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Review

Nanotechnology: The future of fire safety

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ABSTRACT

This study reviews fire protection developments and explores the applicability of nanotechnology for mitigating emerging issues. There are many types of fire retardant materials that can mitigate damage and compartmentalize fire, but nanotechnology has been shown to be more effective in providing adequate protection against destructive fires. This study further examines nanotechnology and how it can be used to minimize fire damages to property and personnel. Nanotechnology is based on miniaturized particles in the order of 10^{-9} in size, which makes it very useful because the materials can be manipulated for beneficial use beyond the capacity of regular materials. This in turn creates a stronger light-weight material that can be used in many fields. In this instance, nanotechnology can be used for fire protection. This study additionally reviews some of the disadvantages with the use of nanotechnology. Presently, there has been minimal research identifying the chronic effects from nanotechnology exposure, preliminary studies of nanoparticles show that there are side effects that mimics the overexposure of asbestos. When nanotechnology penetrates the skin and lung tissues of workers that are exposed to it, it can cause spores to grow in the lungs and can be lethal if overexposed. Nanotechnology has a few concerns but if it is tested and applied properly, it can become the future in not only fire safety but healthcare and manufacturing.

1. Introduction

Fires within the United States have been a problem for several years. The total number of structure fires within the United States between the years of 2005 and 2015 is represented in Fig. 1. There were 3280 civilian deaths and 15,700 civilian injuries (NFPA, 2017a). There was a record $14.3 billion in property damages. This was the result of the 1,345,500 reported fires that occurred during this year (NFPA, 2017a). These numbers are astonishingly high, especially considering the United States is an industrialized nation that places strong emphasis on safety. It is also one of the most technologically advanced nations, which makes it even more surprising it ranks so high in fire death rates per million population. In 2007, the United States ranked 15th in fire death rates (FEMA, 2011). Switzerland, Singapore, Austria, and Italy were just a few of the countries which outranked the United States (FEMA, 2011). The United States had a death rate of 12.4, which was above the average of 10.7.

Noteworthily, structure fires have seen a decrease in recent years. Structure fire is defined as any fire in or on a building or other structure, even if the structure itself was not damaged (NFPA, 2017b). Vehicle fires, outside fires, and other fires, such as trash fire, are not included in this category. During this time frame, the largest number of structure fires occurred in 2007 with 530,500 fires (NFPA, 2017a). Afterwards, the total number of fires decrease immensely until 2012. Since 2013, structure fires have been on the rise again. With 2015 having the most structure fires since 2008. The high number of structure fires occurring indicates a problem with current suppression and prevention methods.

Both civilian injuries and fatalities have decreased slightly since 2005, Fig. 2. However, these numbers are still very high and unacceptable. The number of injuries from fire events centers around 16,000 annually. Some examples of injuries include burns (1st, 2nd, and 3rd degree), respiratory injuries etc. Respiratory injuries occur from not having enough oxygen in the air, inhalation of hot gases, and smoke inhalation. Civilian death totals are around 3000 per year. Most of these deaths are caused by smoke inhalation, not burns as the primary cause of the injuries. These elevated fatality and injury figures suggest that there is a major problem in this sector, though it is possible to decrease the number of fire injuries and deaths occurring through the introduction of innovative and creative solutions, such as the use of nanotechnology for fire prevention and protection.

Other effects of unwanted fire events include the damage costs to property and assets. Property damages were amounted to $14.3 billion in 2015 (NFPA, 2017a), Fig. 3. This was the highest it has been since 2008. Unfortunately, the trend for this data shows an increase in the past few years. If current methods of prevention and suppression are not improved upon or new solutions implemented, this cost could

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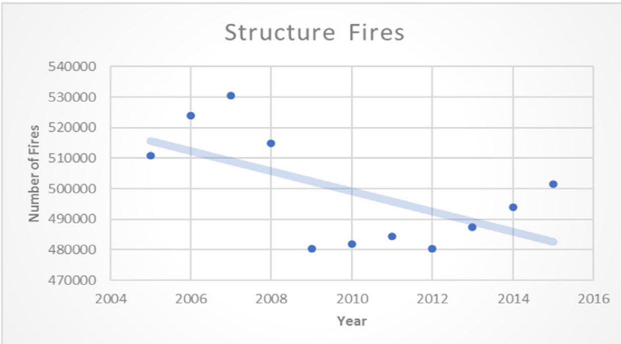

Fig. 1. Number of structural fires between 2005 and 2015 in the US (Courtesy NFPA, 2017a, 2017b)).

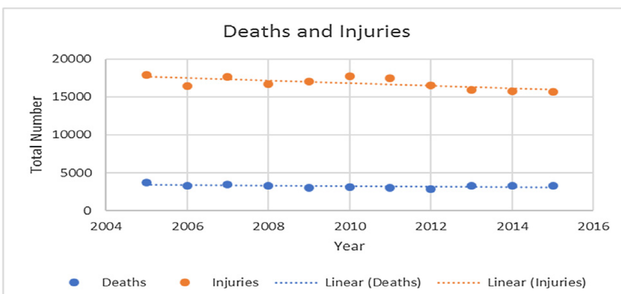

Fig. 2. Total number of injuries and fatalities from structure fire events from 2005 to 2015 (Courtesy NFPA, 2017a).

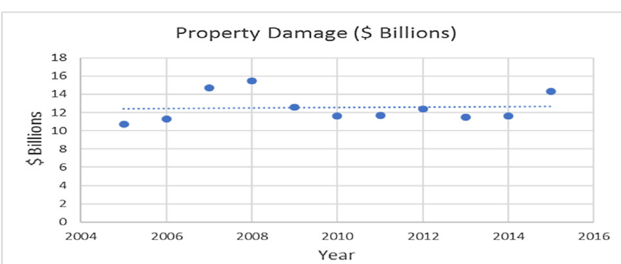

Fig. 3. Property damage costs from 2005 to 2015 due to fire (NFPA, 2017a).

continue to increase.

There are other aspects of the loss analysis that is also problematic. In 2010, property damage was $11.6 billion, this was only 3.5% of the total costs, the total cost of fire was $328 billion (NFPA, 2017a). These losses include human losses (i.e. deaths and medical treatment), economic costs (i.e. property loss and business interruption), and prevention/mitigation costs. Combined, these losses were about 2.2% of the United States GDP (NFPA, 2017a). The exceedingly high costs from the fire accidents is a huge concern however, the promising applications of nanotechnology for fire protection provides reasonable assurances that viable solution for the generational problem is possible.

1.1. Study aim statement

In today's world, there are always improvements made to new and existing things, e.g. structures, materials, methods and procedures. These improvements are intentionally designed to facilitate quality improvements to products and services, to the benefit of the consumers. Examples of such products may include but not limited to; cellular phones, cars, airplanes, home furniture and building materials.

Global economic growth driven by human population increase has lead to exponential increase in the demand of materials for human habitation. Building materials are made and produced as fast as they are being used, that is, all attempts are made to strike a balance between demand and available supply. These materials are made to be lighter, stronger and more durable. However, the problem with these materials can be their resistance to fires. Fire prevention and protection is a growing concern to the use of building materials in the construction industry as well as other industries. Building materials are also being made with materials and composites to improve their overall characteristics. The problem with this approach is that not all manufactures of these materials take into consideration their abilities to catch fire and burn in the event of a fire. The manufactures design includes making products to make the most profits, including using lighter, thinner materials, regardless of their flammability. With the use of nanotechnology, these manufacturers, and producers can make these products with the same lighter and thinner materials, while increasing their fire-retardant abilities (Holder et al., 2017).

Nanotechnology is the science, engineering, and technology conducted at the nanoscale, (which is about 1 to 100 nm) that enables the manipulation of materials to fit existing needs. Nanoscience and nanotechnology involve the ability to see and to control individual atoms and molecules. Everything on Earth is made up of atoms—the food we eat, the clothes we wear, the buildings and houses we live in, and our own bodies (US NNI, 2017). This impacts everything we do, not only in our everyday lives but also in these dangerous fire events. Nanotechnology can be used to create building materials and other coatings to provide a much safer polymeric material and other materials that are highly more resistant to fire and flame (Dong et al., 2014; Wang et al., 2017). Incorporating this technology into existing wood, clay, brick, mortar, cotton textiles, foams, paper, and cardboard along with many other materials, these materials are becoming more resistant to fires and creating safer buildings (Costes et al., 2017) and homes with a higher fire-resistant rating (FRR). Increased FRR's create a safer entrance to emergency workers in the event of a fire. Efforts are underway for the development of innovative solutions that include polymerized fire protection techniques that are innocuous to the environment, and the application of nanotechnologies integrated with polymer surface engineering for fire retardance (Malucelli et al., 2014).

2. Defining the applicability of nanotechnology in fire safety

Many of the solutions for building materials that are now effective against fire effects, started with the integration of nanotechnologies. These technologies drastically change the properties of the materials they are applied to and greatly increase their resistance to fire, fire retardancy, delayed char formations and create a safer environment when exposure to fire occurs. Using this technology can significantly increase fire prevention and protection strategies.

One innovative solution that must be explored is the use of nanotechnology in fire suppression systems such as: fire extinguishers and close loop suppression systems. The idea behind the use of nanotechnology in these systems would aim to provide a more universal and effective approach to putting fires out in all stages. Exploring different mixtures and chemical combinations with nanotechnology by breaking the materials down to particle size (10^{-9}) can help to strengthen the quality of the suppression mixture. This would increase the effectiveness and strength of its firefighting capabilities. Another use for this technology that must be explored further is its use in firefighting equipment and clothing. By using nanotechnology, the strength and durability of fibers in clothing and equipment can better resist fires and high thermal energy. This would help increase the safety for the firefighters while battling any stage of fire. Not only could this help firefighters fight fires in a safer manner, but it can also increase the safety of high risk workers. Some examples of these are people working around electrical hazards, steel workers, and welders.

Another area that could benefit from the use of nanotechnology is the automotive industry. There are many fires that break out in cars, whether it is from an accident or an overheating engine nanotechnology could have an impact. By using nano-coatings on fuel lines and the construction of the engine there could be a better reduction in both the number of vehicle fires and damage. The use of nanotechnologies in a vehicle's body could both extend the life of the car and protect the passengers from potentially significant injury. Other promising developments in flame retardancy of polymeric materials include the concepts of intumescence based on nanotechnology (Bourbigot et al., 2013). This comprises of the chemical, thermal and rheological characteristics, as well as the system simulations and models for obtaining enhanced results. Intumescent coatings can be applied to plastics, metals, wood, steel, films, fabrics, and foams through the bottom up approach of nanomaterial synthesis (Alongi et al., 2015). Numerical intumescence models have been extensively tested, which facilitate the intumescent behavior prediction under different scenarios such as the Boiling Liquid Evaporation Vapor Explosion (BLEVE) or fire incidents including jet-fire tests and furnace tests (Gardelle et al., 2013; Muller et al., 2013).

The biggest challenge with the use of nanotechnology is that not all materials are labeled as if they contain this technology. There are health and safety concerns with materials that are not properly labeled, as workers that handle these materials may not be taking the proper safety precautions when handling, applying or using these materials. The effects of nanotechnology in the health of the individuals who handle these materials is important because health effects may be detrimental to the exposed workers. Cancer and Silicosis are two very well-known problems with the use of nanotechnologies in some materials. Cost is another problem to the use of nanotechnologies. In some materials, the use of nanotechnology is very expensive (Teizer, and Teizer, 2009). It is always necessary to consider the costs and benefits when using nanotechnology in making materials and the use of nanomaterials in the construction industry.

2.1. Global uses of nanotechnology

Nanotechnology is being used in many building materials, surface coatings, and other consumer goods. Some of the more popular nanotechnology made materials include, brick, mortar, cotton textiles, foams, insulation(s), clay and clay composites, silicate epoxy nanocomposites and other nanocomposites. Some non-building materials include the use of nanofiber mats and hydrogels. These materials are all being used to decrease the thermal conductivity of more common materials to increase burn times and increase safety.

Nanotechnology is used in the making of starch based coating that is applied to many cotton textiles, furniture for example, and creates a higher resistance to fire. This is completed by starch being applied in a layer by layer formation to build a bio-based efficient and stainable coating that can protect cotton from fire (Carosio et al., 2015a, 2015b; Costes et al., 2017). The coating of starch can vary in effectiveness depending on the density of the cotton material. Overall, the starch coating reduces the char forming ability and doubles the thermal stable organic residue produced at high temperatures. This means that the material that is covered in this starch material will burn off the starch biolayers and produce a residue that aids in the fire-retardant abilities. These reductions of heat reach up to 40% of the total heat released during the combustion of a fire (Carosio et al., 2015a, 2015b). This bio based system can be used on cotton clothing, furniture and other textile materials which makes it very effective use of nanotechnology in a variety of industries and manufacturing businesses.

Many buildings are made with cinder block, brick and mortar. Nanotechnology is being used in *brick, mortar* and other *clay related products* to achieve a low thermal conductivity, high gas barrier properties and a delayed char formation. Using this nano-paper in clay products the decrease in thermal conductivity and increase in delayed char formation will achieve an overall increase in fire retardant abilities. *Clay nanocomposites*, which are also made with clay nanotechnology, are prepared by simple filtration and used mainly in brick and mortars. The clay nanocomposites have superior fire protection, a higher resistance to flammability and higher exposure to heat flux and also have thermal and thermo-oxidative stability in nitrogen and oxidative atmospheres. The clay nanocomposites can be used in interior and exterior applications.

Nanofiber mats are created and added to materials that are used to provide additional thermal insulation while also increasing the fire-retardant abilities of those materials. Nanofiber mats are created by electrospinning materials to create ultra-fine micro threads that become fire retardant. These fibers are then layered in a mat formation and added to common building materials. The fibers that are formed are more fire resistant and prolong the ignition point of the materials, a thermo-oxidative decomposition process occurs. When excess heat is applied, a flame or fire, the nanofibers attract the heat and consume the heat while self-extinguishing the fire (Gallo et al., 2011; Wang et al., 2017). Overall, the nanofiber mats are created in large quantities, mats, and used in building materials in place of insulation and some foams. The nanofiber mats change the mass and heat transport between the pyrolysis and flame zone of the fire creating their flame retardant abilities. By so doing, the fire spread is limited, and possible damage is prolonged.

Hydrogels are used globally because they have excellent heat resistance, are a less expensive alternative to fire resistant fabric materials. Hydrogels are used in fire resistant blankets, clothing and other apparel because they draw heat from the fire and prevent thermal burns (Illeperuma et al., 2016). Hydrogels are used as a secondary layer and are laminated to fabrics to create a fire-resistant material. Hydrogels contain 90% water, which has a larger heat capacity and allows for a larger amount of energy to be absorbed from a fire. This is done by the hydrogel heating from the fire and evaporating the water, therefore, the clothing and other apparel provides a prolong exposure in fires for fire fighters and other fire personal. The downside to hydrogels are they can be less expensive but also less effective while also decomposing faster when exposed to higher temperatures.

Nanotechnology is used globally for *Polyetherimide (PEI) nanocomposite foams*. These foams are used alone or together with other materials in place of thermal protection of appliances. These foams are lighter and have better thermal resistance. The PEI can be combined with nanoclays to increase the flame-retardant abilities and properties even more (Jiang et al., 2014). *Kraton*, a thermoplastic elastomer, can also combine with PEI's which optimize the thermal protection performance and reduces the mass loss of materials when exposed to fire. These foams and nanoclays can be used by themselves or with Kraton to further increase the materials fire-retardant abilities. Nanotechnology has been incorporated into many coatings that can be applied before and after construction. These coatings can be applied to wood, textiles, paper and cardboards to reduce the flammability of these materials and do not alter or affect the appearance or color of the material that the coating is applied too (US NNI, 2017). The coatings have a high reduction of flammability and prevent the spread of the fire due to the resistance to the fire and flame. These nano-coatings do not release toxic gases when exposed to a flame or fire which is very important for occupants of a building that may be burning or on fire. These nano-coatings decrease the probability of fires to occur and decrease the release of toxic emissions from the materials the coatings are applied to. These nano-coatings help create a safer and less toxic environment.

One of the many components of nano-coatings can include silica and silica related products. Layered silicate epoxy nanocomposites, silica dispersions in the application of UV-curable hybrid coatings and nanopolymers for flame retardancy all focus on the use of silica in the use of nanocomposite materials and coatings. Silica is a material that is well known to cause serious health effects, including silicosis. Silica can be prepared before the application of the nanomaterials, which provides a more stable and safer version of the silica (Schartel et al., 2010). The impact this silica on the construction company is very important if the workers do not know the ingredients of these newer coatings. The impact of nanotechnology in the construction industry have been highlighted in extant literature, especially with the usefulness of the coatings, however cost is still an issue (Teizer et al., 2009). This relates back to the cost and effectiveness of nanotechnologies but with added health risks.

3. Major and minor causes of fire event issues

3.1. Residential

Fires have been a huge part of life in the United States as far back as anyone can remember. The actual definition of fire is, "combustion or burning, in which substances combine chemically with oxygen from the air and typically give out bright light, heat, and smoke." (Dictionary, 2015) There are many different settings in which fire can have a detrimental effect on both life safety and property damage. As shown in Figs. 1 and 3, there were 1.3 million fires in the U.S in 2015, all of which resulted in a loss of 14.3 billion dollars due to property damage. Fires in the U.S. are starting to increase. It is important to note that fires can occur in nearly every setting. In 2014, 50% of residential fires that occurred in the U.S. were attributed to cooking (FEMA, 2017). When it comes to these cooking fires there are many questions that come up including: was it attributed to human error and could the fire have been prevented. Each case is different in what caused the fire, but most of the residential fires are a result of human error or recklessness. To better combat these issues, it is important to push for awareness tips for cooking in papers and other types of print and electronic media. A tip to give a homeowner is to have a kitchen fire extinguisher, with advancements and the inclusion of nanomaterials as fire retardants, the fire extinguisher could help save the lives of the homeowner as well as mitigating property damage. The biggest way to combat this hazard is to have an awareness campaign built around educating homeowners and residents of homes how to cook while staying safe. The back up nanotechnology integrated fire extinguisher will also provide some effectiveness to the rapid extinguishment of the fire.

3.2. Wildfires

In the western parts of the U.S., wildfires occur regular and may even occur multiple times a year in nearby locations. Most wildfires are human initiated which could be from campfires not completely put out, cigarettes tossed out of a window or at a camp site, and many more. Human error is also the leading cause for fires in many other settings as well. Another potential cause for wildfires is lightning strikes. Many states in the Region VIII and IX are considered the Wildland Urban Interface (FEMA, 2017). These states include; California, Nevada, Arizona, Colorado, Utah, Wyoming, The Dakota's, and Montana. In the western USA, for example, ligtning is the primary cause of forest fires. In a ten-year period, over 15,000 forest fires occurred across the USA which have caused damages in excess of of millions/billions of dollars and the destruction of over 2 million acres of forest land (Kovach and McGuire, 2003). There are many causes of these wildfires but if the conditions are not right it cannot occur. Many of the states in the two regions above have a dry season, this is when most of these fires occur. These fires can claim many lives as well as cause detrimental property damage. Wildfires are dangerous, destroying property and habitats, and are very costly as well, extensive forest fires easily do more than $1 billion dollars in damage (Fischetti, 2011). Nanotechnology has an important role in curtailing the spread of these wildfires, as the wildfires continue to intensify and, in some instances, due to the intensity, weather patterns have been altered.

3.3. Automobile fires

All aforementioned topics have discussed the major numbers behind fire deaths, but there is another type of fire that happens less but also has the potential to cause many injuries or fatalities and property damage; automobile fires. While they are not an epidemic, they happen all too often in the United States. Seventeen automobile fires occur every hour in the United States (NFPA, 2018). It was noted that between 2006 and 2010 there were over 150,000 automobile fires that occurred resulting to 209 civilian casualties annually. Automobile fires can be caused by several issues; a car accident, overheating of the engine, or other issues. All the causes mentioned have the ability to cause injuries, death, and property damage. This hazard is often overlooked when other fires can cause up to and even exceed one billion dollars in property damage. This is also crucial and should be addressed. Using nanotechnology coatings and maybe a few other nano materials during the building of automobiles could substantially mitigate these risks to humans, their property and the environment.

3.4. Occupational fires

There are many major and minor causes of fires, from human error to electrical faults. Electrical faults are the leading cause of fires in the occupational setting. This can be attributed to loosened wires, overloaded plugs, and old equipment. An effective solute that can prevent this from happening is by doing some portable appliance testing. These tests can help to determine if the wires pose any form of hazards during domestic usage of the appliances. Another type of testing on electrical panel in the occupational setting is the infrared testing. Infrared testing requires an operator with infrared scanner to scan the electrical panels at a facility. The scanner can help to identify some of the faulty connections in the panel. By using the infrared scanner or performing portable appliance testing, a facility can ensure that the electrical connections are in working order and the facility can be saved from a fire due to electrical faults.

Not only is faulty wiring a cause for an electrical fire but having material too close to an electrical panel can also be a hazard. Some common materials found in the occupational setting that are often found blocking an electrical panel are; pallets, cardboard, material (plastic pellets and other), and certain operations done too close to the panel (grinding material). These are all cause for concern because they all collect debris. Debris collected into the panel as well as faulty wired connections are leading causes for arc flash. An arc flash is different from an arc blast and they relate to arc fault. These phenomena result from electrical explosion or discharge from a low-impedance connection in an electrical system, through air to ground or other voltage phase. Arc flash can also be caused by: sparks stemming from breaks or gaps in the insulation, equipment failure, improper installation, normal wear and tear, and even dust or other impurities on the surface of the conductor.

These types of fires and causes discussed have the potential to result to fatalities, serious injuries and cause major property damages. Therefore, it is important to implement techniques that will mitigate the initialization and propagation of these fires. The application of intumescence based on nanotechnology and fire retardancy will be beneficial as potential solutions.

4. Improvements made in the last ten years

Fires have had a large effect throughout history, not just in the United States but also around the world. There have been many times where fires have caused destruction on a massive scale. On 9/11, the terrorist attack on the world trade center resulted to intense fires that brought down two 1792-foot buildings, although, the circumstances were different as at to what caused the fires. Many improvements have been made in the past ten years to combat these types of fires and a few of them are related to nanotechnology. Nanotechnology has many applications in the fire industry that have changed greatly in the last ten years and as they grow in popularity and effectiveness, nanotechnology could be the future of fire safety and protection.

4.1. Nano-coatings

These nano-coatings are used to strengthen building material and give it a higher thermal ignition point. While the ignition point is not substantially higher than other materials it does help the fire-retardant portion of these materials become more effective (Dong and Wang, 2014). The testing of this material meets many different types of atmospheres to see how it affects the fire resistant nano-coatings. Fire-resistive coatings are used to meet the demands of fire protection in the construction industries, although, the property parameters of fire-resistive coatings are commonly tested based on fresh samples (US NNI, 2017). When the coatings are exposed to a certain atmosphere, solar radiation, moisture and heat may change the chemical structure of the coating, this results in the attenuation of the fire protection. In this facet is where nanotechnology in the coatings can take over and strengthen the materials. The materials themselves cannot withstand some of the atmospheres listed above which makes this nano-coating the best option for aging in the fire resistive materials. These nano-resistive coatings also have the potential to compartmentalize fires. Meaning that if a fire were to break out in one room it will either not spread to the next room at all or it will take a very long time for the fire to spread, giving the fire department time to react and put the fire out. Compartmentalizing fires can be the future of fire protection in that occupants can evade contact with the fire once it is detected and also help the building withstand the fire by not allowing it to spread.

Nano-coatings come in different types and applications. Currently, the biggest material is the nano boron nitride (BN) coating. Boron nitride (BN) is an inorganic compound with high chemical stabilities and excellent thermal stabilities. It has been widely utilized in refractory materials, polymer composites and coatings. In our previous study, it had been proved that nano-BN with multilayered structure could improve the fire protection of fire-resistive coatings. In this study, the influence of nano-BN with multilayered structure on the anti-aging property of fire-resistive coatings was studied (Dong and Wang, 2014).

The experiment conducted showed that the fire-retardant materials lost the fire retardancy when exposed to different methods whether heat or humidity. These materials also lost substantial weight when going through the different types of atmospheres. When BN nano-coatings were added to the materials the fire retardancy was maintained and the weight was also not compromised. This made the material stronger and it also slightly raised the thermal ignition temperature of these materials. By adding BN nano-coatings to materials it raises the fire retardancy and also the strength of the material. If this were added to a number of structures around the world there could be less damage done by fire and it could save many lives.

Another way the nano-coatings affect fire protection is by strengthening the char layer of a material. These char layers can be best described as a chemical process or layer that does not fully allow combustion to occur in solids. The residue like substance that is left over is known as char. This charring occurs most in biological substances. We know that when biological substances are mixed with nano materials the chemical and molecular make-up can change, therefore making the coating “fire resistant”. By in habiting the char layer of a material the nano materials can help to protect the material from debilitating damage, thus making the overall material stronger. With stronger materials in use, the building will have better integrity and last longer in a fire. With the building better withstanding fire we can more easily clear the building of its occupants and save lives while also minimizing property damage.

4.2. Detection systems

In 2010, there was a smoke detector that was developed that used nanotubules to intake smoke into the system (Fink et al., 2012). Functionalized or coated carbon nanotubes are applied for improving the durability, availability life cycle of materials and also for reducing the operating voltage. An example is alkali-metal coated or alkali-salt coated carbon nanotubes. Nanotubes or nanowires of other materials, such as TiO2, Si, ZnO, etc. may also be functionalized or coated (Fink et al., 2012). Nanowires are thin wire with a diameter on the order of a few nanometers (nm) or less, where $1\,nm = 10^{-9}\,m$. The manufacturing of nanowires can be achieved through suspension and deposition processes (Wang et al., 2015). The function of this detector is to control zinc oxide to create nanowires that can detect UV-light with ten thousand times more sensitivity than other detectors made of zinc oxide. Photoelectric smoke detectors are capable of sensing larger particles in denser smoke events, however, are unable to detect smaller particles typical in rapid-burning fires. With increased sensitivity, new ZnO detectors are capable of detecting particles specifically emitted during a fire's incipient stages (US NNI, 2017). This means that we are looking at stopping fires in the incipient stage or maybe even earlier. This can not only save lives but help us mitigate the property damage done by the fires in all different settings.

By implementing nanotechnology on a wide scale in materials as flame retardants and also as detection systems we can cut back immensely on the number of fires we have in the U.S. In the future nano-coatings can be used in a number of materials from home materials, to car materials, and even flame resistant clothing. This would be a huge step in mitigating the damages fires can cause. In these detection systems, it would be a huge step in the right direction as we may be able to evacuate people to safety much earlier, cutting back on the number of fire deaths in the United States. By alarming us of a fire during or earlier than the incipient stage, one could get a better grasp on how to fight these fires.

5. Unidentified problems

There are many questions with nanotechnology, whether that is with the long-term effects on health, dependency on nano-coatings, and cost. These are the three main areas of concern that are holding up the widespread use of nanotechnology. While these are real concerns there is also some contradictions. Like any new technology that comes out, there is a moment of skepticism. From here based on research and experiments conducted one shall see if the risks outweigh the rewards and vice versa.

5.1. Health concerns

According to the Occupational Safety and Health Administration (OSHA), employees using nanomaterials during research or production processes can be potentially exposed to nanoparticles through inhalation, dermal contact, or ingestion, depending material handling procedures in place (OSHA, 2017). Currently, not much is understood about the long-term effects of being exposed to nanotechnology and its related materials, however, scientific studies have concluded that some of the materials are biologically active. It has also been noted that nanomaterials may readily penetrate intact human skin, and have produced toxicologic reactions in the lungs of exposed experimental animals (OSHA, 2017). Engineered nanoparticle toxicity is similar to other chemicals that are used in the production industry. Furthermore, OSHA suggests that the toxicity is dependent upon the physical and chemical properties of the particle such as: particle size, agglomeration state, shape, crystal structure, chemical composition, surface area, and surface chemistry such as charge. The National Institute for Occupational Safety and Health is leading the federal government nanotechnology initiative to determine the risks of exposure to nanotechnology and nanomaterials. NIOSH indicates that the toxcity of low solubility nanoparticles are more than larger particles on a mass for mass basis and nanoparticles are able to migrate from the respiratory system to other organs (NIOSH, 2013). Creating regulations and protective procedures are crucial in protecting people from nanoparticles, unfortunately, due largely to the relative infancy of nanotechnology and the absence of concrete knowledge regarding the effects of nanoscale materials on the human body, there are no current specific medical evaluation protocols (Hoyt and Mason, 2008). Instead, nanoparticles are currently being treated the same as particles that are ultrafine (Iavicoli et al., 2009). Another scare that nanotechnology may produce is cancer causing agents. tests in mice have demonstrated that long and straight multi-walled carbon nanotubes could lead to the same kind of inflammation and lesions in the type of tissues surrounding the lungs, same effects from asbestos exposures. Another study, with mice, concluded that similar carbon nanotubes eventually led to cancerous tumors in the treatment group (Bullis, 2008). While there are different types of nanotechnology there are some that are capable of causing illness to those who both inhale and are around the particles. Some of the risks in this type of nanotechnology outweigh the benefits. What is the point in using a material that is supposed to protect the occupants of a building but it may end up causing some of the same issues as asbestos? Many of these types of materials could end up helping in the future if certain properties are tested normally and also if some of these side effects can be eliminated.

5.2. Cost

Nanotechnology could have great impacts in the world as many applications. Aside from the cancer-causing agents cost is the other big obstacle holding this technology back. Developing nanotechnology on a wide scale could cost a lot of money and in turn it will be very expensive to buy. While many corporations are starting to see safety as important and want to eliminate the overall damages done by fire, they are more willing to buy cheaper materials and use things higher priced suppression systems and detectors. This can help a company in the event of a fire but it will not sufficiently protect the building in the way nanotechnology would. Cost is the big barrier for many things, especially in the safety field. Cost can either make or break a material and while there isn't exactly much that can be done to reduce the cost of nanotechnology while also keeping its effectiveness, it will be interesting to see what happens in this aspect.

5.3. Reliability on Nano-coatings

Though there are not many disadvantages of nanotechnology, as safety professionals one must look into the positives and negatives. With nanotechnology, able to compartmentalize, slow fires, and also resist fires there is a danger that people would take advantage of the materials and not develop a comprehensive fire safety program. There are many cheap companies that will do whatever it takes to save money and with nanotechnology being so expensive there may be issues with this. Nanotechnology carries a big name, and with it, many people may look past the disadvantages and implement it anyway. A few ways a company could bypass a comprehensive fire safety program are; not putting substantial suppression systems in use, not utilizing fire safety drills, bypassing procedures, and not having systems inspected regularly. Bypassing one comprehensive fire safety program, while relying too heavily on nanotechnology could end in more disaster than it set out to prevent. Though nanotechnology is cutting-edge technology that has a great potential of reducing injuries and property damage, if supporting safety systems are not in place the damages may be greater. It is important to note that nanotechnology policies, procedures, training, and inspection must be completed on a regular basis for it to have a lasting effect. If one just simply relies on nanotechnology as a protective measure, many people can be injured, killed, and property damage may be greater. As with all great technology, it has the ability to fail. It must be ensured that if a failure in the technology was to occur, that there are countermeasures in place to combat the fire and get people to safety. By doing these things, and continuing to implement a comprehensive fire safety program, nanotechnology's opportunities are endless.

5.4. Materials, applications and concerns

Nanoparticles can be added into clay and polymers, along with a variety of other materials, such as steel and cotton. Nanocomposites are generally classified into three groups. They are intercalated, exfoliated, or both (Rybiński et al., 2012). Of these exfoliated see the best reinforcement and barrier properties. Flame-retardation works by inert gas dilution, thermal quenching, and formation of a protective liquid/char, increasing heat capacity, and competing with steps in the combustion process (Selvakumar et al., 2012). Nanocomposites use a couple of these methods as a flame retardant. First, a char layer is formed that works as a heat shield during burning (Schartel et al., 2006). This is believed to be the main mechanism of flame retardancy of most nanocomposites (Schartel et al., 2006). This char layer is created due to the breakdown of the polymer matrix (Samyn and Bourbigot, 2014). This barrier is made at the surface of the material and works to slow down heat and mass transfer (Samyn and Bourbigot, 2014). A non-negligible amount of the polymer needs to be burned before the entire surface of the material is protected (Lecouvet et al., 2014). Nanocomposites also increase viscosity of the melt, reducing dripping, bubbling, and melt flow (Schartel et al., 2006). They see a catalytic impact that increases char yield and changes products. This occurs while lowering mass and oxygen transport, furthering nanocomposites ability to act as a flame retardant.

Polymers incorporating nanoparticles have seen improvements in mechanical properties, decreased permeability, thermal stability, flame retardancy, reduced smoke emissions, chemical resistance, electrical/thermal conductivity, and optical clarity. Nanoparticles have seen an increase in commercial activity because of these properties. Its improvement of mechanical properties may have had the biggest impact on its use commercially. These nanoparticles act like a cost-effective "molecular reinforcement" (Schartel et al., 2006). What this means is the nanoparticles add strength, modulus, and dimensional stability. They can improve abrasion and scratch resistance (Wang et al., 2007). While nanotechnology's reinforcement properties cannot be understated, their flame resistance is an advantage that cannot be ignored. With fires being a big cause of injury and death within the United States, nanoparticles use as a fire retardant is extremely beneficial.

It is not just nanocomposites ability as a fire retardant that makes it advantageous to use. It reduces smoke emissions, which could greatly drop the total number of fire deaths. Smoke is the number one cause of deaths in a fire. Materials with nanotechnology produce less smoke emissions, giving individuals involved in fires a better chance at evacuation. Also, only a very small amount of polymer needs to be burned before the entire surface of the material is protected. This means the material will be coated quickly when involved in a fire, decreasing the amount of available fuel for the fire to consume. Again, this provides more time for individuals to either put out the fire or escape the building.

When steel structures are exposed to high temperatures, their strength and rigidity become at risk (Wang et al., 2007). The collapse of the structure may occur is the critical temperature is reached. As previously mentioned, nanocomposites can be added to polymers and coatings. These can be applied to the steel structures. This can reduce the heat released and improve fire retardancy. By improving the integrity of the steel during fires, it can ensure steel structures will see a prolonged time before collapse, giving occupants more time to exit the premise, or will ensure the integrity of the structure even after a fire has occurred, leaving less property damage. Nanocomposites may also be added to fabrics. Cotton fabrics cannot even provide sufficient protection against a low-energy flame (Selvakumar et al., 2012). By adding nanocomposites to fabrics, the fire protection the material has to offer can be increased. Nanocomposites can be added to fabrics using electrospinning and the effects have shown an increase in flame retardancy. Since many fires do start in the home, this is very beneficial. Cellphones overheating due to being under the covers are a cause of fires as are cigarettes. Fabrics with nanoparticles will have a higher flame retardancy, giving occupants more time to either find a fire extinguisher or evacuate the premises.

While originally it was believed that these nanocomposites were very good flame-retardants, limitations have been found. It has been seen that while nanocomposites do not lead to a decrease in the peak of heat release rate, they do not decrease flammability by limiting oxygen index (Samyn and Bourbigot, 2014). They do not influence thermal stability but instead decrease the thermal decomposition rate (Rybiński et al., 2012). However, they appear to have a synergist effect when added with other flame retardants (Samyn and Bourbigot, 2014). This means when the two are added together, their flame-retardant properties are better than their combined potential. Another problem is distribution of the nanoparticles throughout a material. Bubbles form on the surface of a material with nanocomposites when the char is forming. While these provide benefits, such as the development of the physical barrier, they may also pose a risk (Lecouvet et al., 2014). If these bubbles burst, they propel nanoparticles outward. The material no longer is continuously covered, reducing its ability to provide mass and heat transfer limitations. For this reason, it is extremely important for nanoparticles to be evenly distributed throughout the material. If they are not, it leads to the nanocomposite not being as successful in flame retardancy (Maira et al., 2015). However, reactor granule technology has seen success in evenly distributing these nanocomposites with even higher filler loadings than normal. Adding carbon nanotubes may also help in decreasing the bubbling process (Lecouvet et. al 2014). The cost of using nanocomposites may also be an issue. For example, single-walled carbon nanotubes are more effective in flame retardancy than multi-walled carbon nanotubes (Rybiński et al., 2012). After they are crushed, they delay ignition time substantially and reduce the heat released rate. They are very expensive to synthesize so this eliminates them as a flame retardant in industrial settings. So, while nanocomposites may have beneficial flame retardancy properties, these must be compared to manufacturing costs. There may be more cost-effective ways to suppress fires.

6. Conclusion

Harnessing fire has been one of man's greatest achievements. It has led to numerous technological advancements. While fire has been extremely beneficial, it can also be extremely dangerous. Fires within the United States have been a huge problem for a number of years. They cause numerous injuries and deaths, all of which are preventable in some way or another. Fires also cause billions of dollars' worth in damage. Nanotechnology may be the solution needed to combat these issues. Some causes of fires in the home are cooking, appliances, and smoking (NFPA, 2017b). Those most at risk during fires are children, elderly, and those with disabilities. In 2014, there were almost a total of 1,300,000 fires (USFA, 2017). These fires caused 15,775 injuries and 3275 fatalities (USFA, 2017). The good news is that these numbers have all decreased from ten years ago. However, more can still be done to prevent and suppress these fires. New and innovative ways to protect against fire are always needed, not just in industry but also in the home.

Nanoparticles are added to materials to enhance them. For this reason, they have seen use in many different industries. Some industries currently incorporating nanotechnology are information technology, homeland security, medicine, transportation, energy, food safety, and environmental science (U.S. National Nanotechnology Initiative, 2017). Major improvements have been seen in technology since the inception of nanotechnologies. It has enabled smaller transistors for computing, better televisions and monitors, and flexible electronics. In medicine, they have improved imaging and diagnostic equipment. A nanoparticle has even been produced which helps shrink plaque. In energy, nanotechnology has improved fuel production efficiency and created new batteries. Nanotechnology can even be added to consumer products (CPSC, 2016). It can not only be added to electronic equipment but also to fabrics. They are added to polymers and coatings, making it ideal in improving steal integrity (Wang et al., 2007).

Fire prevention and protection are key in saving property, lives, and the environment. Prevention and protection is successful when the fire tetrahedron (fuel, oxygen, heat, and the chemical reaction) is acted upon. By taking out one of these legs, the fire will either not start or will cease burning. Nanocomposites use a couple of different strategies to work upon the fire tetrahedron. Since fires can happen to everyone so it is extremely important to keep developing prevention and suppression strategies. Nanotechnology looks extremely promising in this regard. Their main benefit is they reduce flame retardancy. Since nanocomposites can be added to almost any material, fire protection can be increased in almost any area. These nanocomposites are also more environmentally friendly, making them a better choice than some other suppression methods, such as halogens (Schartel et al., 2010). Since less toxic gas is produced, a fire involving these materials may be less hazardous to those involved. Smoke inhalation is a major cause of fire fatalities. Less toxic gases being present in the air gives occupants more time to find an exit during a fire.

There are some drawbacks to using nanoparticles, however. The first being the nanoparticles do not cause a decrease in flammability by limiting oxygen index (Samyn and Bourbigot, 2014). Since the nanoparticles work as a synergist, this does not pose much of a threat for its use as a flame retardant. The nanocomposites should still be able to produce adequate fire protection as long as it is used with other flame retardants. Distribution of the nanocomposites within a material are also a concern. They will not provide coverage for the entire surface if they are unevenly distributed. New technology has shown that it can combat this defect. Finally, cost may pose problems. Different, less costly elements can be added to the nanocomposites. These will still provide adequate protection while staying within a budget.

Nanotechnology will be extremely beneficial when added to existing fire programs. It should not be used to replace existing fire prevention of suppression methods, such as sprinklers and fire alarms. It should only be used to supplement them. Its use as a flame retardant will provide the extra protection and time necessary for individuals to either put out the fire or escape from the vicinity. It is ineffective at warning occupants or putting out fires. For this reason, individuals should not look to replace current fire prevention and suppression methods solely within nanotechnology.

Overall, the benefits of using nanocomposites far outweigh the risks. The only major drawback is the lack of knowledge on the health risks nanotechnology may pose. In this regard, more testing must be done to ensure the safety of workers and consumers. Since nanoparticles are being incorporated into consumer products, a decrease in house fire fatalities may occur. The flame retardancy properties will give occupants more time to escape their residence or put out an incipient fire. Nanotechnology may also lead to a decrease in structural fire damage. It can be incorporated into not only the construction materials but also the objects within a building. This will increase the time needed to move the fire out of the insipient stage.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.ssci.2018.08.016.

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