THE IMPACT OF RESIDENTIAL AUTOMATIC FIRE SPRINKLER SYSTEMS: AN EXAMINATION OF THE OPPOSITION TOWARD THE IMPLEMENTATION OF AUTOMATIC FIRE EXTINGUISHING EQUIPMENT IN PENNSYLVANIA

A thesis submitted to the Kent State University Honors College in partial fulfillment of the requirements for General Honors

By

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May, 2013
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ACKNOWLEDGEMENTS

I would like to express my gratitude to my thesis advisor, Bill Lucak, and my thesis co-advisor, Dr. Adil Sharag-Eldin, both of whom inspire me with their enthusiasm for the built environment.

I would also like to thank the members of the oral defense committee, including Bill Lucak, Dr. Adil Sharag-Eldin, Diane Davis-Sikora, Jack Hawk, and Dr. Elwin Robison for their participation and support in this academic endeavor.

Dean Don Palmer of the Honors College and Dean Douglas Stiedl of the College of Architecture and Environmental Design at Kent State University worked together to allow me to have this research opportunity, for which I am grateful.

I would like to express my sincerest thanks to my parents Richard and Anne Stegman, sisters Patricia and Louisa Stegman, and boyfriend Robert Copper, Jr., who have given me their constant love and encouragement through school.
CHAPTER I

BACKGROUND

The installation of automatic fire sprinkler systems in newly constructed residential homes impacts the safety of both the occupants and the first responders in a structure fire by improving health safety of air quality, increasing evacuation time to safely exit, and lowering the risk of flashover, thereby decreasing the number of fatalities exhibited in residential structure fires. Despite these benefits, the implementation of automatic fire sprinkler systems remains an issue of debate nationwide at both the state and municipal levels. Pennsylvania is of particular note for its controversial reaction against the 2011 Commonwealth’s Uniform Construction Code (UCC) adoption of Section R313 of the 2009 International Residential Code (IRC), which mandates the installation of automatic fire sprinkler systems in new one- and two-family dwellings. The code change would affect all newly constructed one- and two-family dwellings constructed after January 1, 2011. Many organizations lobbied against this mandate on behalf of the building industry, including the Builders Association of Central Pennsylvania (BACP), as well as the Pennsylvania Builders Association (PBA). This paper will analyze the claims made by the various builder associations, and evaluate the substance of the argument. While the example presented demonstrates the experiences of the Commonwealth of Pennsylvania in regard to the automatic fire sprinkler mandate, the issue is still a matter of strong debate nationwide and the information presented is reflective of similar discourses found in other states.
In 2011 the Pennsylvania Builders Association, a non-profit statewide trade organization, which provides a liaison with state government agencies and represents builders to the Pennsylvania General Assembly, filed a lawsuit against the state to prohibit Pennsylvania’s adoption of the automatic sprinkler portion of the Uniform Construction Code (UCC). Although the lawsuit was dismissed on August 25, 2010, it outlines the argument of the public debate. The PBA argued that the average cost of implementing this system would range from $3,000 to $16,000, depending on the size of the home. Furthermore, the organization argued “the additional costs [would] have a significant impact on the demand for their home building and remodeling services, and [would] adversely affect the availability of financing of homes.”

Although their lawsuit was dismissed, their efforts lobbying the state legislature were eventually successful.

On April 25, 2011 Pennsylvania Governor Tom Corbett signed into law Act 1 of 2011 (HB 377, PN 1520) making a number of changes to Pennsylvania’s Uniform Construction Code. Included in these changes was the repeal of the sprinkler segment for one- and two-family dwellings, retroactive to January 1, 2011. Section 901 (g) of Act 1 of 2011 stipulates that builders must provide information regarding sprinklers to customers before entering into construction contracts. This information must include an option to install or equip, at the buyer’s expense, an automatic fire sprinkler system designed and installed in accordance with the 2009 International Residential Code (and any successor triennial code revisions), and explain to the buyer the initial and ongoing cost of installing and maintaining an automatic fire sprinkler system in the dwelling, as well as

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educating the buyer on the possible benefits of installing an automatic fire sprinkler system as made available by the State Fire Commissioner or the agency’s website (www.osfc.state.pa.us). Act 1 of 2011 does not address how this process must be documented.3

The Pennsylvania Builders Association, along with other building organizations, makes a number of arguments against the policy of requiring sprinkler systems in newly constructed one- and two-family dwellings. These organizations argue that the implementation of automatic fire sprinklers does not significantly impact life safety; that the systems are far too costly to justify the expense; and that they actually damage property through their activation. Additional points advanced by the building industry against the use of automated sprinkler systems can be summarized as follows:

Economics

1. Cost effectiveness of sprinkler systems; sprinklers will harm efforts at providing affordable housing statewide.4
2. Increased Protection and Safety found in current construction assemblies.5
3. Sprinklers in rural homes with well water pose additional problems through higher installation costs.6
4. Accidental discharge of the system drives up overall cost.7

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Health Impact on First Responders and Occupants

1. Risk Assessment; sprinklers will not improve firefighter injuries and fatalities.\(^8\)
2. Home fires and fire casualties have steadily decreased over the last several decades while the number of homes in the United States has increased.\(^9\)

Fire protection safety through other requirements

1. Low Impact on Fire Deaths; smoke alarms potentially save more lives than sprinklers.\(^10\)
2. Low impact on fire service needs; the implementation of automatic fire sprinkler systems would not replace the need for a fire department.\(^11\)

This paper will explore the argument presented above to analyze the impact of the cost of automatic fire sprinkler systems, the impact of sprinkler systems on fire deaths, the health impact fire events pose on both fire fighters and occupants, and the efficacy of increased fire protection safety through other requirements. As more states and municipalities begin to implement mandatory sprinkler legislation for new construction, it is prudent to examine the challenges to, and eventual rescinding of the automatic fire sprinkler mandate in the Commonwealth of Pennsylvania.

\(^8\) Ibid.
\(^9\) Ibid.
\(^10\) Ibid.
CHAPTER II

ECONOMICS OF FIRE

The argument against the implementation of automatic fire sprinkler systems most frequently placed forth by the building industry at large is the burden of increased cost that these systems would place on homebuyers. At the time the mandate was proposed, the housing industry was in a weakened state; naturally these organizations wished to keep costs low. However, the use of automatic fire sprinkler systems in new construction can be an affordable means of increasing protection of a residence against structural fire damage, as well as minimizing the potential loss of life and property seen in cases without the use of this system.

1. A Cost Analysis of Residential Automatic Fire Sprinkler Systems

Robert Meyer of the Quad-Cities Builders and Remodelers Association argued that the implementation of an automatic fire sprinkler system could add a $10,000 or greater cost to a two-story, 2,000 square foot house.\(^\text{12}\) Similar arguments, presented earlier, were made by the Pennsylvania Builders Association. No elaboration was made on the materials, spacing, or type of sprinkler system used to generate these figures by either party. However, Ray Reynolds, fire marshal for the state of Iowa, and Bob Buck, Scott County code inspector, estimated the cost of sprinklers in a 2,000 square foot home to be

$3,220 to $4,440, respectively.\textsuperscript{13} Again, no details were available to note the specific factors generated these estimates. The disparity between these estimates is significant. Tom Ayers, chief building official for the city of Rock Island, Illinois noted that code enforcement officers want to know the real cost of an automatic fire sprinkler system.

Pennsylvania is not the only state to experience controversy over the 2009 International Residential Code automatic fire sprinkler mandate. Making presumptions about the cost of installation can create a barrier between broad adoption of the system and influence decision makers’ opinions on the viability of utilizing the system. In order to clarify the cost of installation of an automatic fire sprinkler system (for both new construction and retrofitting), the NFPA published a report by the Fire Protection Research Foundation (FPRF). The study found that the cost per square foot of installation may vary due to differences in installation requirements. A system installed in a warmer climate with ample water supply and pressure would cost less than a system designed in a colder climate with inadequate water supply pressure. In a cost analysis, the FPRF found that the cost per sprinklered square foot ranged from as low as $0.38 to $3.66, with an average of $1.42 per sprinklered square foot.\textsuperscript{14}

\begin{center}
\begin{tabular}{|c|c|c|c|}
\hline
& Cost ($/sprinklered SF) & Cost ($/living space SF) & Cost With Available Credits ($/sprinklered SF) & Cost with Available Credits ($/living space SF) \\
\hline
Mean & $1.61 & $1.72 & $1.49 & $1.60 \\
Median & $1.42 & $1.49 & $1.23 & $1.38 \\
Minimum & $0.38 & $0.74 & $0.38 & $0.74 \\
Maximum & $3.66 & $3.66 & $3.66 & $3.66 \\
\hline
\end{tabular}
\end{center}

Table 1: Sprinkler system costs to the homebuilder.\textsuperscript{15}

\textsuperscript{15} Ibid, p.6
The type of pipe used in the installation also plays a significant role in the cost of the system. Systems in the study by the FPRF showed a mix of metallic pipe, including copper and nonmetallic, including CPVC or PEX pipe. In communities using only nonmetallic pipe installation costs averaged at approximately $1.18 per sprinklered square foot. In cases where both metallic and nonmetallic piping were used the average cost of installation was approximately $1.56 per sprinklered square foot. In these cases a nonmetallic pipe was used for unexposed areas, while copper was used in exposed areas. Homes that utilized exclusively copper piping saw a significant increase in price, at $3.19 per sprinklered square foot. In order to substantially lower the overall job cost it is recommended to utilize a system composed of either nonmetallic pipe, or a mix of both metallic and nonmetallic pipe. The use of materials clearly plays a significant role in the overall cost of the system. Utilizing a more cost-effective material could make the system more widely available for consumers.

Cost Reduction Recommendations: Localized Installation

The extent of coverage plays a significant role in the cost of an automatic fire sprinkler system. In some local ordinances, sprinkler system provisions go beyond the requirements of NFPA 13D. Modifications to this standard include additional sprinklered spaces, including garages, bathrooms (regardless of size), or attics. When assessing system costs, this additional coverage equates to more material use, creating higher installation costs overall. It could be possible to implement systems in a more localized way, creating systems for high-risk areas. The room of highest risk in a residence is the kitchen. The overall trend of increasing cooking fires in residential buildings, as

17 Ibid.
published by the U.S. Fire Administration, supports this assertion. The number of residential building cooking fires has increased from 161,700 in 2007 to approximately 166,600 in 2011. It could be possible to implement automatic fire sprinkler systems in areas of high risk, rather than equipping an entire home, in order to make the system more cost-effective for both builders and homebuyers. However, the feasibility of such implementation depends on the required standard at the local level, as demonstrated in the modifications to the NFPA 13D standard in the FPRF study.

![Residential Building Cooking Fires](image)

Figure 1: Residential Building Cooking Fires

Kitchens and cooking areas account for 21.5% of areas of fire origin in residential structure fires, and comprise the leading area of origin. Additional common areas of

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origin include bedrooms, at 13.4% and common rooms, dens, family rooms, living rooms, and lounges at 6.5%.\textsuperscript{19} Figure 1 demonstrates an increasing trend in residential building fires in recent years. Cooking fires account for 3% of fatalities for every 1,000 fires, as well as $316,800,000 in financial losses in 2010 alone.\textsuperscript{20} Table 2 shows an increasing trend of cooking fire injuries, deaths, and financial loss. In a topical report on cooking fires in residential buildings from 2008-2010 published by the Federal Emergency Management Agency (FEMA), cooking was found to be the leading cause of all residential building fires and injuries.

![National Estimates of Residential Building Cooking Fires and Losses by Year (2008-2010)](chart.png)

Table 2: National Estimates of Residential Building Cooking Fires and Losses by Year (2008-2010)\textsuperscript{21}

The overall cost of an automatic fire sprinkler system depends on the use of material and the overall area being sprinklered as determined at the municipal level. Installing systems in localized areas of the home that pose the highest risk, kitchens and cooking areas, can mitigate this cost. The future implementation of automatic fire sprinkler


\textsuperscript{21} Ibid, p. 1
systems has the potential to decrease the number of cooking fire injuries, deaths, and financial loss.

Cost Reduction Recommendations: System Materiality

There are various types of automatic fire sprinkler systems to be considered, including wet pipe sprinkler systems which are attached to a piping system containing water allowing immediate discharge from sprinklers responding to heat from a fire; and dry pipe sprinkler systems which are attached to a piping system containing air or nitrogen under pressure. Sprinkler activation releases the air or nitrogen, causing water pressure to open a valve and water to flow into the piping system. In wet pipe systems, the fire death rate per 1,000 reported home structure fires was decreased by 83% while the rate of property damage per reported incident was lower by 69%. Advances in fire sprinkler technologies, as well as the lower cost and improved performance of these systems have improved their cost-effectiveness. In a 2005 NIST report by Brown, *Economic Analysis of Residential Fire Sprinkler Systems*, the estimated costs of sprinkler installation to a homeowner were analyzed. The system presented in this study is multipurpose network into the existing cold-water plumbing system of the home, chosen for its lowest life-cycle cost in comparison to other systems.

Some situations of installation may require additional expenditures as some jurisdictions might require a separate water system to the curb, possibly including a water meter. More rural residences may be unable to meet the requirements of NFPA 13D

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without the use of a tank, pump, and backup electric generator. While these situations may sometimes arise, they are considered atypical. Tables 3, 4, and 5 exhibit the required labor, material, and cost of the multipurpose network system when installed in a 3,338 ft\(^2\) two-story colonial with a basement; a 2,257 ft\(^2\) three-story townhouse; and a 1,171-ft\(^2\) single-story ranch. Each table presents the material cost including fire sprinklers, pipe and fittings, and accessories, and labor costs including both design and installation labor, for a single estimation.\(^{23}\)

It is possible that the initial cost of the system could be recouped over time through both mortgage interest tax deduction as well as local tax savings. For rental units, the interest payments on a loan to finance the purchase of an automatic fire sprinkler system. Local tax investment can be seen at the community level in the form of firefighting and emergency rescue cost reductions from fewer fatalities, injuries, and damage attributed to sprinkler use.\(^{24}\) The cost of a newly constructed home may increase based upon the addition of a fire sprinkler system. Mitigating this increase is the amortization of the cost of the system; as buyers take out a mortgage to pay for a home, the cost of the system becomes a monthly amortized cost over the life of the loan. This amount is further reduced by any homeowners insurance credits received as a result of the installation of the system.\(^{25}\)


\(^{24}\) Ibid, p. 47

Cost Summary: Multipurpose Network System Using PEX for a New 3338 ft$^2$ (310 m$^2$) Single Family Colonial House.

<table>
<thead>
<tr>
<th>Sprinkler System Cost Component</th>
<th>Quantity</th>
<th>Units</th>
<th>Bare material Cost Per Unit</th>
<th>Total Bare Material Cost</th>
<th>Labor Cost</th>
<th>Combined Material &amp; Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Sprinklers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FL/Res 49 (155 °F) (68.3 °C) Recessed Pendant Assembly, White</td>
<td>24</td>
<td>each</td>
<td>$25.03</td>
<td>$600.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe and Fittings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>½ in (12.7 mm) PEX - white, 1000 ft (304.8 m) coil</td>
<td>1</td>
<td>1000 ft</td>
<td>270.00</td>
<td>270.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>½ in (12.7 mm) PEX - white, 300 ft (91.44 m) coil</td>
<td>1</td>
<td>300 ft</td>
<td>81.00</td>
<td>81.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 in (25.4 mm) Copper Branch Manifold, 10 outlets</td>
<td>1</td>
<td>each</td>
<td>26.63</td>
<td>26.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEX Ring ½ in (12.7 mm) (blue print)</td>
<td>150</td>
<td>each</td>
<td>0.36</td>
<td>8.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEX Brass Tee, ½ in (12.7 mm) PEX x ½ in (12.7 mm) PEX</td>
<td>10</td>
<td>each</td>
<td>1.45</td>
<td>14.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessories</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hangers (½ in [12.7 mm], 5/8 in [15.875 mm], ¾ in [19.05 mm] PEX)</td>
<td>4</td>
<td>each</td>
<td>5.95</td>
<td>23.80</td>
<td></td>
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<tr>
<td>Total Bare Material Cost</td>
<td></td>
<td></td>
<td></td>
<td>1024.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design Cost (4 h at $40.00/h)</td>
<td></td>
<td></td>
<td></td>
<td>$160.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Labor Cost (13 h at $50.31/h)</td>
<td></td>
<td></td>
<td></td>
<td>654.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Labor Cost</td>
<td></td>
<td></td>
<td></td>
<td>814.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Material and Labor Cost</td>
<td></td>
<td></td>
<td></td>
<td>$1838.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Material and Labor Cost without cold water system</td>
<td></td>
<td></td>
<td></td>
<td>(117.00)</td>
<td>(100.62)</td>
<td>1621.19</td>
</tr>
</tbody>
</table>

Where possible, generic product descriptions have been substituted for product trade names. Material prices do not include any markup to cover overhead and profit. Labor costs are based on manufacturer’s estimation that it would take a 2 person crew 13 h total to install the system. The sprinkler fitter and plumber trades are estimated at $50.31/h (2007 National Construction Estimator, accessed at www.get-a-quote.net). Design cost of $40/h is provided by manufacturer. Extra sprinkler heads and cabinet exceeding the minimum requirements of NFPA 13D were removed from original estimate. For the estimate without the cold water system, one-third of the combined pipe and 2 h of installation labor are subtracted.

Table 3: Multipurpose Network System Using PEX for a New 3,338 ft$^2$ Single Family Colonial House$^{15}$
### Cost Summary: Multipurpose Network System Using PEX for a New 2257 ft² (210 m²) Single Family Townhouse

<table>
<thead>
<tr>
<th>Sprinkler System Cost Component</th>
<th>Quantity</th>
<th>Units</th>
<th>Bare Material Cost Per Unit</th>
<th>Total Bare Material Cost</th>
<th>Labor Cost</th>
<th>Combined Material &amp; Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire Sprinklers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FJRes-49 (155 °F) (68.3 °C) Recessed Pendent Assembly, White</td>
<td>22</td>
<td>each</td>
<td>$25.03</td>
<td>$550.55</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pipe and Fittings</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2 in (12.7 mm) PEX - white, 1000 ft (304.8 m) coil</td>
<td>1</td>
<td>1000 ft.</td>
<td>270.00</td>
<td>270.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2 in (12.7 mm) PEX - white, 100 ft (30.48 m) coil</td>
<td>1</td>
<td>100 ft.</td>
<td>27.00</td>
<td>27.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 in (25.4 mm) Copper Branch Manifold, 12 outlets</td>
<td>1</td>
<td>each</td>
<td>32.23</td>
<td>32.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEX Ring 1/2 in (12.7 mm) (blue print)</td>
<td>150</td>
<td>each</td>
<td>0.06</td>
<td>8.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEX Brass Tees, 1/2 in (12.7 mm) PEX x 1/2 in (12.7 mm) PEX</td>
<td>10</td>
<td>each</td>
<td>1.45</td>
<td>14.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Accessories</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hangers 1/2 in [12.7 mm], 5/8 in [15.875 mm], 3/4 in [19.05 mm] PEX</td>
<td>3</td>
<td>each</td>
<td>5.95</td>
<td>17.85</td>
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</tr>
<tr>
<td><strong>Total Bare Material Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td>920.38</td>
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</tr>
<tr>
<td><strong>Labor</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Design Cost (4 h at $40.00/h)</td>
<td></td>
<td></td>
<td></td>
<td>$160.00</td>
<td></td>
<td></td>
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<tr>
<td>Labor Cost (12 h at $50.31/h)</td>
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<td>Total Labor Cost</td>
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<td><strong>Totals</strong></td>
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<td>Total Material and Labor Cost</td>
<td>(90.00)</td>
<td>(100.62)</td>
<td>$1584.10</td>
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<tr>
<td>Total Material and Labor Cost without cold water system</td>
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<td></td>
<td>1484.48</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Where possible, generic product descriptions have been substituted for product trade names. Material prices do not include any markup to cover overhead and profit. Labor cost is based on manufacturer’s estimation that it would take a 2 person crew 12 h to install the system. The sprinkler fitter and plumber trades are estimated at $50.31/h (2007 National Construction Estimator, accessed at www.get-a-quote.net). Design cost of $40/h is provided by manufacturer. Extra sprinkler heads and cabinet exceeding the minimum requirements of NFPA 13D were removed from original estimate. For the estimates without the cold water system, one-third of the combined pipe and 2 h of installation labor are subtracted.

Table 4: Multipurpose Network System Using PEX for a New 2,257 ft² Single Family Townhouse
### Cost Summary: Multipurpose Network System Using PEX for a New 1171 ft² (109 m²) Single Family Ranch House

<table>
<thead>
<tr>
<th>Sprinkler System Cost Component</th>
<th>Quantity</th>
<th>Units</th>
<th>Bare Material Cost Per Unit</th>
<th>Total Bare Material Cost</th>
<th>Labor Cost</th>
<th>Combined Material &amp; Labor Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire Sprinklers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>F1/Res 49 (155 °F) Recessed Pendent</td>
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<td>each</td>
<td>$25.03</td>
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<tr>
<td>½ in (12.7 mm) PEX plus - white, 300 ft (91.44 m) coil</td>
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<td>300 ft.</td>
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<tr>
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<td>100 ft.</td>
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<td>21.98</td>
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<td>each</td>
<td>0.06</td>
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<tr>
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<td>each</td>
<td>1.45</td>
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<td>(36.00)</td>
<td>(100.62)</td>
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Where possible, generic product descriptions have been substituted for product trade names. Material prices do not include any markup to cover overhead and profit. Labor cost is based on manufacturer’s estimation that it would take a 2 person crew 12 h to total install the system. The sprinkler fitter and plumber trades are estimated at $50.31/h (2007 National Construction Estimator, accessed at www.get-a-quote.net). Design cost of $40/h is provided by manufacturer. Extra sprinkler heads and cabinet exceeding the minimum requirements of NFPA 13D were removed from original estimate. For the estimates without the cold water system, one-third of the combined pipe and 2 h of installation labor are subtracted.

Table 5: Multipurpose Network System Using PEX for a New 1,171 ft² Single Family Ranch House\textsuperscript{17}
2. The Impact of System Malfunction and Accidental Discharge

A possible argument against this implementation of fire sprinklers as an additional means of fire protection could be their possible malfunction or unsatisfactory performance. The current standard use of smoke detectors has also been seen to fail in nearly five percent of fatal residential building fires. Both smoke detectors and automatic fire sprinkler systems have their own limitations. Although automatic sprinkler systems are often considered the most significant component of a building fire protection strategy, the performance of these systems may be limited by factors unrelated to the design or installation of the system. When properly designed, installed, and maintained, automatic sprinkler systems can significantly reduce the number of deaths, injuries, and property damage while controlling the spread of the fire. The odds of inadvertent or accidental sprinkler activation due to a manufacturing defect are approximately 1 in 16 million; sprinkler systems are designed to activate early in a fire event but not to activate in non-fire situations. Unlike domestic plumbing fixtures, which consist of many parts and are used on a regular basis, an automatic fire sprinkler system consists of a minimal number of parts used in a significantly lesser number of situations. This decreases the likelihood of the failure of the system.

Water released in a fire is generally much less than would occur than the amount used by a fire department to suppress a fire. Reduced water usage is a major source of

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31 Hall, Jr., John R. "NFPA :: Research :: Statistical reports :: Fire protection systems :: U.S. Experience with Sprinklers." NFPA.
savings in terms of both property and overall cost. According to the Scottsdale Report, a residential automatic fire sprinkler system uses on average only 341 gallons of water to control a fire. In contrast, firefighters use 2,935 gallons of water to control a fire. When these systems fail to operate in a fire event, the reason most often given included the shutoff of the system before the fire began, seen in 63% of failures. Other causes included manual intervention that defeated the system (18%), lack of maintenance (6%), and inappropriate system for the type of fire situation (5%). When sprinklers do operate but are ineffective, the cause is usually attributed to an insufficiency in the supply of water to the fire, either because the water did not reach the fire (seen in 53% of cases of ineffective performances of sprinkler systems) or not enough water was released (seen in 18% of cases of ineffective performances). Despite a small overall percentage of ineffectiveness, one and two-family dwellings with a wet-pipe sprinkler system were found to have zero reported fatalities between 2002 and 2005. The value of a fatality averted is estimated to be $7.94 million; therefore, a 100% reduction in fatality rate results in a present value benefit of approximately $3,726 per house fire.

In all building typologies, the damage incurred with the use of wet pipe sprinklers in a fire event was significantly less than those without automatic fire extinguishing equipment. For homes and apartments, the damage incurred in fire events that included

the use of automatic fire sprinkler systems was $6,000 while the damage incurred without
the use of automatic fire extinguishing equipment was $20,000. This demonstrates a
significantly smaller amount of financial cost of damage for those residences utilizing
automatic fire extinguishing equipment.\textsuperscript{35}

3. Environmental Impact

A single fire event contributes significantly to the release of carbon dioxide and other
greenhouse gases generated by the burning of combustible materials. In a study
performed by FM Global Research Division, quantification of the environmental benefit
of automatic fire sprinklers was based on comparisons between two tests. These tests
include total greenhouse gas production, quantity of water required to extinguish the fire,
quality of water runoff, and mass materials requiring disposal. The use of automatic fire
sprinklers significantly reduced heat produced at the peak release rate in a fire event from
13,200 kW to 300 kW. The amount of combustible material consumed in the test fire for
the sprinklered test was less than 3\% compared to the non-sprinklered test result of
between 62\% and 95\% of material. The increased amount of material consumed in the
non-sprinklered test has an environmental impact in terms of the embodied energy
involved in replacing the material lost, as well as the energy used to create the material
destroyed. The increased amount of consumed material demonstrated in the non-
sprinklered test demonstrates an overall increased amount of carbon emissions. Total air
emissions in the sprinklered test were lower than those seen in the non-sprinklered test.

\textsuperscript{35} Hall, Jr., John R. "NFPA :: Research :: Statistical reports :: Fire protection systems :: U.S. Experience
with Sprinklers." NFPA,
Additionally, the use of an automatic fire sprinkler system reduced greenhouse gas emissions by over 97%.  

In terms of water usage, analysis of the tests found that in order to extinguish the fire, the combination of the sprinkler and hose stream used by the firefighters was half that of the hose stream alone. If the results of the experiment are extrapolated to a full-sized home, it is possible that reduction in water use achieved by utilizing automatic fire sprinkler systems could be as great as 91%. Additionally, fewer heavy metals and solids were found in the wastewater sample of the sprinklered test than that of the non-sprinklered test. The wastewater sample of the non-sprinklered test represents cause for environmental concern, as its pH value exceeded the allowable discharge range (5.5 to 9.0) required by most environmental agencies. The sample was also four orders of magnitude higher in alkalinity than that of the non-sprinklered test.

The study utilizing automatic fire sprinklers demonstrated more environmentally desirable solutions, from lower heat production to fewer pollutants released into water; it shows that this system as a preventative measure saves water usage as well as embodied energy. These savings do have a financial impact, as when less water is used and less material is destroyed the overall cost of the fire event decreases. In contrast, both the financial and environmental impact of the study without fire sprinklers showed a significant increase in heat production, water usage, and pollutants produced. The greater amount of destruction seen in this fire event increases the financial impact.

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37 Ibid, p. ii
An examination of precedents in structure fires will demonstrate the issues and failures created by various materials and construction techniques, and how the installation of automatic fire sprinkler systems have the potential to slow the spread of a structure fire. While several of the examples used here are not single-family dwellings, they are residential in nature: each with varying causes, construction types, and fire characteristics. The selected case studies address the issues of containment and flashover.

1. Ammendale, Maryland: 30 Dowling Circle

30 Dowling Circle consisted of a six-unit garden apartment with patios and balconies adjacent to two similar buildings, one on either side. The incident lasted nearly 30 minutes, with flashover occurring three separate times as the fire moved from the first floor unit to third floor unit. The fire originated at apartment T2, located on the south side of the building on the terrace level. The fire was a grease fire originating from the stovetop, igniting the kitchen cabinets, and eventually causing flashover from the kitchen to the living room. The occupant opened the rear sliding door and entrance door to ventilate smoke from the apartment prior to exiting the apartment. These openings allowed ample ventilation, creating an environment of rapid fire growth. At the time of
the fire department’s arrival, the fire in the kitchen and living room was fully developed. The fire resulted in a “Line of Death Duty” of one fire fighter.

In January 2011, the Bureau of Alcohol, Tobacco, Firearms and Explosives (ATF) Fire Research Laboratory (FRL) performed an analysis for a fire at 30 Dowling Circle. Engineering analysis, including computer fire modeling, was used to determine the development of the fire through the building and describe the sequence of events that led to the “Line of Duty Death” of a fire fighter. The ATF Fire Research Laboratory worked to create a computer simulation of the apartment building using Fire Dynamics Simulator (FDS), a computational fluid dynamics modeling program developed by the National Institute of Standards and Technology (NIST). It utilizes computer algorithms to predict the flow of heat, smoke, and other products of fire. Smokeview, another program developed by the NIST, was used to visualize the mathematical output created in FDS. The results of these programs were verified through eyewitness statements, firefighter interviews, burn patterns, and photographs of the incident.

The six units were arranged around a centrally located staircase connecting the three levels, as seen in Figure 3. FDS computer analysis of the ventilation through the apartment demonstrated that a significant unidirectional flow path existed up the central staircase. The flow path developed an inlet at the rear terrace sliding door and outlet at the front apartment entrance door leading to the stairwell. A unidirectional flow path up interior staircases presents a challenge for first responders as they attempt to ascend stairs. Figure 6 indicates the gas velocity in the central staircase. The FDS model indicated air temperatures of 600°F and air velocities of 2.7 meters per second. The
Figure 3: A typical floor plan of the apartments at 30 Dowling Circle.\textsuperscript{38}

Figure 4: A Smokeview frame of the flashover of the kitchen.\textsuperscript{39}


\textsuperscript{39} Ibid, p. 8.
Figure 5: Ignition of the second level balcony, caused by the spread of fire.\textsuperscript{40}

Figure 6: A Smokeview frame indicating gas velocities of 6mph in the stairwell.\textsuperscript{41}

\textsuperscript{40} Wieczorek, Christopher J., Benjamin Ditch, and Robert G. Bill, Jr., "TECHNICAL REPORT: Environmental Impact of Automatic Fire Sprinklers." \textit{FM Global} (2010): 8

\textsuperscript{41} Ibid, p. 9.
convective energy transfer to the structural firefighting gear hindered firefighters as they attempted to descend the stairs. Firefighters were only able to enter the terrace apartment through the stairs when a hose stream was directed through an exterior window. When a portion of the fire was extinguished, gas temperatures and velocities began to decrease.\(^42\)

The fire progressed rapidly. Flames extended from the apartment terrace sliding door and ignited the rear balconies of the second and third level apartments above, as demonstrated in Figures 4 and 5. Fire extended into the next apartment by failing the sliding glass door and igniting plastic vertical blinds above the door. From there, the fire spread to a nearby couch containing polyurethane foam padding, seen in Figure 7. The fire continued unsuppressed and spread to a second couch as firefighters were engaged in rescuing residents from the second level apartment. This opening created a ventilation flow path from the rear balcony through the apartment and upwards into the third floor of the stairwell. This flow of the fire is seen in Figure 8. Flames extended into the stairwell. The combination of fuel, heat, and oxygen combined with the ventilation flow-path of the second level apartment increased the heat release rate and flashover of the second level apartment. Flames extended into the living room of the third level apartment. Flashover of the third level apartment occurred approximately 30 seconds after flashover of the second level apartment experienced flashover.\(^43\)

Two first responders had begun searching the third level apartment for occupants just before flashover had occurred. Two couches near the entry door in the third level apartment blocked the primary means of egress. One of the firefighters attempted to exit


\(^{43}\) Ibid, p. 17
the apartment through the main entry, but was blocked by flames in the living room and stairwell. Trapped in the bedroom, the firefighter exited the third floor headfirst down a ground ladder. The second firefighter’s means of egress were completely blocked; the flames in both the living room and stairwell blocked the entrance door, while the rear balcony was engulfed in flames, shown in Figure 9. There were no other windows located in the rear of the apartment. The firefighter requested assistance and issued a “MAYDAY” from the rear of the third level apartment. Additional firefighters re-entered the structure to locate the trapped firefighter, who was eventually moved to the rear balcony and extricated in a rescue basket down the aerial ladder of a truck. The firefighter was transported to the hospital where he later died.44

The tragic fire at 30 Dowling Circle clearly demonstrates the importance of extinguishing a fire as quickly as possible. Even a small kitchen fire has the potential to spread rapidly, causing severe damage. The use of automatic fire sprinklers in the kitchen of the first unit could have suppressed the fire long enough to allow first responders the opportunity to treat the fire before flashover could occur. Synthetic materials found in furniture and household goods can increase the rapidity of the development of a structure fire, which contributed significantly to the development of flashover in the fire at 30 Dowling Circle. The analyses of the ventilation flow paths for three different scenarios demonstrate the impact of the human factor on a fire scenario. Automatic fire sprinklers act independently to respond to suppress a fire at an early stage. This example demonstrates how the life safety of both occupants and first

Figure 7: The spread of fire to the second level apartment furniture.\textsuperscript{45}

Figure 8: Flashover through the stairs into the third level.\textsuperscript{46}

\textsuperscript{46} Ibid, p. 20
Figure 9: The location of the trapped firefighter in relationship to blocked exits.\textsuperscript{47}

Figure 10: The remains of the second level apartment living room after flashover.\textsuperscript{48}


\textsuperscript{48} Ibid, p. 36
responders, among many other things, can be impacted by the rapid growth of fire. The implementation of an automatic fire sprinkler system in the kitchen, the source of the fire at 30 Dowling Circle, could have made a significant impact in controlling the spread of the fire. The utilization of sprinklers could have proven effective to prevent or delay flashover, while prolonging tenable conditions for fire fighters as they searched for victims. Extending the tenable period increases the likelihood of escape for first responders and building occupants.

2. Charleston, SC: Palace Apartments Fire

The fire at Palace Apartments, located on King Street in Charleston, South Carolina, serves as a contrast example to the findings presented on the fire at 30 Dowling Circle. In this case study, the fire was contained by the building’s automatic fire sprinkler system. No lives were lost in this incident. The two fires are similar in nature. The structure itself, like that of 30 Dowling Circle, was an apartment complex; therefore, the how the life fire would have been compartmental. The incident began with a stove-top fire; the resident tried to put out the fire to no avail.

The spread of the fire eventually triggered the automatic fire sprinkler system. By the time the firefighters had arrived at approximately 10:20pm, the fire was already contained to the kitchen by the sprinkler system. In contrast, the incident at 30 Dowling Circle was not contained in as quick a fashion; by the time firefighters had arrived on the scene, flashover of the first apartment had already occurred. Conditions inside the building allowed the fire to spread, fostering its growth through the stairwell all the way to the second and third floor apartments. In the incident at Palace Apartments, the
building’s sprinkler system quickly contained the fire, limiting the damage to the kitchen alone. Fire Marshal Mike Julazadeh noted that the “fire sprinkler system is a critical component in the life safety system of this property. In this case, a single fire sprinkler head operated and controlled the fire event until the fire department could arrive and mitigate any remaining hazards.” The utilization of a single sprinkler head in this case not only prevented flashover in the compartment fire (as seen in 30 Dowling Circle), but allowed ample time for first responders to address the incident. The activation of the automatic fire sprinkler system prevented the loss of property and life demonstrated in the previous case study.

It is possible to infer that in these two comparable instances, demonstrating similar ignition causes, as well as residential apartment typologies, that the use of the automatic fire sprinkler system in the fire incident at Palace Apartments prevented the spread of the fire from compartment to compartment. The system in place proved effective in preventing flashover and maintaining tenable conditions until the first responders arrived on the scene. The act of maintaining tenable conditions in a fire-environment increases the ease with which first responders can enter the building to search for occupants, as well as control and eventually stop the growth of the fire.


The Sullivan Family house fire occurred in the early morning of May 1, 2012. The fire claimed the lives of four of the five members of the family: Thomas and Donna

Sullivan, as well as their two daughters. Thomas Sullivan, Jr., managed to escape the blaze by evacuating through the garage after being awakened by his father. This fire is noteworthy for the rapid spread of the fire, causing the quick collapse of the structure. In less than ten minutes the rear wall collapsed, followed by a side-wall and the roof. Putnam County investigators determined the cause of the fire to be smoldering cigarette ash, which ignited the home. After five weeks of examining the debris of the home, it was concluded that the sole survivor, Thomas Sullivan, Jr., had caused the accidental fire. The cigarette ash smoldered in the mulch of the front steps for four hours until wind fanned the embers into flame. The dry mulch also fostered the development of the fire.

Hard-wired smoke detectors in the home appeared to have malfunctioned. Due to the rapid spread of the fire, there was no definitive way to determine whether or not the smoke detectors sounded an alarm in time to alert the family. Investigators also noted that the home’s construction consisted of fast-burning materials, including a popular type of pressed board, glue, and lightweight truss construction, contributed to the rapidity of the fire despite the fact that it was up to code. Carmel Fire Chief Bob Lipton noted, “This is what we see now, with lightweight construction. It's all glue and things aren't nailed anymore.” While it is typical of lightweight construction, including synthetic materials, to burn faster than other construction types, the rapid complete collapse of the home is an unusual event. However, this example does demonstrate how these materials

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impact the short time allowed for safe egress from a burning residential structure.

Although the source of the fire began outside the home rather than inside the home (as typically seen), smoking has been found to be the leading cause of fatal residential building fires.\(^5\)

Fire protection through alternative means, including the use of smoke detectors, was a point addressed by the Builders Association of Central Pennsylvania. In this case study, it is not possible to determine whether or not the smoke detectors sounded an alarm. When a fire is expansive, spreading beyond the floor of origin, the efficacy of a smoke alarm may not be determined; in 40 percent of fatal residential fires, firefighters were unable to determine if a smoke alarm was present.\(^4\) This example can demonstrate the need for the use of automatic fire sprinkler systems as an additional method of fire protection, rather than replacing smoke detectors. The two systems could work effectively together to alert occupants to the danger, while suppressing the fire to maintain tenable conditions for occupants to escape safely. While materials may be highly flammable in a particular construction, the utilization of automatic fire sprinklers could limit the spread of the fire, preventing flashover and loss of life.

4. **Bucks County, PA: Single Family House Fire**

On Christmas Day, 2009, a fire occurring in a single-family home (constructed in 2005) was successfully extinguished by an automatic fire sprinkler system installed in the home. The system successfully extinguished the fire using less than 300 gallons of water in under seven minutes, preventing the spread of the fire from the initial point of origin.

\(^4\) Ibid, p.7
This allowed the homeowners to evacuate the house safely. By the time the fire department arrived, the fire was fully extinguished. The house suffered a total of $12,000 in damages; the fire department estimated that the damages would have been at least 15 times greater had the home not been equipped with residential sprinklers, as the home was located more than a mile from the nearest fire hydrant. Firefighters were able to clear the scene within 33 minutes from the time of the 911 call.\textsuperscript{55}

In comparison to the Sullivan family house fire presented previously, the initial source location of the fire is dissimilar. The source of fire ignition in the Sullivan family house fire occurred with smoldering cigarette ash in dry mulch outside the home, while the ignition source location in the Bucks County single-family house fire occurred inside the home. However, this comparative example serves to illustrate the significant difference in terms of damage, as well as the absence of notification of a smoke detector in each case. The use of the automatic fire sprinkler system was limited to only $12,000 in damages and no life loss, while the Sullivan family house fire suffered structural collapse as well as four deaths. The use of automatic fire sprinklers in the Bucks County case study successfully contained the spread of the fire and allowed time for the family to safely escape. The presence of smoke detectors in the Bucks County case study was undisclosed; however, it is noted that an alarm did not sound, and the family was possibly made aware of the fire by the discharge of the automatic fire sprinklers. The system allowed them to safely escape while the fire was contained and successfully extinguished.

\textsuperscript{55} Jakubowski, Greg. "Bucks County, PA." \textit{Case Studies for Sprinklers}: 2.
CHAPTER IV
HEALTH IMPACT ON FIRST RESPONDERS AND OCCUPANTS

Although standard fire protection safety requirements are meant to improve life safety, there are several hazards encountered by those involved in a structure fire that cannot be prevented through these methods alone. These conditions must be addressed to increase tenable conditions in a structure fire. The dangers posed to both occupants and first responders in a structure fire include smoke inhalation, exposure to toxic gases, and compromised structural integrity of the building itself.

1. Fatalities

In the United States, fire is responsible for substantial morbidity and mortality. Both burns and fires are the leading cause of death in the home for children and young adults, the second leading cause of death in the home for all age groups, and the third leading cause of accidental death for all ages. Although many fires and most fire-related injuries are preventable, there are 2.4 million reported fires annually in the United States. Of these reported fires, the average number of civilian injuries is 29,000 while the average number for firefighter injuries is 101,000. Approximately 6,000 civilian fatalities occur each year. It is noteworthy that few medical studies of fire fatalities have been published; fewer than 1000 cases of an estimated 108,000 fire fatalities occurring in the United States between 1971 and 1989 have been reviewed in medical literature. Most fire loss data are collected for the analysis of property protection rather than the
protection of life. A study by Barillo retrospectively analyzed the records of the New Jersey State Medical Examiner’s Office for deaths attributable to fire, burns, or smoke inhalation during the seven year time period, in which 727 fire fatalities were identified. In 471 cases, smoke inhalation and burn injury were identified as the cause of death, while 178 cases attributed cause of death to smoke inhalation without cutaneous burns. 574 of the victims died in structure fires, typically in buildings used as residences. While the average age of victims was 39.4 years of age, a significant number of fatalities were seen in children less than ten years old and elderly over 70 years old. These age groups combined constituted 39.5% of the fire fatalities. The highest fatality rate was seen in children between the ages of two and four years, accounting for 10.6% of total fatalities. Additionally, over 4,000 on duty fire fighter fatalities were recorded in the United States between 1977 and 2011.

![Figure 11: Age distribution of fatalities.](image)

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2. Smoke Inhalation

In the majority of fire fatalities, the cause of death is smoke inhalation. Determining smoke inhalation as the cause of death involves the postmortem examination of fire victims, including both autopsy and blood-gas studies.\(^5^9\) To establish carbon monoxide (CO) as the principal cause of death and evidence that a victim perished from smoke inhalation in a fire situation, a level of \(\geq 50\%\) carboxyhemoglobin (COHb) has been used. Fire victims can have significantly less than \(50\%\) COHb, however, cause of death can be easily attributed to smoke inhalation through evidence obtained in autopsy and fire investigation.\(^6^0\)

Smoke is composed of toxic gases, including carbon monoxide and hydrogen cyanide, described in the previous section.\(^6^1\) It is the product of thermal demutation process of created by pyrolysis or combustion. The process of pyrolysis involves the decomposition of complex solids into simpler solids or liquids, ultimately forming gases. This smoldering of materials occurs in areas with low levels of oxygen. Conversely, the process of combustion occurs in environments with adequate oxygen supply. The products generated by these processes differ, with variance based on the configuration of the fuel and fire and the chemical composition of the fuel and retardants modified by temperature and heat rate.\(^6^2\) The effects of smoke inhalation differ between a single exposure and the long-term exposure of a fire fighter. Smoke can challenge one’s ability

\(^{5^9}\) Fire and Smoke: understanding the hazards. Washington, D.C.: National Academy Press, 198. p. 17
\(^{6^1}\) Fire and Smoke: understanding the hazards. Washington, D.C.: National Academy Press, 198. p. 18
to safely evacuate a structure; it can obscure vision through eye irritation and lacrimation, impairing mobility, straining breathing, and impairing mental acuity.\textsuperscript{63} When smoke delays evacuation from a structure fire, the amount of time exposed to hazardous substances is prolonged.

Single exposure to the products of combustion in a structure fire can put victims at risk for disease. Fire victims have shown chronic obstructive pulmonary disease after single exposures to smoke inhalation. Studies performed among smoke inhalation victims demonstrated varying types and severities of persistent pulmonary dysfunction.\textsuperscript{64} Whitener et. al conducted a series of pulmonary function measurements in 28 patients who suffered severe burn injury and smoke inhalation. Notable pulmonary obstruction was observed within hours of exposure in the six patients who suffered from smoke inhalation only. Further recovery of function was observed five months after the initial injury.\textsuperscript{65} In addition to single exposure, one must consider the impact of long term repeated exposure as experienced by a firefighter. A number of studies among firefighters have identified acute pulmonary complications of smoke inhalation. Studies have attributed pulmonary function changes to repeated smoke exposure. A study of pulmonary function of Boston firefighters examined 1,430 firefighters in 1970 and again in 1972.\textsuperscript{66} The firefighters were observed to have twice the degree of pulmonary function loss that would have been anticipated in the two-year period. This decline in pulmonary function was significantly correlated with the frequency of fire exposures. Firefighters have also been observed with acute and chronic respiratory and neurological dysfunction.

\textsuperscript{63} Fire and Smoke: understanding the hazards. Washington, D.C.: National Academy Press, 198. p. 18
\textsuperscript{64} Ibid, p. 74
\textsuperscript{66} Fire and Smoke: understanding the hazards. Washington, D.C.: National Academy Press, 198. p. 75
after exposures to the combustion products of pesticides and polyvinyl chloride. These findings are consistent with the Fire Fighter Fatality Investigation Reports published by the Center for Disease Control (CDC); of the 40 recorded fire fighter fatalities in Pennsylvania since 1990, 11 deaths were cardiovascular-related, including heart-attack, atrial septal aneurysm, acute aortic dissection, and hemopericardium. The United States Fire Administration noted that of recorded firefighter fatalities occurring between 2007 and 2011, heart attack accounted for 46.5% of fatal injuries.

3. Oxygen Depletion

A study by the U.S.A.-Canada-Japan Cooperative investigated the relationship between heat transfer and oxygen concentration in a series of full-scale tests. The experiment consisted of a propane gas burner as a fire source, a burn room with walls lined with calcium silicate boards, and an adjacent room. In this fire experiment, it was demonstrated that a strong correlation exists between the concentration of oxygen and the elevation of temperature. As the intensity of the fire source increased, the temperature in the burn room also increased; with the rise in room temperature, oxygen concentration is depleted. This depletion occurs as a natural result of the combustion of polymers, as well as other burning materials. The decrease in oxygen depends on both the material combusted and ventilation conditions present in the fire. Only a fifteen percent oxygen level is required to support the combustion of most burnable materials. As oxygen levels

decrease in a fire, levels of carbon monoxide and other toxic gases increase. Insufficient amounts of oxygen to brain tissue can result in irreversible brain damage or death. Additionally, lower levels of oxygen to the brain in a high stress fire situation can generate atypical behavior and poor judgment.  

4. Toxic Gases

As the incorporation of artificial materials into common household items has increased over the course of the last fifty years in the form of building materials, furnishings, and consumer goods and electronics, so has the potential for exposure to toxic gases released by these materials in the event of a fire. Factors that affect the burning of materials and production of toxic gases include the thermal conditions posed on materials, as well as the atmospheric environment in which materials combust.

Additional immediate toxic threats include irritant organic chemicals in smoke. Many of the large quantities of synthetic polymers increasingly found in buildings contain nitrogen or halogens, resulting in the release of hydrogen cyanide, a toxic chemical, in fire smoke. While carbon monoxide is still likely to be the main toxicant in modern building fires, the toxicants released by synthetic polymers can sometimes be attributed to the principal cause of death or can cause much lower COHb levels in fire victims. An analysis by Yves Alarie of the Department of Environmental and Occupational Health at the University of Pittsburgh demonstrated that high levels of hydrogen cyanide (HCN) are likely in the victims in modern building fires.  

\footnote{Junod, Thomas L.. *Gaseous emissions and toxic hazards associated with plastics in fire situations: a literature review*. Washington: National Aeronautics and Space Administration, 1976. p.6}


HCN is a
colorless, flammable gas. Slightly lighter than air, it is easily swept away from the fire area by air currents. When inhaled or absorbed through the skin, it acts as a chemical asphyxiant by deactivate catalysts needed for oxidative processes in the body.

Urethane, ABS, acrylic, melamine, and polyamide all produce concentrations of HCN when burned. While in typical fire conditions, the quantity of HCN produced would most likely not present a hazard by itself; however, low concentrations of HCN combined with other toxic gases may produce more toxic effects. Inhalation of low concentrations of HCN will lead to a reflex that stimulates breathing, thereby increasing inhalation of toxic gases.\textsuperscript{72} A schematic representation of these gases can be seen in Figure 12.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure12.png}
\caption{A schematic representation of the behavior of plastics in a fire.\textsuperscript{73}}
\end{figure}

\textsuperscript{73} Ibid, p. 10
CHAPTER V

FIRE PROTECTION AND SAFETY THROUGH OTHER REQUIREMENTS

While all fires differ, they share many common characteristics in terms of progression of fire threats. The overall affect of the progression, magnitude, and interaction of toxicants in a fire depend on a person’s location either in the room of origin or away from the room of origin. Additional factors include whether or not the person is capable of escaping, age, health, and mental alertness. In an experimental scenario illustrated in Figure 13, the progression of a fire is examined. This analysis shows that the smoke alarm is able to warn occupants of a fire before toxic threats occur. The results of this scenario also show that had the activation of the fire sprinkler occurred, all toxic threats would have been prevented. Automatic sprinkler system is beneficial because it suppresses toxic threats without action from occupants, regardless of their location or state. When no sprinkler system activated by an air temperature of 150°C at ceiling level is utilized, 74

The overall trend of fire related fatalities in the United States has been declining over the course of the last 30 years. However, the United States does remain among the highest in the world in terms of fire related fatalities. While this decline is relevant, the overall decline cannot be fully explained by improvements in fire suppression

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Figure 13: Time vs. Products of Combustion (Flashover)"}

technologies. This decrease may reflect improvements in firefighting techniques, advancements in building fire codes, and the utilization of home smoke detectors. Additionally, most fire deaths in the United States occur in one and two-family dwellings.

An improved understanding of the hazards associated with fires, including the nature of fire, smoke, and airflow, will assist those who are exposed to fire and its consequences, be they first responders or those threatened by fire.

1. The Nature of a Compartment Fire

Compartment fires refer to fires that occur within an enclosed space. This type of fire is representative of indoor fires, which are of paramount importance considering personal safety. Typical compartments can hold in heat and combustion products, thereby increasing the severity of a fire. A compartment fire typically begins with a fire of some minimal size. This may include ignition caused by a dropped cigarette, a frayed electrical connection, or other typical ignition sources. The fire then grows in size by spreading to a major fuel source, which can include an item of furniture. This is the same type of ignition pattern demonstrated in the 30 Dowling Circle Case Study. The burning will quickly deplete available oxygen in the compartment as products of combustion increase. These products rise from the fire forming a hot, smoky upper layer that deepens as the fire continues to burn. When the hot layer extends to an opening, be it a doorway,

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77 Ibid, p. 21
78 Ibid, p. 18
79 Ibid, p. 25
window, or vent, smoke will move out of the initial room of ignition and move to other parts of the structure.

Openings provide both additional oxygen necessary for the continued development of the fire, and a path for the fire to flow. Cold air flows in through openings as hot air and gases move upward and outward. The availability of air influences the development of the products of combustion as well as the intensity of the fire itself. Once fire has consumed all available oxygen, a state will be reached in which the rate of burning is limited by the rate at which new air is supplied. As a fire develops to its maximum size, oxygen depletion becomes pronounced and the amount of carbon monoxide present increases significantly, while complex pyrolysis products are likely to appear. Toxicity of the fire depends on the amount of air available to the fire. A small fire will produce mainly carbon dioxide and water vapor, while combustion products of the same fire approaching flashover conditions may produce large quantities of carbon monoxide. This demonstrates that the amount of ventilation available to a fire, rather than the size of the compartment itself, determines the rate of energy output of the fire.  

Heat

The development of the fire is also influenced by infrared radiation generated by the hot upper layer of smoke and air. This intense influx provides radiant heat energy to the fuel bed, making the fuel burn faster than it would otherwise. Combustible items in proximity to the original fire become exposed to this heat, thereby raising the temperature of the object. This increases the fuel source of the fire. Hot gases created by the fire heat the ceiling and upper walls of the compartment as well as other combustible materials.

As a result, all of the surfaces and objects in the room become hotter, radiating heat back into the compartment. If the ignition temperature of an object is met, burning may no longer be confined to a single item. This phenomenon, called flashover, occurs when more combustible fuel vapor is being produced than can be consumed by air coming in. Hot gases move through openings where they encounter more air. Flashover occurs when all oxygen has been depleted from the compartment by the fire. This introduction of cooler air dramatically increases the production of heat. The temperature of hot gases as the fire approaches flashover typically exceed 700°C. Fuel is consumed at a rate of approximately 0.5 kg/s, while carbon monoxide content of smoke may be 5%, which is high enough to be disabling or lethal with only a few breaths. A fire at flashover produces hot gases at several cubic meters per second, with the potential to fill an entire floor of a structure with smoke within a few minutes.

2. The Impact of Smoke Alarms

While smoke alarms may be useful in alerting building occupants of a structure fire, their failure can cause a large-scale impact. In 2001, a smoke alarm failed in a fatal upstate New York house fire. This caused safety experts to postulate whether popular models met the threat posed by common synthetic materials in American homes. The two most common types of smoke alarms include ionization alarms, detecting the smoke utilizing radioactive material. This type of alarm typically sounds earlier in fast-burning fires. Photoelectric alarms, which detect pattern changes in light. These alarms are more effective in slow, smoldering fires, which take greater time in transitioning to open flame.

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82 Ibid, p. 28
The impact of fast-burning synthetic materials in furniture, carpets, and other synthetic-based goods on the development of a structure fire has drastically shortened the time available for safe escape. Either alarm has been acceptable under longtime national standards; however, current Underwriters Laboratories (UL) smoke alarm standards were first developed in the 1970s. This standard require smoke alarms to respond within four minutes of a flaming fire, and before smoke obscures visibility by more than 10% per foot in smoldering fires.

Construction techniques and common household materials have changed drastically since then, with an increase in easily flammable synthetic materials, including nylon, polyester. These materials are typically found in furnishings, fabrics, and carpeting, causing smoldering fires. These materials tend to burn faster than natural materials, including wood and cotton. While synthetic materials melt and pool, these natural materials char as they burn, giving off less heat energy. According to Tom Chapin, head of the Fire Protection Division of the UL, this increase in synthetic materials has shortened the time period leading up to flashover from an average of twelve to fourteen minutes in the 1970s to about two to four minutes. In flaming scenarios, escape times are notably shorter.\textsuperscript{83}

A federal court jury found the design of a popular ionization smoke alarm defective in a house fire near Albany in 2001, trapping and killing two people inside the home. Survivors contended that despite their knowledge of the disadvantages of cheaper ionization detectors, First Alert and its manufacturing subsidiary BRK, continued to make and sell millions of the product. Family attorney James Hacker stated, “BRK had

exclusive knowledge that sometimes in real world fires, sometimes these ionization detectors don’t go off at all.” The companies, which control 85% of the market, were ordered to pay $4.15 million in compensation and $500,000 in punitive damages to the family. In response, the companies filed motions for a new trial and to block the award. According to attorney James Heller, the family admitting disconnecting batteries in some of the smoke alarms.84

Approximately 750 written complaints since the 1990s from customers who noted that their ionization detectors did not sound in actual fires were discovered by plaintiffs in the trial Executive vice president and chief engineer for the National Fire Protection Association (NFPA), Arthur Cote, noted that “Almost all of the time you had a ‘failure,’ the detector has been disabled.”85 Regardless of whether the alarms actually failed or were purposefully disabled by occupants, unreliability of this system has been established; be it from mechanical failure or human action.

In addition to the Pennsylvania Builders Association, Quad-City area homebuilders and building code officials in Iowa were also in disagreement over the implementation of the sprinkler mandate in the 2009 International Residential code. On behalf of the Quad-Cities Builders and Remodelers Association, Robert Meyer stated that, “We also feel smoke detectors do a much better job than sprinklers will do,” in terms of alerting and saving people from fires.86 This claim appears to be unsubstantiated, and is in conflict with the findings presented. If evacuation time is

limited between two to four minutes by the burning of synthetic materials, while ionization detectors sound at approximately four minutes after the development of a flaming fire, a smoke detector system alone is not enough to give fire victims enough time to safely evacuate their homes.

3. Deflection and Failures at Floor Joists

As there are an increasing number of new materials and innovative products and systems used in the construction of houses, it is important to develop an understanding of the performance of these products in a structure fire and the impact they pose on the life safety of both occupants and first responders in a fire scenario. As part of an ongoing research project by BRE Global to investigate the performance of construction products and techniques in fire, a large-scale fire test was carried out to determine the response of various floor materials in an incident of fire. The intent of this study was to determine the process of failure of differing floor typologies when exposed to fire. The results of this study provide key information for those exposed to these conditions, including fire fighters and first responders.87

The performances of the floor types were evaluated through a standard furnace test. The drawback of this type of test includes limited dimensions of floors with small, unrealistic boundary conditions. However, the intent of this experiment was to analyze the performance of a floor system connected to load bearing walls through proprietary connections. The test compartment was designed to dimensionally reflect a compartment of a typical domestic dwelling with gross dimensions of 4m x 3m and joists spanning in

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the long direction. These constructions were then subject to a typical value of imposed load and the direct flame impingement of a fire scenario. Joists, spaced according to manufacturer specifications, were connected to the supporting masonry walls using common joist hangers, manufactured from thin steel sheets. Hangers were embedded into the mortar between the block work courses of the test compartment. The test concluded that when directly exposed to fire, some engineered joists may fail more quickly than solid timber joists. While engineered floors may be able to offer the same fire resistance as solid timber joists and floors, the engineered joists must be properly protected from fire in order to provide a level of safety.

The performance of engineered I-section joists in this experiment demonstrated that this floor type may be capable of providing up to 60 minutes of fire resistance, provided that the joists are constructed with two layers of 15mm fire resistant plasterboard. The success of the I-section joists in a fire scenario depended on the additional fire protection provided by the two layers of fire resistant plasterboard. In contrast the engineered truss joint floors tested, when exposed to fire directly, resulted in more rapid failure. This floor system resulted in the development of large deflections in fire conditions, and continued to deflect at a high rate over a short period of time. This resulted in the sudden failure of this floor system. The steel modules forming the web of the section became detached due to the charring of timber, causing the connecting plate to lose its bond. After 60 minutes of fire exposure, the deflection of the engineered truss joints was nearly three times greater than that of the solid timber joints tested. While the

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89 Ibid, p.169
90 Ibid, p. 180
experiment by BRE Group noted that more testing must be done to determine if the use of thicker plasterboards, different types of connectors, or a combination of the two could improve the performance of floor constructions under fire conditions.\textsuperscript{91}

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