



# Environmental Impact of Automatic Fire Sprinklers: Part 1. Residential Sprinklers Revisited in the Age of Sustainability

*Louis A. Gritzko, Robert G. Bill Jr., Christopher J. Wieczorek\*  
and Benjamin Ditch, FM Global, 1151 Boston-Providence Turnpike,  
Norwood, MA 02062, USA*

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**Abstract.** A recent study on the environmental impact of automatic fire sprinklers is documented in a two part series. The current paper provides a background on residential sprinkler technology from its inception until the present, and analyzes the contribution of risk factors, such as fire, on the total lifecycle carbon emissions of one- and two-family dwellings and the reduction to that contribution achieved via the use of automatic fire sprinklers. The analysis shows that the risk of fire increases the carbon emissions of a building over its' lifecycle. The results illustrate that sound risk management is necessary to achieving sustainability and avoiding unintended consequences. These findings are especially important as society seeks to design and build more energy- and resource-efficient, environmentally sustainable buildings.

**Keywords:** Risk factors, Residential automatic fire sprinklers

## 1. Introduction

Past research in residential automatic fire sprinkler technology has identified sprinkler characteristics necessary to provide reliable life safety in residential occupancies [1–3]. This research further resulted in a standardization of the requirements for reliably certifying and installing residential hardware to meet desired performance requirements [4–10]. A new factor to be considered in the assessment of the value of residential sprinklers is the desire to achieve sustainability through the potential positive impact of sprinklers on the lifecycle carbon emissions of homes.

As part of the sustainability assessment, carbon emissions from a facility are estimated under normal operating conditions. Recently, Gritzko et al. [11] have shown that, in industrial and commercial facilities (including light hazard, i.e., hotels and condos), the impact of fire on lifecycle carbon emissions is significant and needs to be accounted for due to the release of emissions during the fire and the carbon associated with rebuilding or reconstruction. Thus, in addition to their life safety and property protection functions, sprinklers promote sustainability.

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\* Correspondence should be addressed to: Christopher J. Wieczorek, E-mail: Christopher.wieczorek@FMGlobal.com

In this paper, a brief review of residential sprinkler technology from its inception until the present is provided. The main focus of the paper is a risk factor analysis, following the methodology of Gritzo et al. [11], for one- and two-family dwellings. In a companion paper, *Environmental Impact of Automatic Fire Sprinklers: Part 2. Experimental Study* [12], an experimental study aimed at the quantification of the environmental benefits achieved by the use of automatic fire sprinklers is detailed. The complete study can be found in Ref. [13].

## 2. Background

Deaths in residential occupancies remain the key problem in the U.S. for the fire safety community. Although fire deaths have been reduced in the United States from 6,135 in 1977 (83% of all U.S. fire deaths) [14] to 2,895 in 2007 (84% of all U.S. fire deaths) [15], the level of deaths throughout the last decade has remained persistently high, i.e., between 2,620 (2006) and 3,445 (2000) [15]. Reductions to date have been achieved presumably through the use of smoke detectors, improved construction materials, education, and changes in personal behavior such as reduced cigarette smoking. As a means of attacking the persistently high number of fire deaths, residential sprinklers technology was developed from the mid 1970s through the 1980s in large-part by research funded by the United States Fire Administration (USFA) [16].

To date, the use of residential automatic fire sprinkler technology has been extremely limited with less than 3% of one- and two-family dwellings taking advantage of its benefits [16]. The 2007 American Housing Survey reported sprinkler usage in 1.5% of single family detached dwellings and 2.9% in buildings with two to four units [17]. Hall [18] reports that only 1.2% of fires in the U.S. occurred in one- or two-family dwellings with automatic extinguishing systems in 2006. The effectiveness of the residential sprinkler has, however, been increasingly recognized by communities through regulations requiring installation in one- and two-family dwellings. Of particular note are the long-term ordinances for Scottsdale, Arizona, and Prince George's County, Maryland. In both cases, experience with the resulting installations led to clear documentation of the benefits to life safety and property protection (see, e.g., Refs. [16, 19]). In 2006, the NFPA model codes, i.e., NFPA 1, *Fire Code*, NFPA 101, *Life Safety Code*, and NFPA 5000, *Building Construction and Safety Code*, adopted the requirement for residential fire sprinklers in one- and two-family dwellings [20–22]. The USFA has supported the position that: "All homes should be equipped with both smoke alarms and automatic fire sprinklers" [23]. Such support led to the approval of a requirement in the International Code Council (ICC), *International Residential Code*, on September 21, 2008, for residential sprinklers in all new one- and two-family homes and townhouses [24]. However, only about 400 out of the thousands of jurisdictions in the U.S. were mandating the installation of residential sprinklers in 2008 [23].

In the 1970s and 1980s the USFA partnered with FM Global (then Factory Mutual Research Corporation), Underwriters Laboratories (UL), the National Fire Protection Association (NFPA), various members of the Fire Service, and

other fire research organizations to successfully identify characteristics of sprinklers which could reliably and practically provide life safety in homes [16]. Of particular note was the Los Angeles Residential Test Program where a living room fire was identified as the most challenging scenario [1]. The results of this research and others of this period (see, e.g., [2, 16] for a review of such research), led to a complete revision of NFPA 13D, *Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes*, in 1984 [4]. In 1983 and 1986, respectively, FM Global [5] and UL [6] developed test standards to provide certification for commercial residential sprinklers. A wide variety of certified residential sprinklers have been available from that time through the present [25, 26].

Residential sprinkler research has continued since the installation standards [4] and certification standards [5, 6] were developed. A recent review of this research is given by Madrzykowski and Fleming [27].

Research resulting in changes in the installation and certification standards was conducted and reported in 2002 by Bill et al. [2]. FM Approvals original fire test for residential sprinklers was conducted using commercial furnishings similar to those used in the Los Angeles Test Program [1]. The fire test of the UL 1626 residential sprinkler standard [6] used a simulated furnishing package. In order to harmonize the fire test standards, in 1996 FM Approvals, working with the research unit, initiated the use of the UL 1626 fire test. Use of this fire test, however, indicated that insufficiently specified flammability characteristics of the fuel package in UL 1626 led to a lack of reproducibility in the test results. Working with UL, new criteria using bench-scale tests were developed to select materials for use in a new fire test using simulated furnishings. The details of this research are given in Ref. [2]. The current certification tests used by UL and FM Approvals for the residential sprinklers are available in Refs. [7] and [8], respectively.

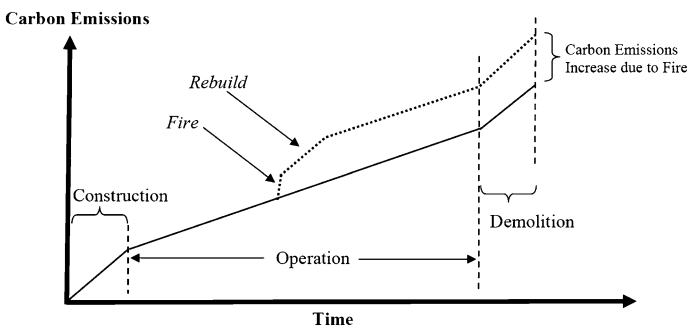
In addition to addressing reproducibility of fire test results, the research conducted by Bill et al. [2], indicated that acceptable sprinkler performance required sprinkler densities of 4.1 mm/min (0.1 gpm/ft<sup>2</sup>) (tests at the time included densities as low as 1.3 mm/min (0.03 gpm/ft<sup>2</sup>)) [28]. Based in part on these results, NFPA 13D was revised in 2002 to require a minimum density of 2.0 mm/min (0.05 gpm/ft<sup>2</sup>) for a two sprinkler operation design [4]. The purpose of NFPA 13D is “to provide a sprinkler system that aids in detection and control of residential fires and thus provides improved protection against injury and life loss” [9]. FM Global’s Data Sheet 2–5, *Installation Guidelines for Automatic Sprinklers in Residential Occupancies*, requires a minimum of 4.1 mm/min (0.1 gpm/ft<sup>2</sup>) [10]. In regard to the density requirement, it is noteworthy that Bill et al. [3] report that the required density for suppression of the vinyl-covered polyurethane reclining chair used in the original FM Approvals residential fire test was bracketed between 3.7 mm/min and 6.6 mm/min (0.09 gpm/ft<sup>2</sup> and 0.16 gpm/ft<sup>2</sup>). The research reported in Ref. [1] and experience at FM Global indicates that the increased density will significantly reduce property damage by increasing the chance for fire extinguishment. FM Global also requires a 1 h water supply compared with the 10 min supply currently stated in NFPA 13D.

### 3. Methodology for Estimating Life Cycle Emissions Including Risk Factors

The construction, renovation, or improvement of facilities increasingly includes measures to improve sustainability by reducing environmental impact over their operational lifecycle. Of primary environmental concern is the emission of greenhouse gases associated with the consumption of energy during normal operations, or required for the production and transportation of materials, and construction. Emphasis to date has focused on reduction in emissions related to energy consumption during normal operations, with a secondary emphasis on reducing carbon emissions associated with the fabrication and transport of construction materials, construction processes, and facilities decommissioning, i.e., the “embodied carbon emissions.” Within the United States, the Leadership in Engineering and Environmental Design Organization (LEED) has established metrics and certification levels for construction and renovation [29]. LEED certification checklists provide guidance for options and measures to reduce the environmental impact of facility construction and operations on carbon emissions. Gritzo et al. [11] supplemented the analysis of normal operations with an analysis taking into account risk factors of such events as fire, wind, and flood as well as the use of mitigating technologies such as sprinklers.

The impact of risk factors on lifecycle carbon emission, LCE, is illustrated in Figure 1. The plot indicates the carbon emission for an occupancy as a function of time. Note that proportions are not to scale, but are expanded for readability. The lower curve may be considered the carbon emissions under normal conditions; the upper curve shows the deviation from that of normal conditions due to a fire.

The carbon emission cycle can be divided into three portions: (1) that due to construction,  $CE_{\text{construction}}$  (including that associated with manufacture of material, transportation, and equipment usage), (2) that due to normal operation over the lifetime of the occupancy,  $LCE_{\text{operation}}$  (primarily power consumption, utilities, and maintenance if applicable), and (3) that due to decommissioning,  $CE_{\text{decommissioning}}$



**Figure 1. Contribution of risk factors to total lifecycle carbon emissions.**

(including that due to equipment usage for demolition, and transportation for disposal).

Thus the total lifetime carbon emissions ( $TCE$ ) are given as

$$TCE = CE_{\text{construction}} + LCE_{\text{operation}} + CE_{\text{decommissioning}} \tag{1}$$

The carbon emissions associated with normal operations are typically estimated on an annual basis,  $ACE_{\text{operation}}$ , in which case,  $LCE_{\text{operation}}$  depends on the lifetime of the occupancy,  $LT$ :

$$LCE_{\text{operation}} = LT \cdot ACE_{\text{operation}} \tag{2}$$

The annual rate of emission for operation is typically referred to as the “carbon footprint.” Due to the primary importance of energy consumption on emissions associated with normal operations, annual rates of carbon emissions can readily be determined using standard guidance [30].

The emissions due to construction and decommissioning are typically considered one time events and referred to as embodied emissions,  $CE_{\text{embodied}}$ , given their inclusion in the physical facility rather than resulting from normal operations. Hence,

$$CE_{\text{embodied}} = CE_{\text{construction}} + CE_{\text{decommissioning}} \tag{3}$$

Note that the embodied emissions are estimated in the literature on a per unit area basis (see, e.g., Ref. [30]) and can be annualized over the lifetime,  $LT$ , of a facility:

$$ACE_{\text{embodied}} = \frac{CE''_{\text{embodied}} \cdot A}{LT} \tag{4}$$

The event of a fire requires taking into account additional considerations in the analysis, namely, the carbon emissions associated with the fire,  $CE_{\text{fire}}$ , and those associated with replacement of the damage caused by the fire,  $CE_{\text{replacement}}$ . These may be estimated as

$$CE_{\text{fire}} = F_b \cdot m''_f \cdot e_{\text{CO}_2} \cdot A \tag{5}$$

and

$$CE_{\text{replacement}} = F_r \cdot CE_{\text{embodied}} \tag{6}$$

where  $F_b$  is the fraction of material burned;  $m''_f$  is the total mass of combustible material per unit area;  $e_{\text{CO}_2}$  is the carbon dioxide released per mass of material burned; and  $F_r$  is the fraction of material to be replaced during reconstruction.

Figure 1 reflects additional carbon emissions resulting from the fire, referred to as the lifecycle carbon emissions due to fire risk,  $LCE_{\text{risk}}$ . Evaluating the risk on a

statistical basis over the lifetime of the structure requires knowledge of the frequency of fires,  $f_f$ . Thus,

$$LCE_{\text{risk}} = f_f \cdot LT \cdot (CE_{\text{fire}} + CE_{\text{replacement}}) \quad (7)$$

A risk factor,  $RF_{\text{fire}}$ , indicating the relative importance of carbon emissions due to risk events such as fire compared to normal operation over the lifetime can be defined as

$$\begin{aligned} RF_{\text{fire}} &= \frac{LCE_{\text{risk}}}{TCE} = \frac{f_f \cdot LT \cdot (CE_{\text{fire}} + CE_{\text{replacement}})}{TCE} \\ &= f_f \cdot LT \cdot \left( \frac{F_b \cdot m_f'' \cdot e_{\text{CO}_2} \cdot A}{TCE} + \frac{F_r \cdot CE_{\text{embodied}}}{TCE} \right). \end{aligned} \quad (8)$$

The risk fraction, therefore, represents the increase that risk factors pose to the sustainability posture of a home over its lifetime.

### 3.1. Effect of Risk Management

A reduction in the risk fraction can be achieved through effective risk management strategies, which can serve to reduce the fire frequency and/or serve to reduce the extent of damage produced and reconstruction required. In the context of the home, such risk management includes smoke detectors, fire retardant furnishings, and adoption of ignition source control. The latter two factors can reduce the frequency of fires; however, they cannot in themselves suppress a fire once it has occurred. Automatic fire sprinklers are the most common and cost effective method to reduce both the frequency of large fires and the severity of damage (and hence the fraction required for reconstruction). Fire frequency data implicitly include some minimum threshold for fire size, since very small or incipient fires cause minimal damage and are frequently extinguished without record. Furthermore, fire severity data are often expressed in terms of loss values, which may or may not include full cost of replacement.

The effect of automatic sprinklers on the risk factor is expressed by reductions in the fraction burned,  $F_b$ , and the replacement fraction,  $F_r$ , values used in Equation 8.

## 4. Quantification of Risk Factors for One- and Two-Family Dwellings

Values used in the present analysis for the variables in Equation 8 are provided in Table 1. In the following sections, justification for these values will be provided relative to typical one- and two-family dwellings and the impact of using automatic fire sprinklers. Due to the uncertainty including variability associated with a number of variables, a lower (Case 1) and upper (Case 2) bound is provided.

Evaluating the TCEs for a typical one- and two-family dwelling from its components as in Equations 1–3 is quite complex given the diversity of construction

**Table 1**  
**Selected Values for Variables in Equation 8**

Symbol	Parameter (units)	Case 1	Case 2
$f_f$	Frequency of residential fires (fires/year)	0.0032	0.0032
$LT$	Lifetime (year)	50	50
$m_f$	Fuel density (kg/m <sup>2</sup> )	13.2	21
$e_{CO_2}$	Mass of CO <sub>2</sub> generated per unit mass of fuel burned (kg/kg)	3.0	3.0
$TCE$	Total lifecycle carbon emissions (kg <sub>CO<sub>2</sub></sub> )	278,000	278,000
$CE_{embodied}$	Total embodied carbon emissions (kg <sub>CO<sub>2</sub></sub> )	60,680	60,680
$F_b$	Fraction burned, no AFS (-)	0.07	0.34
$F_r$	Fraction replaced, no AFS (-)	0.11	1.0
$F_{AFS}$	Reduction in property loss achieved by AFS (%)	51	90
$F_{b,AS}$	Fraction burned, AFS (-)	0.03	0.034
$F_{r,AS}$	Fraction replaced, AFS (-)	0.05	0.051
Results			
$RF_{fire}$	Fraction of total carbon emissions due to fire risk, no active protection (%)	0.40	3.7
$RF_{fire,AS}$	Fraction of total carbon emissions due to fire risk, with AS (%)	0.20	0.20

and patterns of energy consumption in the U.S. For example, in a report on per capita carbon footprints from residential energy use of the 100 largest U.S. metropolitan areas, Brown et al. [31] indicate a factor of 5.6 between the metropolitan area with the lowest per capita emissions (0.350 metric tons carbon—Bakersfield, CA) and the highest (1.958 metric tons carbon—Washington, DC). The average per capita carbon emission from residential energy use was 0.925 metric tons. The objective of the present study was not to evaluate the range of carbon emissions resulting from such diversity in the housing population, but to provide a typical result indicative of the significance of the use of automatic sprinklers to sustainability.

Estimates of annual greenhouse emissions characterized as  $ACE_{operation}$  and  $ACE_{embodied}$  are taken from Norman et al. [32] from a study published in 2006 comparing lifecycle energy use and greenhouse emissions in high and low density residential dwellings. In this study, the low density residential case study consisted of single detached dwellings located near the border of the city of Toronto, Ontario, Canada. All houses consisted of wooden structure and primarily brick façade. The housing is considered to be typical of current and upcoming residential construction.

The major component of TCE is typically that associated with normal operation over the lifetime of the building,  $LCE_{operation}$ . Norman et al. [32] estimate the  $LCE_{operation}$  based upon total emission for the residential sector for 1997 obtained from the 2003 Office of Energy Efficiency, Natural Resources Canada. This report, however, did not distinguish between housing types. The authors proportioned the emission based upon the total residential energy use attributable to single-detached dwellings (72%). They also noted that this choice is expected to be reasonable given that the majority of residential greenhouse gas emissions results

**Table 2**  
**Home and Fire Statistics from 1999 to 2008**

Year	Home statistics		Fire loss statistics		Loss estimates	
	Average size m <sup>2</sup> (ft <sup>2</sup> )	Median price	Number of fires	Dollar loss (in billions)	Cost per loss	Percentage damaged (%)
1999	161 (1,730)	\$108,999	282,500	\$5.3	\$18,761	17.2
2001	161 (1,737)	\$124,569	295,500	\$5.7	\$19,289	15.5
2003	163 (1,755)	\$140,269	297,000	\$5.9	\$19,865	14.2
2005	167 (1,795)	\$165,344	287,000	\$6.4	\$22,300	13.5
2007	168 (1,807)	\$191,471	300,500	\$6.5	\$21,631	11.3
Average	164 (1,765)	\$146,130	292,500	\$6.0	\$20,525	14

from the burning of fuel and use of electricity for heating/cooling, which are also the most significant factors in total energy use. In their analysis, they use an annualized value per unit area for  $ACE''_{\text{operation}}$  of  $33.9 \text{ kgCO}_2/(\text{m}^2 - \text{year})$ .<sup>1</sup>

To calculate  $LCE_{\text{operation}}$  the lifetime and area of the dwelling need to be taken into account. Following Norman et al. [32], a value of 50 years was taken for the lifetime. A reasonable estimate for the area is the average of the median area reported in the American Housing Survey (AHS), conducted by the U.S. Census Bureau, for single-detached and manufactured/mobile homes for 1999, 2001, 2003, 2005, and 2007 [17, 33–36]. The data are summarized in Table 2. The average area of these dwellings was  $164 \text{ m}^2$  ( $1,765 \text{ ft}^2$ ). Using these values the  $ACE_{\text{operation}}$  is equal to  $5,560 \text{ kgCO}_2$  per year and  $LCE_{\text{operation}}$  is equal to  $278,000 \text{ kgCO}_2$ .

To evaluate the embodied carbon, Norman et al. [32] analyzed the annual greenhouse gases emitted and energy used during manufacturing of the home construction materials. Materials that did not form part of the dwelling structure, such as, appliances or carpeting, were not considered in the analysis. Materials considered in the analysis included brick, window (glass and metal frames), dry-wall, structural concrete, reinforcing bar, structural steel, plywood, asphalt shingles, aluminum siding, hardwood flooring and stairs, insulation (fiberglass and polystyrene), high-density polyethylene vapor barrier, and sub-foundation aggregate. Of these, the first four materials accounted for between 60% and 70% of the total embodied greenhouse gases. Proportioning the greenhouse gases over a lifetime of 50 years, Norman et al. [32] estimated that the average equivalent annual embodied greenhouse gases per unit area is  $7.4 \text{ kgCO}_2/(\text{m}^2 - \text{year})$ . For a 50-year lifetime and a typical area of  $164 \text{ m}^2$  ( $1,765 \text{ ft}^2$ ), the total embodied carbon emissions,  $CE_{\text{embodied}}$ , is  $60,680 \text{ kgCO}_2$ .

No effects corresponding to decommissioning were discussed by Norman et al. [32]. Gritzo et al. [11] reported that, for office buildings, the total embodied fraction of total carbon emissions were on the order of 15% to 20%. As the ratio

<sup>1</sup>Note that gases other than  $\text{CO}_2$  are considered in terms of  $\text{CO}_2$  equivalents normalized in terms of global warming potential calculated according to the United Nations framework Convention on Climate Change. Greenhouse gases considered by Norman et al. were carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons [32].



of  $CE_{\text{embodied}} / (CE_{\text{embodied}} + LCE_{\text{operation}})$  in the present analysis is 18%, no further additions to the embodied carbon emissions are considered here.

Some of the parameters needed to estimate  $LCE_{\text{risk}}$  (Equations 5–7) can be obtained from NFPA [37] and AHS [17, 33–36] statistics—for example, the frequency of fires and some insight into the fraction burned,  $F_b$ . Key data needed for these estimates are summarized in Table 2. Using the same years as the AHS statistics, NFPA statistics indicate that the average number of fires per year for one- and two-family dwellings, including manufactured homes, was 294,350. The average number of occupied attached or detached single units and manufactured homes reported by the AHS for the specified years was 90,797,000. Thus, the frequency of fires per year was 0.0032.

The fraction of structural damage as a result of a fire event is not well documented; therefore, the fraction burned was estimated based on the reported dollar losses. The estimated average of total property damage per year was US \$6.0 billion. This represents an average loss per fire of US \$20,370. The average of the median house values reported by AHS [17, 33–36] for the same years was US \$146,130, for an average loss due to fire of 14%.

It is important to recall the wide variation in fire behavior that is not represented by the average loss. The fire statistics for Prince George's County, Maryland, for the period of 1992 to 2007, in which sprinklers were mandated in newly constructed one- and two-family dwellings, provide a particularly clear example [19]. For the 15-year period, the average loss in 13,494 non-sprinklered fire incidences was US \$9,983 while in 101 non-sprinklered fire incidences in which there was a fatality, the average loss was US \$49,503, or an increase by a factor of five for these fires. The median value of a single-family home in Prince George's County was reported as US \$145,600; therefore, the average loss due to fire is estimated to be between 7% and 34%.

Since the NFPA data indicate an average loss due to fire that is bounded by the Prince George's County data, in this analysis the fraction burned,  $F_b$ , will be assumed to be the two bounding values of 7% and 34%.

In addition to the fraction of material burned and the area of the home, estimating of the carbon emissions due to a fire event requires the total mass of combustible material per unit area,  $m'_f$ , and the carbon dioxide released per mass of material burned,  $e_{\text{CO}_2}$ . Davoodi [38] reports fuel loads of 19.0 kg/m<sup>2</sup>, 13.2 kg/m<sup>2</sup>, 21.0 kg/m<sup>2</sup>, 17.6 kg/m<sup>2</sup>, and 15.6 kg/m<sup>2</sup> for living rooms, family rooms, bedrooms, dining rooms, and kitchens respectively. For the present analysis the minimum, i.e., 13.2 kg/m<sup>2</sup>, and maximum, i.e., 21.0 kg/m<sup>2</sup>, values will be used as the bounding cases.

The carbon dioxide released per unit of material burned,  $e_{\text{CO}_2}$ , is taken as 3.0 kg/kg based upon combustion analysis and flammability data from Tewarson [39].

Finally, the replacement fraction needs to be determined. A conservative assumption is that the replacement fraction,  $F_r$ , is equal to the fraction burned,  $F_b$ ; however, information indicates that after a fire event “the per-square-foot cost can increase by as much as 50% for readying a space for reconstruction” [40]. In this analysis, the replacement fraction is assumed to be 1.5 times the fraction

burned; however, if the replacement fraction exceeds 50% it is assumed that a total constructive loss occurred and a value of 100% is used.

Based on these values, the contribution of fire risk to the total lifecycle carbon emissions of a home without sprinklers (Equation 8) is between 0.4% and 3.7%.

The installation of automatic sprinklers is expected to reduce  $LCE_{\text{risk}}$  (Equation 7) and the Risk Factor (Equation 8) through a reduction in the burn, and hence, replacement fractions. The reduction in burn fraction can be estimated from reduction in property loss with sprinklers. The fire statistics for Prince George's County [19] provide a significant record of the effect of residential sprinklers on fire fatalities and property damage.<sup>2</sup> Between 1992 and 2007, there were 13,494 fires in single-family dwellings or townhouses. There were 245 fires in such homes with residential sprinklers installed. No fatalities occurred in any of the sprinklered fires; however, there were 101 fatalities in the non-sprinklered fires. The average loss per event with a sprinkler system was US \$4,883.83. Using the dollar loss values for events with and without sprinklers, the reduction in property loss achieved by automatic sprinklers is estimated to be between 51% and 90% in Prince George's County.

The contribution of a fire risk to the total lifecycle carbon emissions of a home is reduced to 0.2% when sprinklers are used, as all large fires are eliminated. In addition to saving lives, the presence of sprinklers ensures a reduction in carbon emissions and decreases the need for structural replacement as the fire will be limited to the housing contents initially ignited, and damage due to smoke and water will be minimized and limited to the room of fire origin.

## 5. Conclusions

A recent study on the environmental impact of automatic fire sprinklers [13] is documented in a two part series. The current paper provides a background on residential sprinkler technology from its inception until the present, and analyzes the contribution of risk factors, such as fire, on the total lifecycle carbon emissions of one- and two-family dwellings and the reduction to that contribution achieved via the use of automatic fire sprinklers. In support of this analysis, an experimental effort was conducted to quantify the reduction in the environmental impact via the use of sprinklers [13], the experimental work is presented in a companion paper [12].

Previous work on sustainable design has appropriately focused on energy efficiency as the main source of carbon related emissions. In this study, consideration is expanded to consider the influence of risk factors. Although these factors may include any potential hazard to the building, the most relevant for one- and two-family dwellings is due to fire. Using the method presented herein, analysis of the

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<sup>2</sup>Hall [18] has analyzed the performance of automatic sprinklers in one- and two-family dwellings. He reports that, for the period of 2003 to 2006, fire damage was only reduced from an average of US \$19,000 to US \$14,000 as a result of automatic sprinklers. Hall comments that "only 1% of reported dwelling fires involve sprinklered properties, which means any loss estimate for sprinklered dwelling fires will tend to be statistically unstable" [18].

nominal contribution of a fire to the lifecycle carbon emissions of a one- and two-family dwellings provides the following conclusions:

- The contribution of fire risk to the total lifecycle carbon emissions of a home without sprinklers is between 0.4% and 3.7%.
- Fire risk factors can be effectively addressed by the addition of automatic fire sprinkler systems.
- The contribution of a fire risk to the total lifecycle carbon emissions of a home is reduced to 0.2% when sprinklers are used.

In addition to saving lives, the presence of sprinklers ensures a reduction in carbon emissions and decreases the need for structural replacement as the fire will be limited to the housing contents initially ignited, and damage due to smoke and water will be minimized and limited.

The results illustrate that risk management is inherent in achieving sustainability due to the contribution of risk to potential emissions. In the future, risk management will gain increased importance as advances in sustainable designs that do not consider risk factors have the potential for unintended consequences with even greater emissions. These findings are especially important as society seeks to design and build more energy- and resource-efficient, environmentally sustainable buildings.

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