRODUCTION

Wood has long been used as a material in construction due to its natural abundance, aesthetic warmth, and structural versatility.[1] Over the past few years, role of wood has grown in modern building designs and sustainable building practices, making it a important component in both residential and commercial structures. But, one of the most critical limitations of wood is its natural flammability, which raises serious safety risks in fire-prone environments.[2] As the demand for wood-based construction grows, so does the urgency to develop and implement effective fire protection strategies. Among the various fire protection methods, fire-retardant coatings have become a practical solution for improving the fire resistance of wood while maintaining its structural and visual qualities.[3] These coatings are classified into two categories: intumescent and non-intumescent. Each type uses different methods to slow down flame spread, reduce heat release, and protect wooden structures during a fire for a longer time. Intumescent coatings are passive fire protection system that swell and forms a thick, insulating barrier, when exposed to a high temperature. This foam behaves as a thermal barrier, protecting the substrate (e.g., steel, wood, or plastic) from heat and flames. The intumescent coating involves four key components i.e. Char Former, acid source, blowing agent and binder. On heating, the acid donor/source, char source, and blowing agent (typically melamine) chemically react to release gases—NH_3, CO_2, H_2O, which expand the coating. This creates a low-density, carbon-rich insulating char layer. It delays the substrate temperatures from reaching critical levels, which helps maintain structural integrity.[4] non-intumescent flame-retardant coatings enhance fire resistance without expanding upon heating. The primary protective mechanisms involve thermal Barrier Formation, cooling, block the migration of combustible gases generated during pyrolysis and carbonaceous char layer that insulates and protects the substrate. There are mainly four types of non-intumescent coatings Inorganic based, hydrogel based, aerogel based, ceramic based coatings.[5]

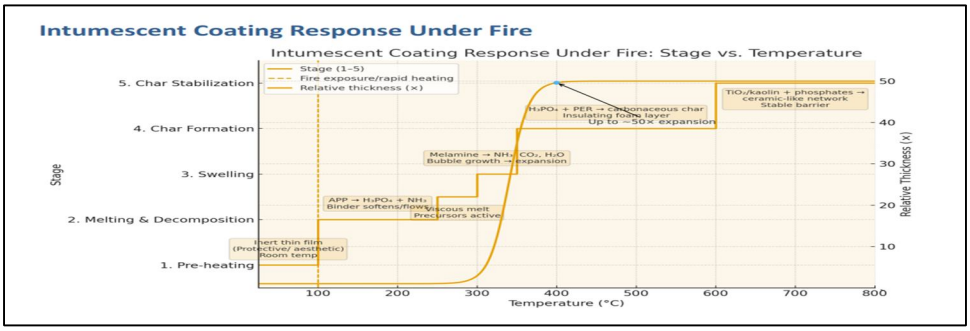

Fig 1. Intumescent Coating stage by stage Process of coating response under Fire

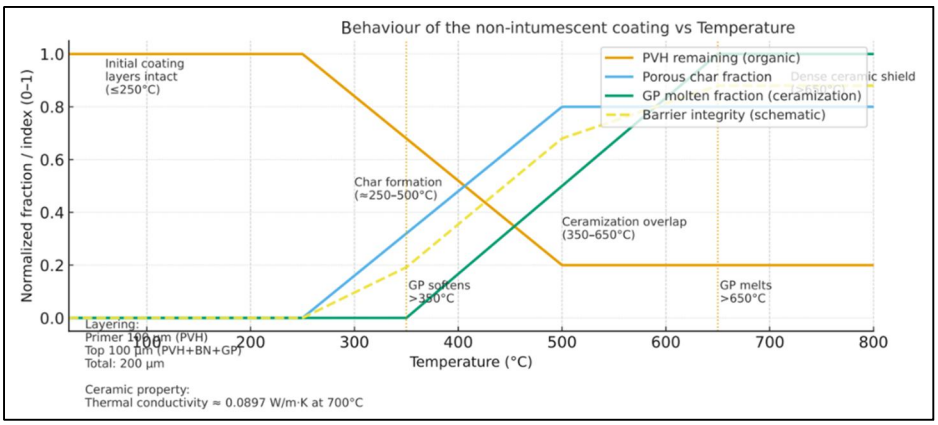

Fig 2. Non-intumescent Coating stage by stage Process of coating response under Fire

II. LITERATURE REVIEW

Y. Zou et al. (2025)[6] prepared a fire-retardant sodium silicate composite coating by a simple one-pot sol-gel method. They used polyvinyl alcohol (PVA), aminopropyl double-ended polydimethylsiloxane (2NH2-PDMS), Triton X-100 and $CH_3COOC_2H_5$ to form the coating. The hybrid organic–inorganic network (C–O–Si–OH–NH_2) overcomes the classic drawbacks of water-glass coatings, delivering superior flame retardancy (with LOI > 95%), water resistance (gel rate from 0% to 61%), mechanical integrity (hardness 5H, improved wear resistance), and high transparency (L* = 75). Cone calorimetry revealed drastic reductions in peak heat release (–96.6%), smoke emission (–96.2%), and CO_2 output (–91.7%), with ignition delayed by 252 s. This shows excellent flame retardancy and giving it an edge over other coatings.

Giuseppe Sciont et al. (2023)[7] researched on how flame-retardant acrylic-based coatings work when improved with eco-friendly fillers, specifically magnesium hydroxide (Mg(OH)2) and aluminum hydroxide (Al(OH)3), at low loadings of 2 wt.%. As a part of their methodology, a direct flame exposure test was conducted for 15 and 30 seconds and the thermal performance was observed. The coatings which contain fine Mg(OH)2 particles shows better fire resistance, as evidenced by their ability to reduce the backside temperature up to 40°C compared to untreated samples. This improved performance comes from the intrinsic properties of Mg(OH)2, specifically its higher dehydration enthalpy and temperature, which allows for better thermal insulation and heat absorption during fire exposure. Coatings with aluminum hydroxide performed moderately, while larger particle sizes of both fillers needed longer activation times and provided less protection. The outcomes from this study shows that using low-content, fine-particle Mg(OH)2 fillers offers an efficient and eco-friendly solution for fire-retardant coatings, especially in naval applications, providing a good balance of flame retardancy and mechanical durability.

B N Mallick et al. (2015)[8] conducted a study on the synthesis of starch-g-poly(butyl acrylate) (starch-g-PBA) bio-nanocomposite hydrogels reinforced with mica at concentrations ranging from 0 to 0.25% (w/v). They used a variety of analytical techniques to confirm successful grafting. FTIR spectra graph showed characteristic peaks for a carbonyl stretch at 1735cm-1 for PBA; Si–O at 972cm-1 and Al–O at 694cm-1 for mica). XRD and TEM analysis reveal interlayer spacings in mica increasing from 4.8 nm to 6.2 nm after intercalation with starch-g-PBA. TGA review shows improved thermal stability, with the onset decomposition temperature exhibiting a higher shifting as mica content increased. Water absorbency tests showed that uptake improved, peaking at 0.1% mica before declining due to less space for water. Cone calorimeter outcomes showed a significant seven-fold increase in ignition time for starch-g-PBA-coated wood compared to uncoated wood (23 s), along with a 1.29-fold reduction in peak heat release rate. Adding mica further reduces the peak heat release rate (1.06-fold) and increases the time to peak heat release rate by 1.4-fold. Biodegradation by activated sludge was highest at 0.1% mica and lowest at higher mica content. These observations show the composite's potential for eco-friendly, fire-retardant coatings with high water retention.

Ying Ran et al. (2024)[9] created a fresh type of organic-inorganic composite flame-retardant coating to improve the fire safety for the wood. This coating is formed by making the inorganic part called CaAl-LDH and mixing it with an organic acrylic emulsion. This modified CaAl-AA-LDH coating has more gaps between its layers as per the numeric data its thickness increases from 0.78 nm to 1.27 nm. This change aids its spread evenly in the acrylic emulsion making the surface more smoother. The surface roughness is measured in units of Ra and Rz, and it dropped by 57.91% and 54.72% compared to the coating without the modification. When wood was coated with 20% of this new composite its ability to resist fire enhanced a lot. The Limiting Oxygen Index, which measures how flammable a material is , went up from 20.1% to 27.9%. This way it meets the required standards for flame

retardancy. Now It took longer for the wood to catch fire as the ignition time increased by 11.5%. The tests using cone calorimetry displayed that the peak heat released during burning dropped by 20.24%, and the total heat released decreased by 25.22% compared to untreated wood. The smoke production also went down by 35.37% and the amount of char left after burning was increased to 22.47%. This means that the coating helps to create a more protective char and it reduces the smoke. The composite coating also shows an excellent flame retardancy and smoke control by offering a guaranteed solution for making wood safer and more sustainable in fire protection.

C.A. Giúdice et al. (2001)[10] examines zinc borates (2ZnO·3B2O3·3.5H2O and 2ZnO·3B2O3·7.5H2O) as partial or full replacements for antimony trioxide in chlorinated alkyd resin flame-retardant coatings. They tested nine formulations with a constant pigment volume concentration of 42.9% on Araucaria Angustifolia wood panels. Thermal analysis showed that 2:3:7.5 had better thermal stability and heat absorption compared to 2:3:3.5. Limiting oxygen index (LOI) tests showed that all coatings, except for the iron oxide control, surpassed the 28% self-extinguishing threshold. Coating 5, which contained antimony oxide and zinc borates in a 1/1/1 ratio, achieved the highest LOI. Flame cabinet tests rated coatings 1–8 as Class A, with scores over 100. Coating 5 had the highest score at 142. Two-foot flame tunnel tests demonstrated that coating 5 had the lowest flame spread index (FSI) of 0.08, significantly better than the commercial alkyd paint, which had an FSI of 1.23. Zinc borates effectively reduces HCl release below 0.02% w/w, improving fire safety and environmental friendliness. Total replacement with zinc borates produced efficient and cost-effective flame retardants.

CM Popescu et al. (2019)[11] doing treatments and modifications to improve the fire reaction of wood and wood-based products. Wood combustion involves water evaporation (~150°C), pyrolysis, and carbon annealing (~800°C). Fire retardants work by changing the pyrolysis process, forming protective char layers, or reducing combustible gases. Some retardants include halogen-based options, which are highly effective but unfortunately toxic. Inorganic salts like potassium carbonate (K_2CO_3) significantly enhances fire resistance and leaching resistance. Boron compounds facilitate char formation, whereas phosphorus-based retardants provide low toxicity. Silicon-based coatings offer thermal stability. Intumescent coatings expand 50 to 200 times when heated, creating insulating char layers. The right formulation is necessary to measure its effectiveness. Chemical modifications like phenol-formaldehyde resins improve fire resistance by promoting char formation. Acetylation can increase ignition time but might reduce overall fire performance. Emerging methods include surface charring and ionic liquids, which limit flame spread. Using wood modification along with fire retardants can provide better protection. Notably, a phosphorus-nitrogen lignin-based foam extinguished flames in just 49 seconds, showing significant fire-retardant potential.

G.C. Lainioti et al. (2022)[12] studied environment-friendly hybrid organic-inorganic halogen-free coatings for wood fire resistance. The coatings composed of waterborne polymer matrix (Vilacryl DS55K), a huntite-rich mineral (H5) or its nano-$Mg(OH)_2$ form (H5-m), and a reactive oligomer P(SSNa-co-GMA20) to improve filler-matrix compatibility. Lab-scale films showed a significant improvement in flame resistance, with Limited Oxygen Index (LOI) values over 80% (e.g., WF-7: 13% matrix, 73% H5, 14% RO). When scaled up, plywood coatings applied using a layer-by-layer technique at 370–1,370 g/m² achieved Euroclass fire ratings B and C. Notably, two-layer coatings (WF-13, WF-14, WF-15) reached Euroclass B with a time to ignition (TTI) of 32–38 seconds and heat release rate (HRR) peaks of 115–150 kW/m², surpassing untreated plywood (Euroclass D, TTI 24–28 s, HRR 216 225 kW/m²). The combination of reactive oligomers and inorganic fillers led to sturdy char formation, which reduced fire risks while keeping the coating quality intact. These coatings provide a sustainable and effective solution for protecting wood in construction and restoration.

S.U. Chambhare et al. (2016)[13] made a phosphorus and nitrogen based reactive diluent, tris-diethanolamine spirocyclic pentaerythritol bisphosphorate (TDSPBRD), was synthesized and incorporated into UV-curable epoxy acrylate wood coatings at 5–25 wt% with 3 wt% photo initiators. Structural confirmation was done via FTIR, 1H and 31P NMR, and EDAX, revealing 52.48% C, 21.12% N, 17.19% O, and 9.21% P at 25 wt%. Increasing TDSPBRD reduced epoxy oligomer viscosity up to 10-fold. Thermogravimetric analysis showed better thermal stability and char yield, rising from 2.53% to 17.9% as TDSPBRD increased from 5 to 25 wt%. LOI values increased steadily, showing better flame retardancy. All formulations achieved a UL-94 V-0 rating and self-extinguished within 5 to 10 seconds. Gloss increased by 40%. Gel content and hardness also increased, while water absorption went down, showing improved crosslinking and hydrophobicity. The coatings showed excellent solvent resistance, exceeding 450 MEK rubs, and stain resistance, rated 5 out of 5 at 15 wt% or more. This study showed that TDSPBRD works well in environmentally friendly, flame-retardant UV-curable coatings with better performance and easier processing. LOI values increased steadily, showing better flame retardancy. All formulations achieved a UL-94 V-0 rating and self-extinguished within 5 to 10 seconds. Gloss increased by 40%. Gel content and hardness also increased, while water absorption went down, showing improved crosslinking and hydrophobicity. The coatings showed excellent solvent resistance, exceeding 450 MEK rubs, and stain resistance,

rated 5 out of 5 at 15 wt% or more. This study showed that TDSPBRD performs efficiently in an environmentally friendly manner, flame-retardant UV-curable coatings with better performance and easier processing.

Fang-Fang Li et al. (2023)[14] studied recent advancements in flame-retardant coatings for building materials. They focused specifically on chemical composition, micromorphology, and processing techniques. Flame-retardant coatings effectively reduce fire risks by blocking heat and mass transfer at combustion interfaces. This offers various benefits as compared to bulk additive methods. Inorganic minerals such as montmorillonite and vermiculite, along with bio-ashes, improve thermal stability. Adding wollastonite increases char expansion by 34%. Organic molecules like phytic acid (around 6 wt% on PVA) reduce the peak heat release rate by 37%. Tannic acid coatings (12 wt%) raised cotton's LOI to 35%. Layered nanomaterials, including graphene oxide and hexagonal boron nitride, significantly improves flame resistance; for instance, a three-layer graphene oxide/chitosan coating (10 wt%) cut pHRR by 54% and smoke release by 59%. MXene coatings at low content (2 wt%) on PU and 5.2 mg/cm² on cotton boosted LOI from 19% to 36.5%. Polymer coatings using photoinitiated polymerization increased PU foam LOI from 18.2% to 24.8% and lowered pHRR from 359.9 to 200 kW/m². Techniques like layer-by-layer assembly and hot pressing enable fine control over coating structures and durability. Practical application requires further study on long-term stability and environmental impact.

Harada et al. (2007)[15] examined the synergistic effect of polyphosphatic carbamate fire retardant and ceramic coating (CRB-90) on the fire performance and weatherability of wood. Applying them both to Japanese red pine and linden, the authors showed enhanced fire-resistance based on the cone calorimeter test having heat flux of 50 kW/m². The key findings indicates that coating at ≥100 kg/m³ fire retardant plus 50 g/m² of ceramic coating reached a quasi-noncombustible rating (THR10 ≤ 8 MJ/m²). For non-combustible performance, actual minimum density was at least 150 kg/m³ for red pine and 210 kg/m³ for linden with CRB coating. Top fire-retardant specimens achieved total heat release rate of only 2.6–2.8 MJ/m² and maximum heat release rates of 8–9 kW/m², respectively, without ignition. Weathering tests shows that ceramic coating had better light stability (ΔE ≈ 10–12 after 120h) and humidity resistance (preventing chemical efflorescence for 240h) compared to other coatings. The work highlights that ceramic coatings enhanced fire retardant efficiency and durability in treated wood materials.

Ali.S et al. (2019)[16] investigated how wood reacts when exposed to fire, the methods used to analyse it, and impact that fire-stopping chemicals have on it. The natural constituents of timber are cellulose, hemicellulose and lignin. These organic substances begin to decompose at temperatures ranging from 180°C to 500°C. When heated at temperature 900°C, they leave a carbonized residue that accounts for a substantial proportion of the material. The residue is absolutely essential for the wood's capacity to withstand fire. Some of the standard ways to evaluate fire resistance are cone calorimeter test, room-corner test, and others like LOI test and furnace test. Fire retardants that can be applied by soaking or as a coating reduce the flammability of wood and enhance its ability to form a protective char. The main disadvantage is that they can also reduce the wood's strength, making it more absorbent, and decreases its lifespan. The review reflects the gaps in detecting the effects on tropical species and long-term performance. More research is needed on how fire retardants affect timber's natural properties.

Hussain A et al. (2021)[17] developed a intumescent waterborne coatings for wood microencapsulated with ammonium polyphosphate (EAPP) to improve protection against fire and moisture content. The EAPP-based coating not only improves water resistance, but also enhances better thermal stability. As measured by thermogravimetric analysis, the improved thermal stability is accompanied by a comparable decomposition temperature of 539°C and an increase in residue formation. The results from the cone calorimeter test indicates increased fire performance with 80% lower peak heat release rate reducing it to 48 kW/m² compared to 240 kW/m² for untreated wood. A 36% lower mass loss rate of (0.041 g/s), an ignition time delay from 10 seconds to 65 seconds, and 35% reduction in total heat release rate (from 83.6 MJ/m² to 55.5 MJ/m²) were also observed. Although polysiloxane-encapsulated coatings suffered durability loss from accelerated weathering due to leaching of binders, the treated wood sample outperformed untreated samples. This encapsulation shows an environmentally friendly way for developing fire-retardant and moisture-resistant coatings. However, further research work is needed to test their outdoor durability.

Tsapko Y et al. (2019)[18] studied the impact of flame-retardant treatments on the burnout rate of pine wood. Untreated wood burned at 18 g/(m²·s), and increasing the burner intensity by 25% and 50% raised the burning rate by 1.4 times and 1.8 times respectively. Treatment with ammonium sulfate/phosphate solutions reduced the burnout rate to 4.8 g/(m²·s), showing a 3.9-fold decrease. The inorganic coating forms a heat-resistant ceramic layer, which reduced the burnout rate by 3.8 times, however this protection becomes weak at higher temperatures. The organic-mineral bloater coating was the most effective, reducing the burnout rate to 3 g/(m²·s), which is nearly a sixfold decrease. This was due to the formation of a foamed coke layer that blocked heat transfer. The experimental data matching well with the proposed analytical models. The findings indicate that the coatings release non-combustible gases and form protective layers, which significantly reduce combustion. This study concentrates on the bloater

coating having exceptional fire protection, particularly having high thermal stress and provides support for further advancements of wood in fire safety applications.

Kmeťová E et al. (2024)[19] examined experimentally how effectively expandable graphite (EG) and wood glass (WG) coating works on spruce wood. The results were compared with those of commercial fire retardants such as Bochemit Antiflash and Bochemit Pyro. They conducted a custom radiant heat test with a power of 1,000 W for 600 seconds. The EG+WG coating performed much better than the commercial fire retardent treatments. It shows only 10.52 ± 0.63% mass loss, while Bochemit had 35.59 ± 2.32% mass loss and untreated wood had mass loss of 84%. The peak burning rate for the EG+WG coating was lower(0.04%·s^{-1}) compared to Antiflash 0.07%·s^{-1}, Pyro 0.11%·s^{-1}, and untreated wood 0.34%·s^{-1}. Thermal analysis shows that EG+WG-treated surfaces remained below 320°C. In contrast, untreated wood surpassed 600 °C and ignition occurs in untreated samples at about 260 seconds. The results shows that EG+WG forms a very effective insulating char layer, which greatly reduces combustion and flame spread. However, further improvement is needed to tackle application challenges for practical use in increasing wood fire safety.

Mazela B et al. (2020)[20] studied Expandable Graphite (EG) as a fire retardant. It is eco-friendly and can be used in cellulosic materials. EG is a low-density carbon material that can expand up to 100 times its original thickness when heated between 280 and 438°C. This process creates a porous, heat-resistant char layer that insulates and protects the material. EG enhance flame retardancy by acting as a both blowing agent and carbonization agent. It significantly raises the oxygen index in coatings from 22% to 42% with a loading of 25 wt.%. The best production involves a KMnO4:C ratio of 0.4:1.0 and an H2SO4:C ratio of 5:1, achieving expansion volumes up to 550 mL/g and initiation temperatures of around 165°C. EG also improves thermal stability in polymers such as PVC, PLA, and PET. Even a small amount of 0.025% graphene can improve thermo-oxidative resistance. Combination with ammonium polyphosphate in a 1:1 ratio greatly enhances fire retardancy in wood-polypropylene composites. Despite their advantages, EG production leads to high sulfur content and environmental issues. Overall, EG creates more char formation when burned leads to better fire resistance in materials like wood and other cellulosic materials, making it prominent intumescent flame retardant alternatives significantly preserve fire-retardant chemicals and fire resistance. These coatings are recommended for outdoor fire-retardant wood applications

Harada.T et al (2009)[21] studied the weatherability and combustibility of sugi wood impregnated with a fire retardant after 2,000 h of accelerated weathering. In this research polyphosphatic carbamate is used which had initial retention of 220 kg/m^3. Four different coating systems were tested: water-borne film-forming (A), solvent-borne pigmented penetrating (B), thin-film pigmented (C), and clear polyurethane (D). Uncoated wood retention reduced to 11 kg/m^3 at 2,000 hours, whereas pigmented coatings maintained higher retention, reached up to 150 kg/m^3 for type B. Fire performance which was measured by total heat release rate (THR), remained below 8 MJ/m^2 for type B up to 2,000 hours, meeting quasi-noncombustible standards. Whereas, uncoated and clear-coated samples exceed 27 to 29 MJ/m^2. Without a protective coating, environmental exposure caused leaching of elements, and SEM-EDX showed that this effect penetrated up to 150 µm below the surface of material after 500 hours of exposure. However, this was reduced under pigmented penetrating coatings. The results show that pigmented penetrating coatings significantly preserve fire-retardant chemicals and fire resistance making them recommended for outdoor fire-retardant wood applications.

III. CONCLUSION

Non-intumescent coatings are generally superior for modern wooden applications where maximum thermal insulation is not required but thin, tough, and moisture-resistant protection with excellent smoke suppression ignition delay and environmental durability are needed. Because when heated, the non-intumescent coating undergoes a chemical reaction which hardens and form a glaze-like shell and release water vapors and free radicals which combines with fire to stop the fire and flame spread. And this layer behaves as a physical barrier and resist moisture and heat transfer while maintaining relatively thin coating at 250ºC to 500ºC.

Intumescent coatings remain the best choice for structural steel or where maximum thermal insulation during fire is needed, but they usually require more maintenance and are less suitable for humid environments. Because the intumescent coating expands 50 X to 100 X and forms a physical barrier of expanded char material that can withstand a fire up to its rated time i.e. 60 min, 120 min, 240min. by maintaining the structural temperature below 400ºC to 550ºC which is useful for steel structure as steel structure losses it's load bearing capacity by 500ºC - 550ºC.

Thus, for maximum thermal insulation and fire resistance Intumescent coatings are preferred. And for combined flame retardancy, smoke suppression, ignition delay, and durability, non-intumescent coatings provide a modern, superior solution for building wooden structures.

IV. SCOPE

As the fire resistance coating advances further the need for a fire resistance coating which can have properties of both intumescent coating and non-intumescent coating grows. Development of a multi-functional coating which enhances flame retardancy, mechanical strength, is aesthetically pleasing and has long-term aging and weatherability and moisture resistance. And further integration of novel processing techniques like layer-by-layer assembly and nano material technology will give more robust fire protection solutions.

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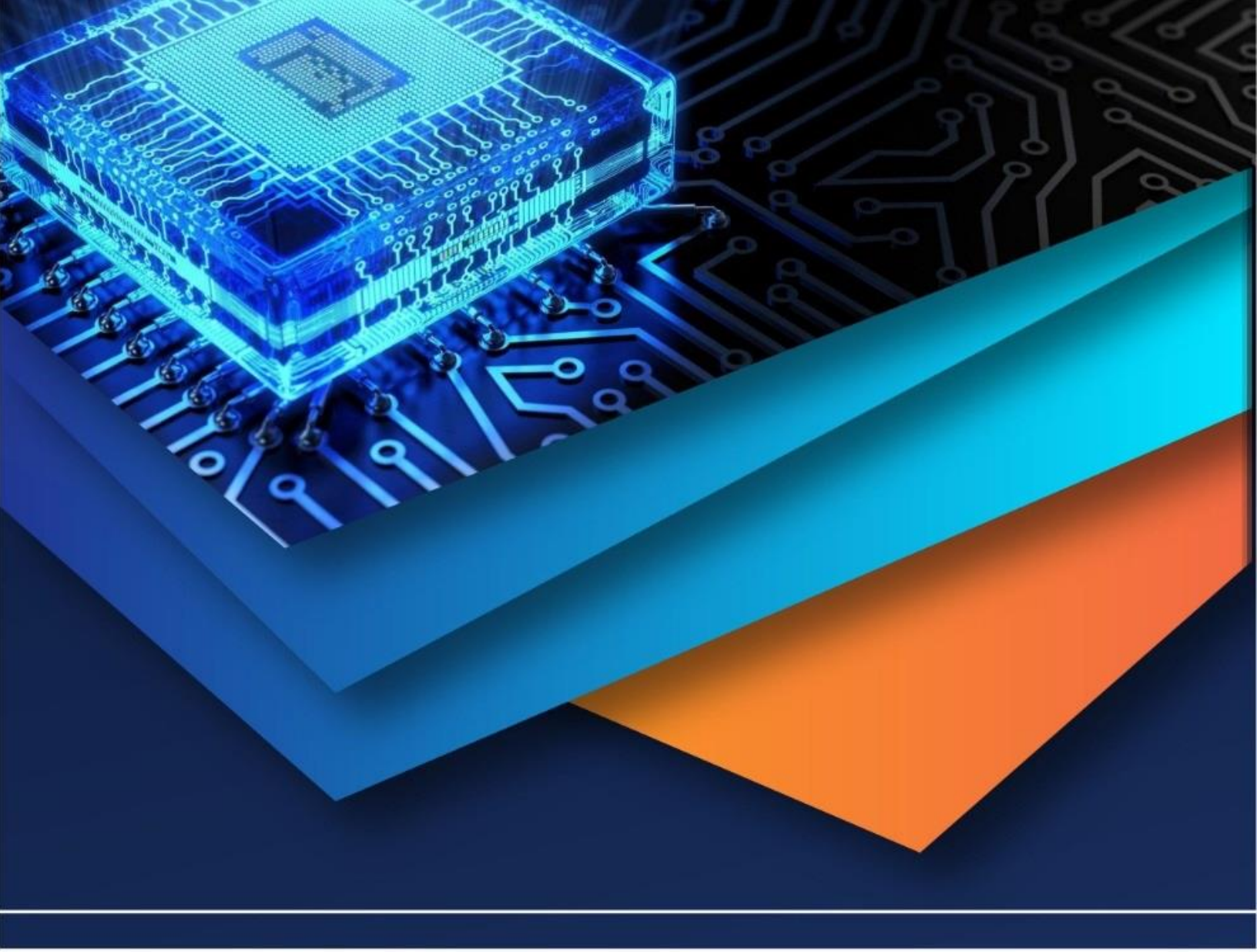

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