RESEARCH TECHNICAL REPORT

Environmental Impact of Automatic Fire Sprinklers

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EXECUTIVE SUMMARY

Currently, efforts to improve sustainability and reduce lifecycle carbon emissions are achieved primarily by increasing the energy efficiency of an occupancy and reducing embodied carbon. Recently, a methodology has been developed that expands the assessment of lifecycle carbon emissions to incorporate risk factors such as fire. The methodology shows that in all occupancies, from residential dwellings, to office buildings, to high hazard facilities, the lack of proper risk management and effective fire protection, e.g., automatic fire sprinklers, statistically increases carbon emissions over the lifecycle of the occupancy.

Furthermore, typical benefits gained from "green" construction and energy efficient appliances and equipment can be negated by a single fire event. This is due to the subsequent carbon dioxide, and other greenhouse gases, generated from burning combustible material, in addition to the embodied carbon associated with disposal of damaged materials and reconstruction.

To further support the risk factor methodology, an experimental study was conducted to quantify the environmental impact of automatic fire sprinklers. Large-scale fire tests were conducted using identically constructed and furnished residential living rooms. In one test, fire extinguishment was achieved solely by fire service intervention. In the other test, a single residential fire sprinkler controlled the fire until final extinguishment was achieved by the fire service.

Quantification of the environmental benefit of automatic fire sprinklers was based on comparisons between the two tests, including total greenhouse gas production, quantity of water required to extinguish the fire, quality of water runoff, potential impact of wastewater runoff on groundwater and surface water, and mass of materials requiring disposal.

The use of automatic fire sprinklers reduced the peak heat release rate from 13,200 kW to 300 kW and reduced the total energy generated by a factor of 76. The fraction of combustible material consumed in the fire was less than 3% in the sprinklered test and between 62% and 95% in the non-sprinklered test.

The total air emissions generated from the sprinklered test were lower than those from the non-sprinklered test. Of the 123 species analyzed in the air emissions, only 76 were detected in either the sprinklered or non-sprinklered tests. Of the species detected, the ratio of non-sprinklered to sprinklered levels for 24 of the species was in excess of 10:1. Eleven were detected at a ratio in excess of 50:1, and of those, six were detected at a ratio in excess of 100:1. The remaining species were detected at the same order of magnitude. The use of automatic fire sprinklers reduced the greenhouse gas emissions, consisting of carbon dioxide, methane, and nitrous oxide, and reported as equivalent mass of carbon dioxide, by 97.8%.

Comparing the water usage between the two tests, it was found that in order to extinguish the fire, the combination of sprinkler and hose stream discharge from the firefighters was 50% less than the hose stream alone. Additional analysis indicates that the reduction in water use achieved by using sprinklers could be as much as 91% if the results are extrapolated to a full-sized home. Furthermore, fewer persistent pollutants, such as heavy metals, and fewer solids were detected in the wastewater sample from the sprinklered test compared to that of the non-sprinklered test. The pH value of the non-sprinklered test wastewater exceeded the allowable discharge range of 5.5 to 9.0 required by most environmental agencies and was four orders of magnitude higher in alkalinity than the wastewater from the sprinklered test. The non-sprinklered test wastewater represents a serious environmental concern.

Analysis of the solid waste samples indicated that the ash/charred materials from neither the sprinklered nor the non-sprinklered test would be considered “hazardous waste,” and that the wastes are not anticipated to significantly leach once disposed of in landfills.

In the sprinklered room, flashover never occurred; however, in the non-sprinklered test, flashover occurred at approximately five minutes after ignition. The occurrence of flashover prior to fire service intervention is an indication that the fire would have propagated to adjacent rooms, resulting in greater production of greenhouse gases, greater water demand to extinguish the fire, and additional materials to be disposed of in landfills. However, in the sprinklered test where the fire was confined to the area of origin, the damage, greenhouse gas production, and water consumption represent maximum values independent of additional rooms.

The greater fire damage in the non-sprinklered test has a direct impact on the carbon emissions of the building. This is due to the embodied carbon associated with the building materials necessary for reconstruction and those associated with the manufacturing of furnishings and contents.

It has been known for years that automatic fire sprinklers provide life safety and limit property damage; the current study has shown quantitatively that automatic fire sprinklers are also a key factor in achieving sustainability. Although the current study was conducted using a residential setting, the environmental benefits of automatic fire sprinklers apply to other occupancies as well.

FOREWORD

Since 1996, the nonprofit Home Fire Sprinkler Coalition (HFSC) has been helping the public understand the need for, and the unique value of, fire sprinkler systems in new houses. The HFSC's effort is necessary because thousands of lives are lost in house fires every year, yet only a tiny fraction of new houses are built with sprinkler protection – a technology proven to save lives if a fire starts.

For as long as data has been collected, the U.S. fire death problem has been a residential one. The numbers have dropped over the past 30 years, but the rate has remained steady. More than eight out of every 10 civilian structure fire deaths and most civilian fire injuries occur in homes. On a percentage basis, these properties are also the most dangerous fireground scene for firefighters. Obviously, these are the properties we must target if we are going to make inroads to the overall fire problem.

Fire sprinklers could save lives if more systems were installed in homes. Increasing awareness about sprinklers leads to more home installations and that protects public safety and improves communities. But educating new homebuyers and others about fire sprinklers isn't simple. Surveys over the years have consistently shown that most people don't believe a fire will happen in their own home or understand that a house fire can grow to deadly flashover within a few minutes.

There is also the challenge of education on fire sprinkler cost, activation and maintenance. Recognizing these outreach challenges, HFSC works to find new partnerships and innovative methods to help the public understand how dangerous house fires truly are, and how critical fire sprinklers are to life safety.

The idea to explore the environmental impact of sprinklered and non-sprinklered house fires was born a few years ago during an HFSC strategic planning session. We were confident that home fire sprinklers are also indeed "green" and we wanted to tap into the nation's heightened interest in the environment as a means to draw attention to their overall benefit. But we wanted to make a scientific case for it.

That led us to FM Global and to a lengthy joint effort that has made it possible to prove, without doubt, that sprinklers not only save lives and protect property; they also protect our planet.

We are grateful to FM Global, one of the world's largest business property insurers, for partnering with HFSC in this residential safety effort. One of the reasons we turned to FM Global is because of the leadership role they have taken in fire sprinkler research over the past 50 years. And we knew the remarkable scientific testing facilities at FM Global's Research Campus would benefit our study and ensure its findings would be unimpeachable.

As you'll see when you read this technical report, the fire safety community's efforts to increase awareness of all aspects of home fire sprinkler technology will benefit from this new environmental data. Consumers, homebuilders, the fire service, and local officials now have a new and important way to view home fire sprinkler protection.

This research would not have been possible were it not for the generosity of FM Global, specifically the management leadership of Dr. Lou Gritzo and the personal commitment of Dr. Christopher Wieczorek. Thanks to their vision, professionalism and dedication, HFSC now has the data to prove that sprinklers are indeed "green" in addition to the benefit they offer to protect lives and property.

Gary S. Keith
Chair, Home Fire Sprinkler Coalition Board of Directors

ABSTRACT

The present study examines the relationship of automatic fire sprinkler technology to environmental sustainability. The work includes the evaluation of risk factors, such as fires, on the total lifecycle carbon emissions of a typical single- or two-family home. Additionally, an experimental quantification of the environmental benefits achieved by the use of automatic fire sprinklers was conducted.

Large-scale fire tests were conducted using identically constructed and furnished residential living rooms. In one test, fire extinguishment was achieved solely by fire service intervention, and in the other, a single residential automatic fire sprinkler was used to control the fire until final extinguishment was achieved by the fire service. Comparisons of the total greenhouse gas production, quantity of water required to extinguish the fire, quality of water runoff, potential impact of wastewater runoff on groundwater and surface water, and mass of materials requiring disposal between the two tests were made.

The results show that in addition to providing life safety and limiting property damage, the use of automatic fire sprinklers is a key factor in achieving sustainability.

ACKNOWLEDGEMENTS

This project would not have been successful without the efforts and contributions of numerous individuals. The authors would like to thank Mr. Gary Keith, Ms. Peg Paul, and the entire board of directors of the nonprofit Home Fire Sprinkler Coalition (HFSC) who worked in partnership with FM Global to define the scope and objectives of this project. The input from the board members in planning the testing was greatly appreciated.

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A special thanks to Mr. Wayne Milette, and all of the firefighters at the Research Campus, along with Mr. Dana Haagensen of the Massachusetts State Fire Marshal's Office, for their input and consultation on appropriate firefighting techniques.

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NOMENCLATURE

Symbol	Definition	Units
A	Average Area of a Residence	m^2
$ACE_{embodied}$	Annualized Embodied Carbon Emissions	$kg_{CO_2}/year$
$ACE_{operation}$	Annualized Carbon Emissions Associated with Normal Operations	$kg_{CO_2}/year$
$ACE''_{operation}$	Annualized Carbon Emissions Associated with Normal Operations per Unit Area	$\frac{kg_{CO_2}}{(m^2 - year)}$
$CE_{construction}$	Carbon Emissions Associated with Construction Activities	kg_{CO_2}
$CE_{decommissioning}$	Carbon Emissions Associated with Decommissioning Activities	kg_{CO_2}
$CE_{embodied}$	Embodied Carbon Emissions	kg_{CO_2}
$CE''_{embodied}$	Embodied Carbon Emissions per Unit Area	kg_{CO_2}/m^2
CE_{fire}	Carbon Emissions Associated with a Fire Event	kg_{CO_2}
$CE_{replacement}$	Carbon Emissions Associated with Reconstruction	kg_{CO_2}
$CO_{2,equivalent}$	Equivalent Mass of Carbon Dioxide for a Gas	kg_{CO_2}
e_{CO_2}	Mass of CO_2 generated per Unit Mass of Fuel Burned	kg_{CO_2}/kg_{fuel}
F_b	Fraction Burned	--
f_f	Frequency of Residential Fires	Fires/year
F_r	Fraction Replaced	--
GWP_{gas}	Global Warming Potential of a Gas	--
LCE	Lifecycle Carbon Emissions	kg_{CO_2}
$LCE_{operation}$	Lifecycle Carbon Emissions Associated with Normal Operations	kg_{CO_2}
LCE_{risk}	Lifecycle Carbon Emissions Due to Fire Risk	kg_{CO_2}
LT	Lifetime of the Structure	Years
m''_f	Fuel Load per Unit Area	kg/m^2

m_{gas}	Mass of Greenhouse Gas	kg
RF_{fire}	Fraction of Total Carbon Emissions due to Fire Risk	%
$RF_{fire,AS}$	Fraction of Total Carbon Emissions due to Fire Risk with Automatic Sprinklers	%
TCE	Total Lifecycle Carbon Emissions	kg_{CO_2}
$TCE_{construction}$	Total Carbon Emissions Associated with Construction Activities	kg_{CO_2}

1 INTRODUCTION AND BACKGROUND

1.1 PROBLEM STATEMENT

Past research in residential automatic fire sprinkler technology has identified sprinkler characteristics necessary to provide reliable life safety in residential occupancies [1,2,3]. This research further resulted in a standardization of the requirements for reliably certifying and installing residential hardware to meet desired performance requirements [4,5,6,7,8,9,10]. The present study treats a relatively new issue: the relationship of residential sprinkler technology to environmental sustainability.

1.2 BACKGROUND

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 [11]. 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 [12]. Hall [13] 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., Reference 11 and 14). 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 [15,16,17]. The United States Fire Administration (USFA) has supported the position that: “All homes should be equipped with both smoke alarms and automatic fire sprinklers” [18]. 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 [19]. However, only about 400 out of the thousands of jurisdictions in the U.S. were mandating the installation of residential sprinklers in 2008 [18].

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, Gritzo *et al.* [20] 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.

1.2.1 Methodology for Estimating LCE 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 [21]. 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.* [20] 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.

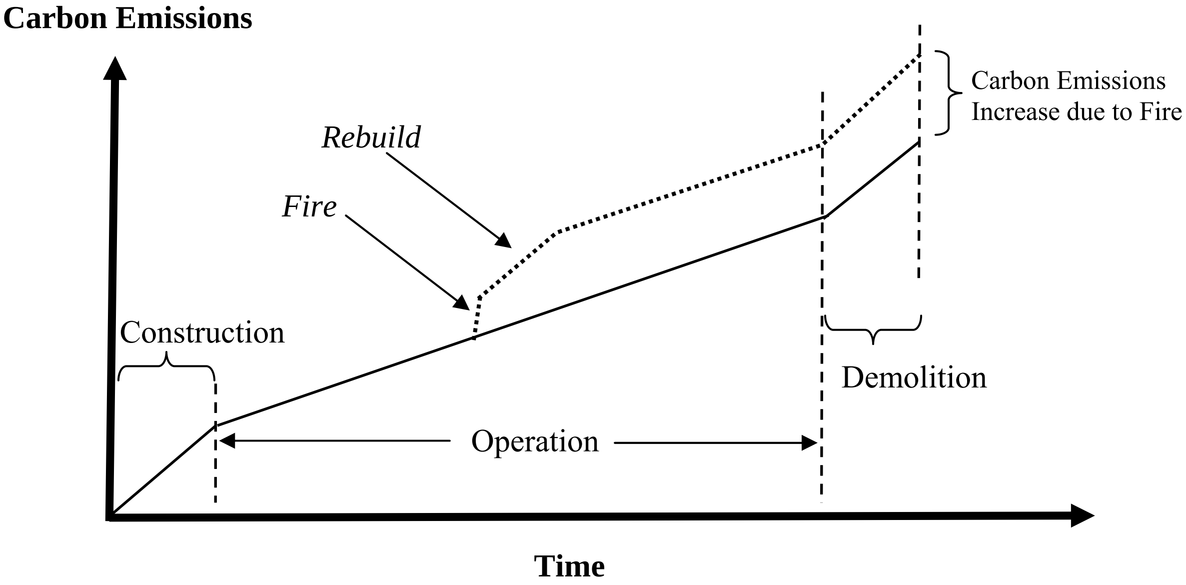

Figure 1: Contribution of risk factors to total lifecycle carbon emissions.

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

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

$$TCE = CE_{construction} + LCE_{operation} + CE_{decommissioning} \qquad (1)$$

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

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

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 [22].

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

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

Note that the embodied emissions are estimated in the literature on a per unit area basis (see e.g., Reference 22) and can be annualized over the lifetime, LT, of a facility:

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

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

$$CE_{fire} = F_b \cdot m''_f \cdot e_{CO_2} \cdot A \tag{5}$$

and

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

where F_b is the fraction of material burned; $m_f^{''}$ is the total mass of combustible material per unit area; e_{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_{risk}. Evaluating the risk on a statistical basis over the lifetime of the structure requires knowledge of the frequency of fires, f_f. Thus,

$$LCE_{risk} = f_f \cdot LT \cdot \left(CE_{fire} + CE_{replacement}\right) \tag{7}$$

A risk factor, RF_{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

$$\begin{aligned} RF_{fire} &= \frac{LCE_{risk}}{TCE} = \frac{f_f \cdot LT \cdot \left(CE_{fire} + CE_{replacement}\right)}{TCE} \\ &= f_f \cdot LT \cdot \left(\frac{F_b \cdot m_f^{''} \cdot e_{CO_2} \cdot A}{TCE} + \frac{F_r \cdot CE_{embodied}}{TCE} \right) \end{aligned} \quad . \tag{8}$$

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

1.2.2 Effect of Automatic Sprinklers on LCE

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.

1.2.3 Quantification of TCE in One- and Two-Family Dwellings

Values used in the present study 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 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 to 3 is quite complex given the diversity of construction 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.* [23] 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.

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 (yr)	50	50
m_f	Fuel Density (kg/m^2)	13.2	21
e_{co2}	Mass of CO_2 Generated per Unit Mass of Fuel Burned (kg/kg)	3.0	3.0
TCE	Total Lifecycle Carbon Emissions (kg CO_2)	278,000	278,000
$CE_{embodied}$	Total Embodied Carbon Emissions (kg CO_2)	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

Estimates of annual greenhouse emissions characterized as $ACE_{operation}$ and $ACE_{embodied}$ are taken from Norman *et al.* [24] 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.* [24] 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 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 $ACE''_{operation}$ of $33.9\ kg_{CO_2}/(m^2 - year)$.[*]

To calculate $LCE_{operation}$ the lifetime and area of the dwelling need to be taken into account. Following Norman *et al.* [24], 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 [12, 25, 26, 27, 28]. The data are summarized in Table 2. The average area of these dwellings was 164 m^2 (1,765 ft^2). Using these values the $ACE_{operation}$ is equal to 5,560 kg_{CO_2} per year and $LCE_{operation}$ is equal to 278,000 kg_{CO_2}.

Table 2: Home and Fire Statistics from 1999 to 2008

	Home Statistics		Fire Loss Statistics		Loss Estimates	
Year	**Average Size m^2 (ft^2)**	**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**

To evaluate the embodied carbon, Norman *et al.* [24] 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

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[*] Note that gases other than CO_2 are considered in terms of 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 [24].

and metal frames), drywall, 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.* [24] estimated that the average equivalent annual embodied greenhouse gases per unit area is $7.4\ kg_{CO_2} / \left(m^2 - year\right)$. For a 50-year lifetime and a typical area of 164 m^2 (1,765 ft^2), the total embodied carbon emissions, $CE_{embodied}$, is 60,680 kg_{CO_2}.

No effects corresponding to decommissioning were discussed by Norman *et al.* [24]. Gritzo *et al.* [20] reported that, for office buildings, the total embodied fraction of total carbon emissions were on the order of 15% to 20%. As the ratio of $CE_{embodied} \big/ \left(CE_{embodied} + LCE_{operation}\right)$ in the present analysis is 18%, no further additions to the embodied carbon emissions are considered here.

1.2.4 Effect of Fire on LCE in Homes

Some of the parameters needed to estimate LCE_{risk} (Equations 5-7) can be obtained from NFPA [29] and AHS [12, 25-28] 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 [12, 25-28] 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 [14]. 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_{CO_2}. Davoodi [30] reports fuel loads of 19.0, 13.2, 21.0, 17.6, and 15.6 kg/m^2 for living rooms, family rooms, bedrooms, dining rooms, and kitchens respectively. For the present analysis the minimum, i.e., 13.2 kg/m^2, and maximum, i.e., 21.0 kg/m^2, values will be used as the bounding cases.

The carbon dioxide released per unit of material burned, e_{CO_2}, is taken as 3.0 kg/kg based upon combustion analysis and flammability data from Tewarson [31].

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 percent for readying a space for reconstruction" [32]. 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%.

1.2.5 Improved Sustainability with Automatic Sprinklers

The installation of automatic sprinklers is expected to reduce LCE_{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 [14] provide a significant record of the effect of residential sprinklers on fire fatalities and property damage.[†] 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.

[†] Hall [13] 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" [13].

1.3 OBJECTIVES

The objective of the present study was to quantify the reduction in the environmental impact via the use of automatic fire sprinklers. To meet the objective, large-scale fire tests were conducted using identically constructed and furnished residential living rooms.[‡] In the non-sprinklered test, fire extinguishment was achieved only by fire service intervention, while in the sprinklered test a single residential sprinkler was used to control the fire until final extinguishment was achieved by the fire service. In the tests, the fire service initiated water application 10 minutes after the fire was detected.

Quantification of the environmental benefit of automatic fire sprinklers was based on comparisons between the sprinklered and non-sprinklered tests including total greenhouse gas production, quantity of water required to extinguish the fire, quality of water run-off, potential impact of wastewater runoff on groundwater and surface water, and mass of materials requiring disposal.

[‡] The primary analysis in this report is based on two fully instrumented tests, referred to as sprinklered and non-sprinklered. An additional, non-sprinklered test was conducted as a demonstration test. This test is referred to as non-sprinklered (b) and only used to supplement the water analysis.

2 FIRE TEST SETUP AND PROCEDURES

2.1 FACILITY

Testing was conducted under the 20-MW calorimeter in the Large Burn Laboratory (LBL) of the Fire Technology Laboratory located at the FM Global Research Campus in West Glocester, Rhode Island. The LBL measures 43 m (140 ft.) by 73 m (240 ft.) by 20.4 m (67 ft.) high and consists of three test locations: the north and south movable ceilings, and the 20-MW calorimeter. An illustration of the Large Burn Laboratory is shown in Figure 2. A separate air emission control system (AECS) is provided for each test location. The 20-MW calorimeter consists of a 10.7 m (35 ft.) diameter inlet that tapers down to a 3.05 m (10 ft.) diameter duct. The inlet to the calorimeter is at an elevation of 11.3 m (37 ft.) from the floor. Gas concentration, velocity, temperature, and moisture measurements are made within the duct downstream of an orifice. Beyond the measurement location, the exhaust duct connects to a wet electrostatic precipitator (WESP) prior to cleaned gases venting to the atmosphere. All tests were conducted with the ventilation rate set to 94.4 m^3/s (200,000 scfm).

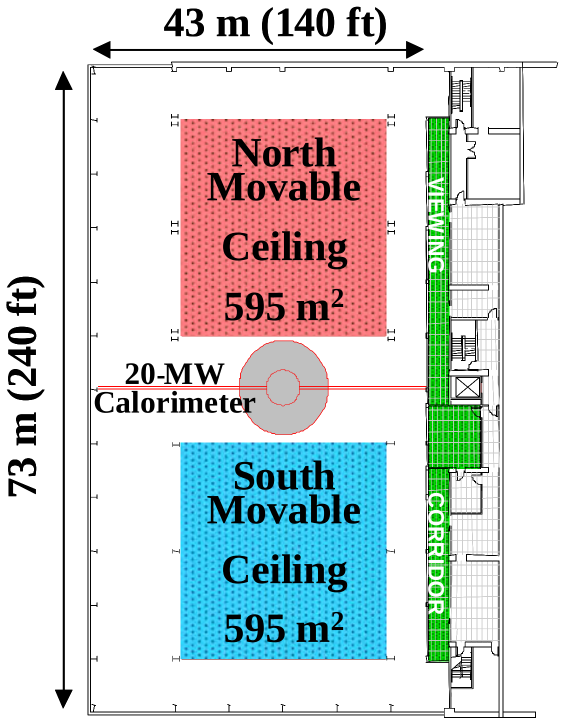

Figure 2: Illustrations of the large burn laboratory test sites.

The rooms, described in Section 2.2.1, were positioned under the 20-MW calorimeter as shown in Figure 3. The room centerline was offset relative to the calorimeter bell centerline by approximately 1.1 m (3.75 ft.) in the north-south direction to ensure that the gases exiting the room were collected within the calorimeter.

The demonstration test, non-sprinklered (b), was conducted with the room located under the north movable ceiling. The room was offset to the south-east corner of the ceiling and the movable ceiling was set to a height of 12.2 m (40 ft.).

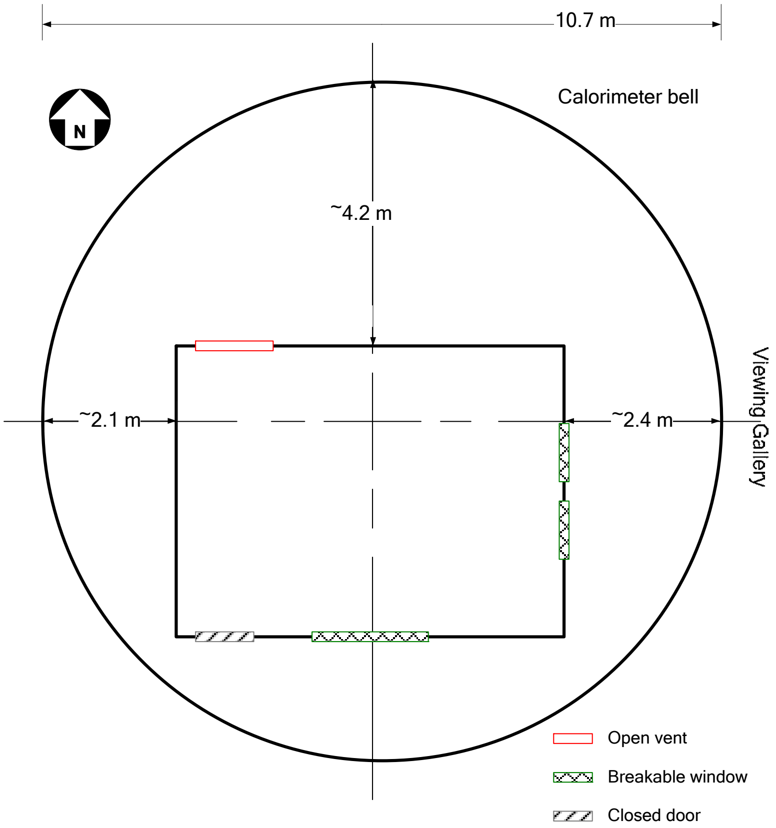

Figure 3: Room position relative to 20-MW calorimeter.

2.2 TEST CONFIGURATION

2.2.1 Living Room Construction

The living room was constructed by an outside contractor, R&R Wolf Construction, Inc. of North Attleboro, Massachusetts, using standard industry practices. The room measured 4.6 m (15 ft.) wide by 6.1 m (20 ft.) long, and had a 2.4 m (8 ft.) high ceiling. To simulate a single room of a larger house, two of the walls were considered exterior walls and included windows and an exterior door. The other two walls were considered interior house walls, with one being solid with no openings and the other having a 1.2 m wide x 2.1 m tall (4 ft. x 7 ft.) archway. Figure 4, Figure 5, and Figure 6 present illustrations of the room construction, location of the room penetrations, and a description of common construction terms.

The main deck of the enclosure had interior dimensions of 4.6 m x 6.1 m (15 ft. x 20 ft.) and was constructed with 50.8 mm x 203 mm (2 in. x 8 in.) lumber. The perimeter decking joist boards forming the box frame for the floor were constructed with 4.9 m and 6.7 m (16 ft. and 22 ft.) boards. These boards were doubled up along the perimeter and cut to provide exterior dimensions of 4.9 m x 6.4 m (16 ft. x 21 ft.). The frame was then filled with kiln dried #2 grade spruce boards spaced 406-mm (16-in.) on center, which were supported by joist hangers at each end. The framed deck was then covered with 19.1 mm (3/4 in.) CDX fir tongue-and-groove plywood flooring.

Figure 4: Room exterior walls (south and east walls).

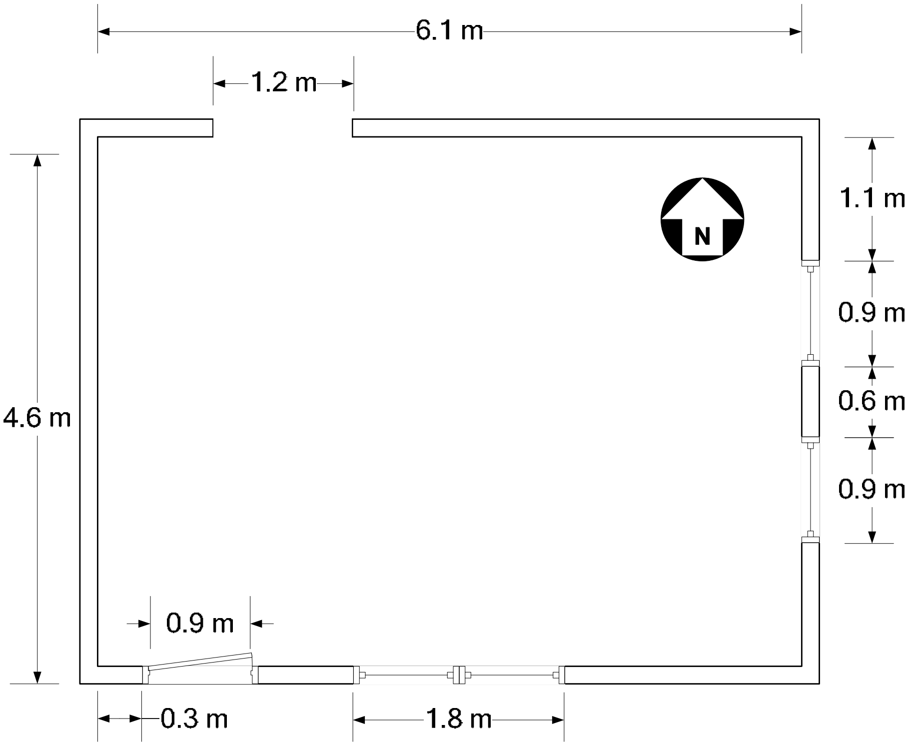

Figure 5: Location of room exterior door, archway, and windows.

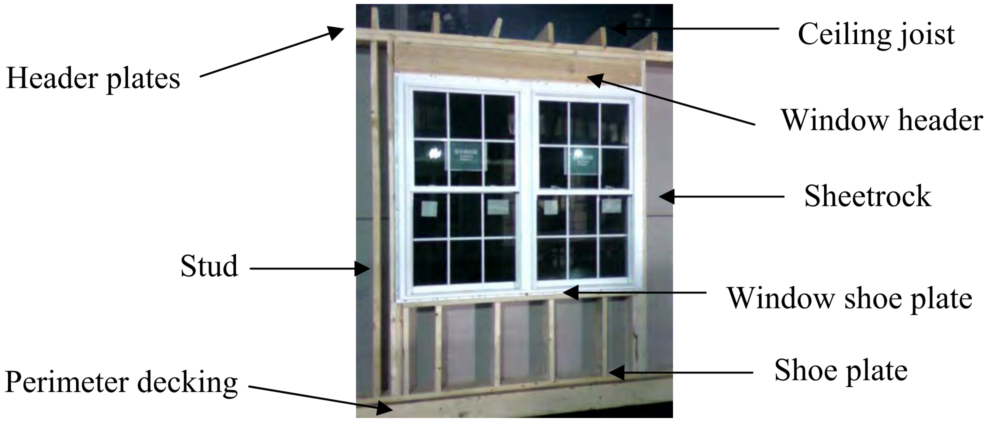

Figure 6: Room frame construction.

The enclosure sides consisted of two walls having interior dimensions of 4.6 m x 2.4 m (15 ft. x 8 ft.) and two walls with interior dimensions of 6.1 m x 2.4 m (20 ft. x 8 ft.) that were of consistent construction using 50.8 mm x 152.4 mm (2 in. x 6 in.) lumber. A shoe plate and two header plates constructed of 4.9 m (16 ft.) long boards were used for the shorter walls and 6.4 m (21 ft.) long boards for the longer walls. The walls were then filled with 2.4 m (7 ft. 8 in.) studs spaced 406-mm (16-in.) on center. The stud pattern was disrupted to allow for windows and door/archway openings. The window openings included a double shoe plate and single header, while the door and archway openings had only a single header. The inside walls were finished with 15.9 mm (5/8 in.) fire rated sheetrock that was taped, spackled, and painted a tan color.

The ceiling was constructed using 50.8 mm x 152.4 mm (2 in. x 6 in.) lumber spaced 406-mm (16-in.) on center. Since no perimeter boxing was necessary, the joists were towed-in to the wall header plates. To support the ceiling sheetrock, 25.4 mm x 76.2 mm x 4.9 m (1 in. x 3 in. x 16 ft.) spruce strapping, spaced 406-mm (16-in.) on center, was installed perpendicular to the ceiling joints. The ceiling was finished with 19.9 mm (5/8 in.) fire rated sheetrock that was taped, spackled, and painted bright white.

The two exterior walls and the ceiling were insulated using R13 and R19 fiberglass insulation respectively. The main deck also included *Alias* (Style 2760) carpeting with an Endure®Plus backing from J&J Industries. Carpet specifications taken from the manufacturer's website are provided in Table 3.

Table 3: Manufacturer's Carpet Specifications (J&J Industries' website)

Alias Style (2760)	
Yarn	100% Nylon: Encore® SD Ultima® (with recycled content) Bulked Continuous Filament
Dye Method	Solution Dyed
Surface Texture	Level Loop
Pattern Repeat	N/A
Gauge	1/8 (3.15 rows/cm)
Tufted Stitches Per Inch	8.5 (3.35 stitches/cm)
Yarn Weight	882 grams/m^2 (26 oz./yd^2)
Finished Pile Thickness	3.05 mm (0.120 in.) (ASTM D-418)
Density	7,800
Weight Density	202,800
Secondary Backing	Endure® PLUS
Special Treatments	ProTex® Fluorochemical
Width	3.66 m (12 ft.)
Flammability	Class 1
Smoke	Less Than 450 flaming
Static Generation	Less than 30 kV (AATCC-134)
ADA Compliance	Compliant For Accessible Routes

The windows installed in the room were Kasson & Keller, Inc., double hung, replacement windows measuring 0.9 m by 1.47 m (3 ft. by 4 ft. 10 in.). The windows were constructed of PVC frames with double-pane glass. The total weight of the windows was 23.6 kg (52 lb.) and the weight of the frame alone was 9.1 kg (20 lb.). The exterior door was steel clad with an insulated core and had dimensions of 0.9 m by 2.0 m (36 in. by 80 in.). The door had a 0.51 m wide by 0.9 m tall (20 in. by 36 in.) single pane window. The exact locations of the exterior door and windows are shown in Figure 4, and each was installed with a 203 mm (8 in.) sill.

2.2.2 Room Furnishings

Each of the rooms was furnished with the items listed in Table 4. The items are grouped into four categories: primary fuel items, secondary fuel items, decorative items, and ignition package. Each category of items will be discussed in detail in Sections 2.2.2.1 to 2.2.2.4. A schematic of the room with relative positions of the primary and secondary fuel items, and the ignition package is presented in Figure 7.

Table 4: Room Furnishings

Quantity	Item
Primary Fuel Items	
1	Recliner
1	Sofa
1	Loveseat
Secondary Fuel Items	
1	Coffee Table
1	Console Table
1	End Table
1	TV Stand with Shelves
2	Bookcase
1	37-inch LCD Television
Decorative Items	
1	Ceramic Table Lamp
1	Picture Frame (330 mm x 432 mm) (13 in. x 17 in.)
6	Picture Frame (127 mm x 178 mm) (5 in. x 7 in.)
1	Mirror (400 mm x 972 mm) (15 ¾ in. x 38 ¼ in.)
1	Poster Frame (610 mm x 914 mm) (24 in. x 36 in.)
1	Wall Clock (248 mm) (9 ¾ in. Diameter)
13.5 lbs	Magazines
1	Alarm Clock
8	CD Box with Lid
5	Hardcover Books
1	Plant Pot
6	Drapes
Ignition Package	
1	Magazine Rack
3	Newspapers

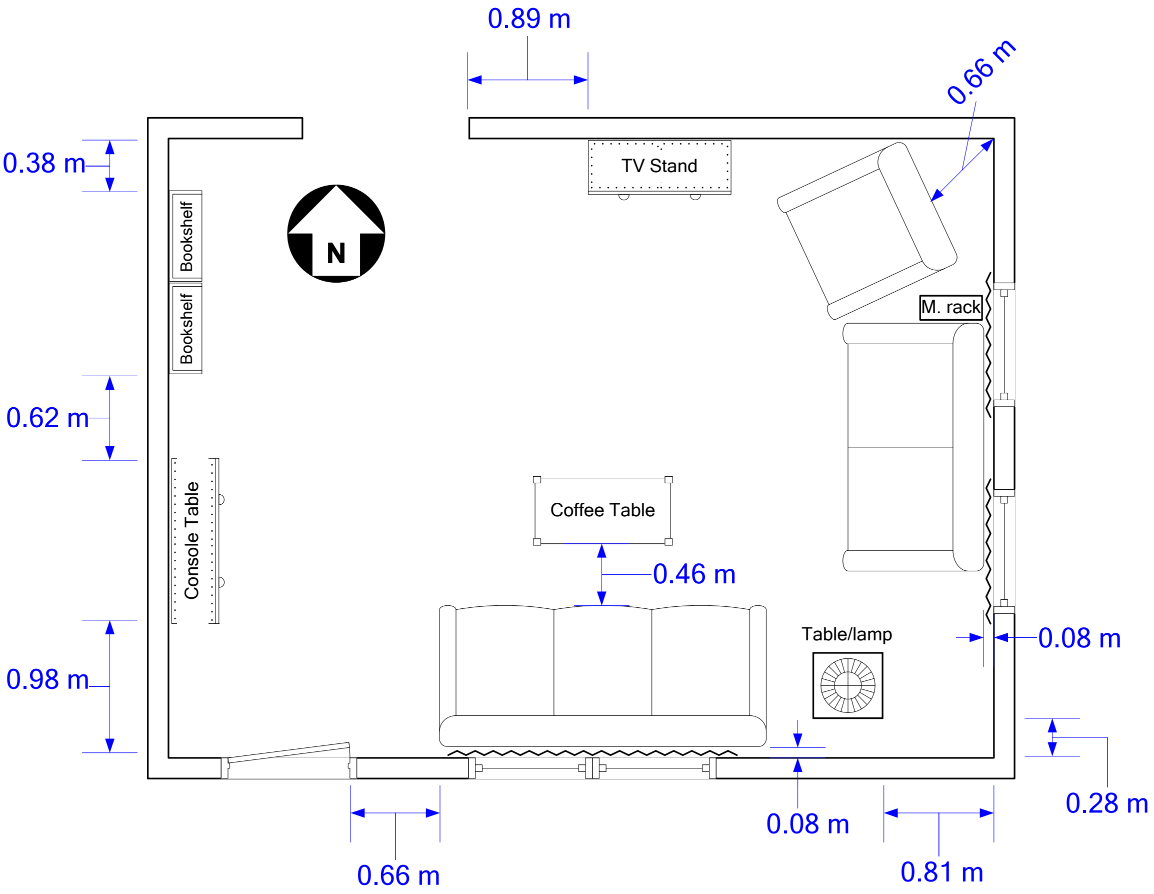

Figure 7: Furnishing positions and locations within the enclosure.

2.2.2.1 Primary Fuel Items

The primary fuel items consisted of a "Big Easy" Recliner and a "Kick Back" Sofa and Loveseat. The loveseat and sofa came with eight decorative throw pillows that are considered part of the package as shown in Figure 8. The dimensions, total weight, and major combustible materials for each item are listed in Table 5. The weights of the sofa and loveseat include four throw pillows.

Table 5: Primary Fuel Items

Item	Dimensions (L x D x H) m x m x m (in. x in. x in.)	Total Weight kg (lb.)	Principle Combustible Material
Big Easy Recliner	0.99 x 1.12 x 1.04 (39 x 44 x 41)	44.5 (98.1)	Urethane foam, wood frame
Kick Back Sofa	2.41 x 1.04 x 0.97 (95 x 41 x 38)	69.9 (154.1)	Polyurethane foam, wood frame
Kick Back Loveseat	1.83 x 1.04 x 0.97 (72 x 41 x 38)	56.9 (125.5)	Polyurethane foam, wood frame

Figure 8: Images of the "Big Easy" recliner and "Kick Back" sofa and loveseat combination (from store website, not to scale).

2.2.2.2 Secondary Fuel Items

The total mass, dimensions, and combustible material for each of the secondary fuel items are listed in Table 6. Images of each item, taken from the retail store websites, are shown in Figure 9 and Figure 10.

Table 6: Secondary Fuel Items

Item	Dimensions (L x D x H) m x m x m (in. x in. x in.)	Total Weight kg (lb.)	Principle Combustible Material
Mission Natural Coffee Table	1.0 x 0.5 x 0.4 (40.5 x 20 x 16.5)	15.1 (33.3)	Rubberwood
Mission Natural Console Table	1.2 x 0.4 x 0.8 (48 x 15.25 x 30)	15.6 (34.4)	Rubberwood
Mission Natural End Table	0.5 x 0.48 x 0.5 (20.1 x 19 x 20.1)	8.3 (18.3)	Rubberwood
TV Stand with Shelves	1.1 x 0.44 x 0.5 (41.5 x 17.25 x 20)	21.2 (46.7)	Laminated composite wood
Kilby Bookcase	0.67 x 0.24 x 1.9 (26.4 x 9.5 x 76.4)	18.5 (40.8)	Laminated composite wood
37-inch LCD Television	0.9 x 0.2 x 0.67 (36.75 x 9.5 x 26.5)	16.7 (36.8)	Unexpanded plastic

Figure 9: Images of secondary fuel items: coffee, console, end tables, and bookcase (from store website, not to scale).

Figure 10: Images of secondary fuel items: 37-inch LCD TV and TV stand (from store website, not to scale).

2.2.2.3 Decorative Items

The decorative items listed in Table 4 were arranged throughout the room as shown in Figure 11. Due to the low fire load contribution of these items to the overall heat release rate, a detailed breakdown of the individual components has not been made. The primary combustible materials were cotton, soft woods, polystyrene and polypropylene plastic, cardboard, and paper. The total weight of all of the decorative materials was 26.7 kg (59 lb.) and is based on the listed shipping weights.

Figure 11: Orientation of decorative items on console table, bookcases, and coffee table.

2.2.2.4 Ignition Package

The fire was initiated in a magazine rack filled with three rolled up newspapers (see Figure 12a), which was positioned adjacent to the loveseat as shown in Figure 12b. The dimensions of the magazine rack were 338 mm x 152 mm x 279 mm (13.3 in. x 6 in. x 11 in.). The magazine rack was constructed of medium density fiberboard and weighed 1.7 kg (3.75 lb.). The newspapers were ignited using a propane torch.

(a) (b)

Figure 12: (a) Ignition source and (b) Magazine rack relative to loveseat and curtain.

2.3 FIREFIGHTING

Fire control and suppression was achieved in the non-sprinklered test by manual fire service intervention only; in the sprinklered test, a single residential sprinkler was used to control the fire until final extinguishment was achieved by the fire service.

2.3.1 Sprinkler Protection

A single FM Approved Tyco Fire Suppression & Building Products recessed residential sprinkler (TY4234), Figure 13, was installed at the ceiling center within the living room. The sprinkler was equipped with a fast-response fusible link, which had a temperature rating of 68°C (155°F). A nominal operating pressure of 1.3 bar (19.0 psig) was used, resulting in a 4.1 mm/min (0.1 gpm/ft^2) water density, in accordance with FM Global Property Loss Prevention Data Sheet 2-5, *Installation Guidelines for Automatic Sprinklers in Residential Occupancies* [10].

Figure 13: Tyco Fire Suppression & Building Products Residential Sprinkler (TY4234).

2.3.2 Fire Service Response Tactics

In all of the tests, the fire service response was initiated via smoke detector activation. Upon activation a 10-minute response clock was started. The 10-minute delay accounted for fire service notification, dispatch, arrival, and setup and was based on nationally accepted standards, including NFPA 1710 [33], NFPA 1720 [34], and other published literature [35]. NFPA 1710, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments*, Section 5.2.4.1.1 states that “The fire department's fire suppression resources shall be deployed to provide for the arrival of an engine company within a 240-second travel time to 90 percent of the incidents” [33]. For volunteer fire departments, NFPA 1720, *Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Volunteer Fire Departments*, states that for structural firefighting of a “low-hazard occupancy such as a 2000 ft^2 (186 m^2), two-story, single-family home without a basement” [34] in urban areas shall be 9 minutes, 90% of the time, and in rural areas the response time increases to 14 minutes, 80% of the time (see Table 7). Furthermore, Section 4.3.3 states “Upon assembling the necessary resources at the emergency scene, the fire department shall have the capability to safely commence an initial attack within 2 minutes 90 percent of the time” [34].

Table 7: Table 4.3.2 Staffing and Response Time taken from NFPA 1720

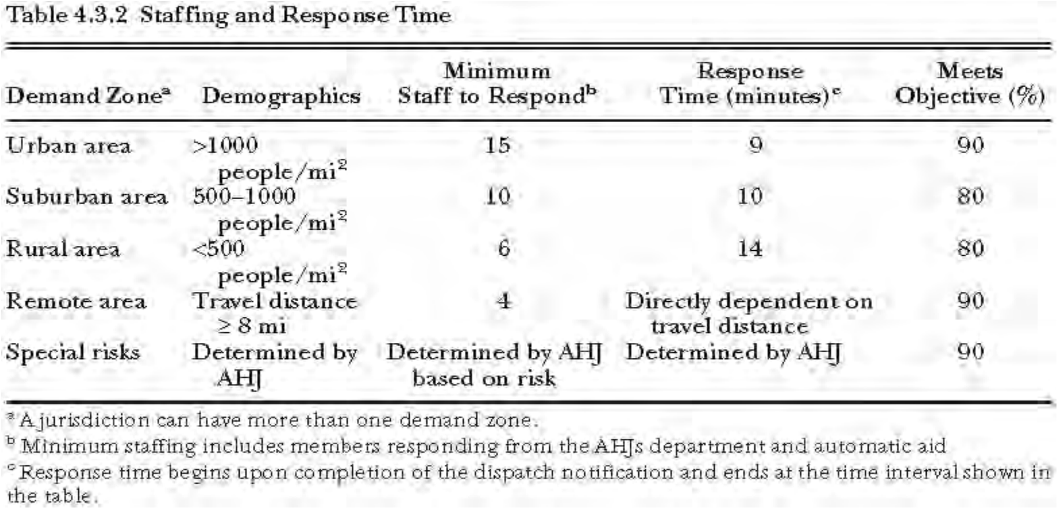

Table 4.3.2 Staffing and Response Time

Demand Zone[a]	Demographics	Minimum Staff to Respond[b]	Response Time (minutes)[c]	Meets Objective (%)
Urban area	>1000 people/mi^2	15	9	90
Suburban area	500–1000 people/mi^2	10	10	80
Rural area	<500 people/mi^2	6	14	80
Remote area	Travel distance ≥ 8 mi	4	Directly dependent on travel distance	90
Special risks	Determined by AHJ	Determined by AHJ based on risk	Determined by AHJ	90

[a] A jurisdiction can have more than one demand zone.
[b] Minimum staffing includes members responding from the AHJs department and automatic aid
[c] Response time begins upon completion of the dispatch notification and ends at the time interval shown in the table.

A publication by the Illinois Fire Inspectors Association states that the average time for firefighters to open hose nozzles after a fire is detected is 10 minutes (see Figure 14).

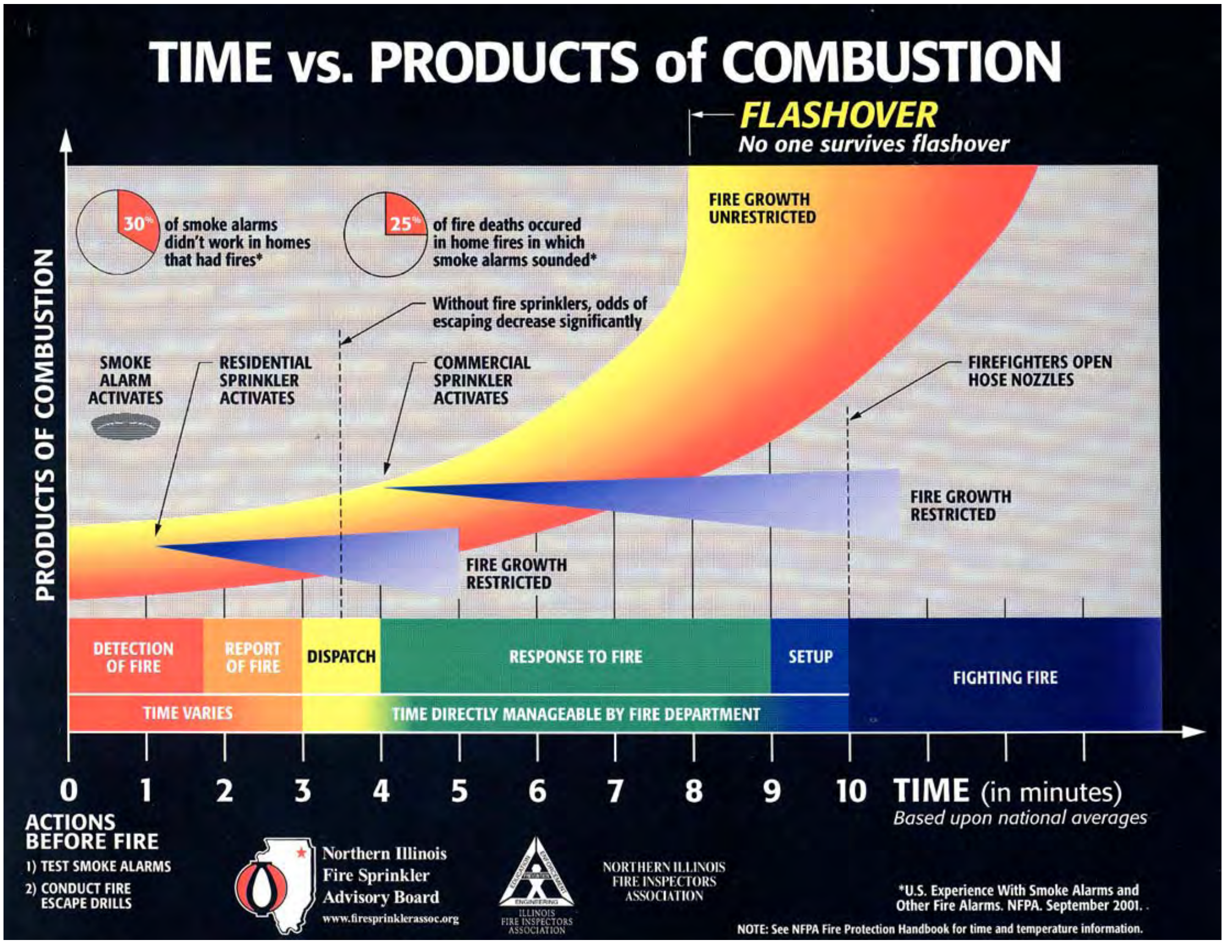

Figure 14: Timeline of fire development versus typical fire service response (taken from http://www.illinoisfireinspectors.org/ifia.htm).

Firefighting activities were in compliance with recognized fire service attack standards including NFPA and Oklahoma State University's "*Essentials of Fire Fighting and Fire Department Operations*" [35].

NFPA 1710, Section 5.2.4.2.2 recommends "establishment of an effective water flow application rate of 300 gpm from two handlines, each of which has a minimum flow rate of 100 gpm" [33]. This is for an "initial full alarm assignment to a structure fire in a typical 2000 ft^2 two story single-family dwelling" [33].

To comply, two 30.5-m (100-ft.) long, 1 ¾ in. attack handlines with Task Force Tip Thunder Fog Nozzles, model #FTS200, set at 360 lpm (95 gpm), were staffed with two trained firefighters each. A constant 6.9 bar (100 psi) nozzle pressure was supplied. For safety reasons, a third identical attack line was staffed and supported but not utilized.

During the non-sprinklered test, firefighting tactics as recommended by Reference 35 were closely followed. A realistic and aggressive interior attack occurred once deemed practical as a result of a direct exterior attack. This was executed by straight stream water application to obtain maximum cooling and darkening down of visible fire immediately at the 10-minute fire interval.

Interior entry was gained as soon as possible and a short period of 40-60 degree fog spray was applied to obtain maximum cooling and fire extinguishment. Proper ventilation had occurred as the windows and door had already burned out and fallen out of the structure. A straight stream was then applied to conduct and pursue final extinguishment.

In the sprinklered test, only an interior attack was required because of the sprinkler activation and subsequent fire control. At the 10-minute mark, firefighters approached the room, pried open the exterior door and used a single fire hose line to attack the fire. The second attack line provided backup only. A short period of 40-60 degree fog spray was applied to obtain maximum cooling and fire extinguishment. Final extinguishment occurred through direct application of a straight stream.

2.4 INSTRUMENTATION

Scientific measurements internal and external to the room were made in each test. Each room was instrumented with ceiling and elevation thermocouples, heat flux gages, and gas measurements. All instrumentation was calibrated in accordance with ISO/IEC 17025-2005 [36]. The instrumentation layout within the room is shown in Figure 15. The following sections describe each of the instruments used in the tests.

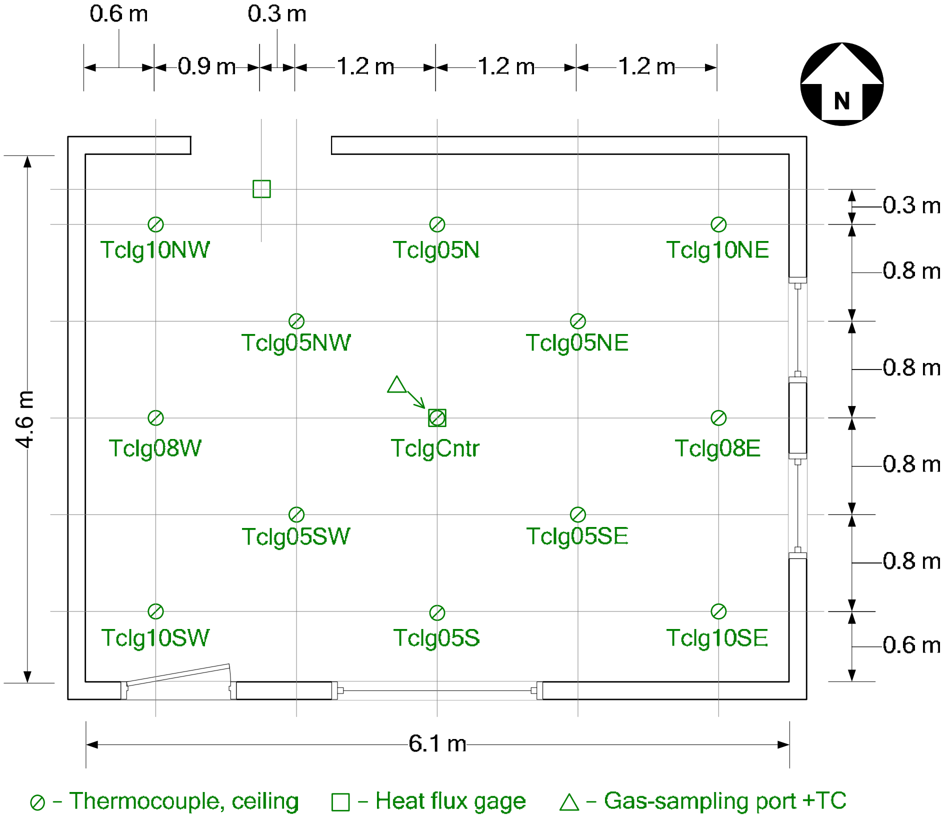

Figure 15: Instrumentation layout within the room.

2.4.1 Gas Analysis Measurements within the Duct

Multiple gas measurements were made, within the 20-MW calorimeter duct, to evaluate the products of combustion generated during the fire tests. The data was used to quantify the reduction in greenhouse gases and pollutants between the sprinklered and non-sprinklered tests, and to determine the chemical heat release rate and total energy released.

2.4.1.1 FM Global Instrumentation

Continuous real-time gas measurements within the 20-MW calorimeter duct include oxygen, carbon monoxide, carbon dioxide, and total hydrocarbons. A Rosemount Analytical MLT series analyzer, model MLT-4T-IR-IR-PO2, was used to measure carbon monoxide, carbon dioxide and oxygen. The analyzer comprises infrared sensors to measure carbon monoxide and carbon dioxide, and a paramagnetic sensor to measure oxygen. Total hydrocarbons were measured, as equivalent methane, using a Rosemount Analytical analyzer, model NGA2000 FID2. The analyzers were set to operate with ranges indicated in Table 8.

Table 8: FM Global Gas Analyzer Measurement Ranges (Duct)

Species	Range
Carbon Dioxide (ppm)	0 - 25,000
Carbon Monoxide (ppm)	0 - 5,000
Oxygen (%)	0 - 21
Total Hydrocarbons (ppm)	0 - 5,000

2.4.1.2 External Instrumentation

Standard FM Global measurements within the duct were supplemented by an outside contractor, Air Pollution Characterization and Control, Ltd. (APCC), retained by Woodard & Curran. Measurements included the following:

- Criteria Pollutants
- Volatile Organic Compounds (VOCs)
- Greenhouse Gas Pollutants
- Particulate Matter
- Heavy Metals
- Semi-Volatile Organic Compounds (SVOCs)
- Other Organic and Inorganic compounds
- Total Hydrocarbons
- Oxygen

Full details on the measurement techniques and instrumentation are reported in Reference 37.

2.4.2 Gas Analysis Measurements within the Room

Continuous real-time gas samples for measurement of carbon monoxide, carbon dioxide, oxygen, and total hydrocarbons were obtained at the center of the room at a 1.5 m (5 ft.) elevation. For the sprinklered test a Rosemount Analytical MLT series analyzer, model MLT-4T-IR-IR-PO2, was used to measure carbon monoxide, carbon dioxide, and oxygen. The analyzer comprises infrared sensors to measure carbon monoxide and carbon dioxide, and a paramagnetic sensor to measure oxygen. Total hydrocarbons were measured as equivalent methane, using a Rosemount

Analytical analyzer, model NGA2000 FID2. The analyzers were set to operate with ranges indicated in Table 9. For the non-sprinklered test, units were rented from Clean Air Instrument Rental of Palatine, Illinois. The analyzers used were Fuji Electric Systems Co., Ltd. model ZRH carbon monoxide analyzer, Horiba, Ltd. model VIA-510 carbon dioxide analyzer, J.U.M. Engineering GmbH model 3-300A total hydrocarbon analyzer, and a Servomex Ltd. model 1420C oxygen analyzer. The analyzers operated within the ranges indicated in Table 9.

Table 9: Gas Analyzer Measurement Ranges (Room)

Species	Sprinklered	Non-Sprinklered
Carbon Dioxide (ppm)	0 - 50,000	0 - 250,000
Carbon Monoxide (ppm)	0 - 10,000	0 - 100,000
Oxygen (%)	0 - 21	0 - 25
Total Hydrocarbons (ppm)	0 - 5,000	0 - 100,000

2.4.3 Ceiling and Room Thermocouples

Temperatures under the ceiling were monitored during each test using 13 20-gage Type K bare-bead thermocouples. These thermocouples have a 19-mm (0.75-in.) exposed length of wire. The time response of these thermocouples has been measured[§] and is characterized by an RTI value of 8 ±1 $(\mathrm{m{\cdot}s})^{1/2}$ (14.5 ±1.8 $(\mathrm{ft{\cdot}s})^{1/2}$). The thermocouples were positioned as shown in Figure 15 and the beads were located approximately 76 mm (3 in.) below the ceiling. The 13 thermocouple labels are identified in Figure 15.

An additional thermocouple with the same characteristics as those described above was installed adjacent to the gas sampling location at the center of the room described in Section 2.4.2.

2.4.4 Heat Flux Measurements

Heat flux gages were used to evaluate the heat transfer from the gases near the ceiling to the floor and ceiling. The gages were water cooled Schmidt-Boelter sensors. Three gages were used in each test; two were located on the floor—one at the center of the room and one at the

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[§] H-Z Yu, "Sensitivity of the certified Omega 20-gage thermocouple used at LBL," Email dated June 2, 2008. Also: "RE: Sensitivity of 20-gage TCs," Email dated August 27, 2008.

archway; a third gage was located at the ceiling directly above the one installed on the floor at the archway. The floor mounted gages were installed with the top surface flush with the top of the carpet as shown in Figure 16. The model and maximum measurement value of each gage, at each location, are listed in Table 10.

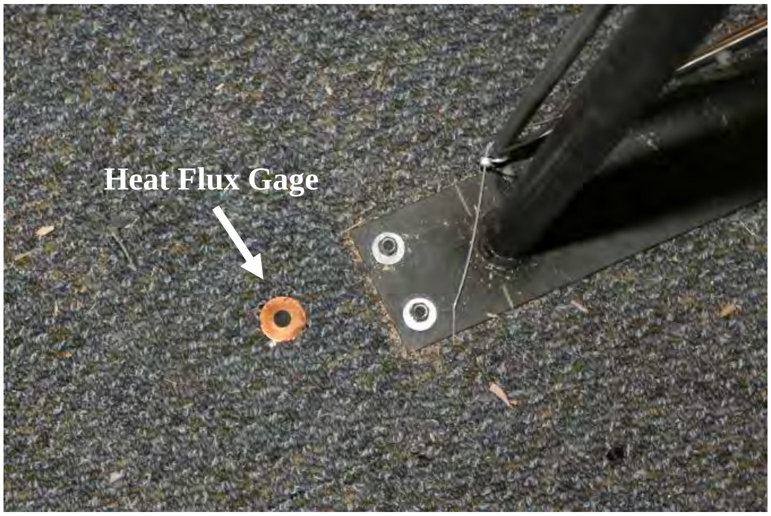

Figure 16: Heat flux gage installation at the floor.

Table 10: Heat Flux Gage Information

Location	Model	Maximum Value
Non-Sprinklered Test		
Floor (center)	64-5SB-20KS	57 kW/m^2 (5 BTU/ft^{2}s)
Floor (archway)	64-5SB-20KS	57 kW/m^2 (5 BTU/ft^{2}s)
Ceiling (archway)	64-15SB-20KS	170 kW/m^2 (15 BTU/ft^{2}s)
Sprinklered Test		
Floor (center)	64-5SB-20KS	57 kW/m^2 (5 BTU/ft^{2}s)
Floor (archway)	64-5SB-20KS	57 kW/m^2 (5 BTU/ft^{2}s)
Ceiling (archway)	64-5SB-20KS	57 kW/m^2 (5 BTU/ft^{2}s)

2.4.5 Smoke Detectors

Each room was instrumented with two smoke detectors, one ionization detector and one photoelectric detector. The ionization detector was a Kidde, Model 0916 (Part Number 440375) and the photoelectric detector was a Kidde, Model PE9 (Part Number 440378).[**] Detector operation was monitored and recorded by connecting the speaker signal to the data acquisition system.

The detectors were installed on the interior wall with the centerline of the detectors 22.9 cm (9 in.) below the ceiling. The photoelectric detector was 20.3 cm (8 in.) inward from the edge of the archway and the ionization detector was 35.6 cm (14 in.) from the edge.

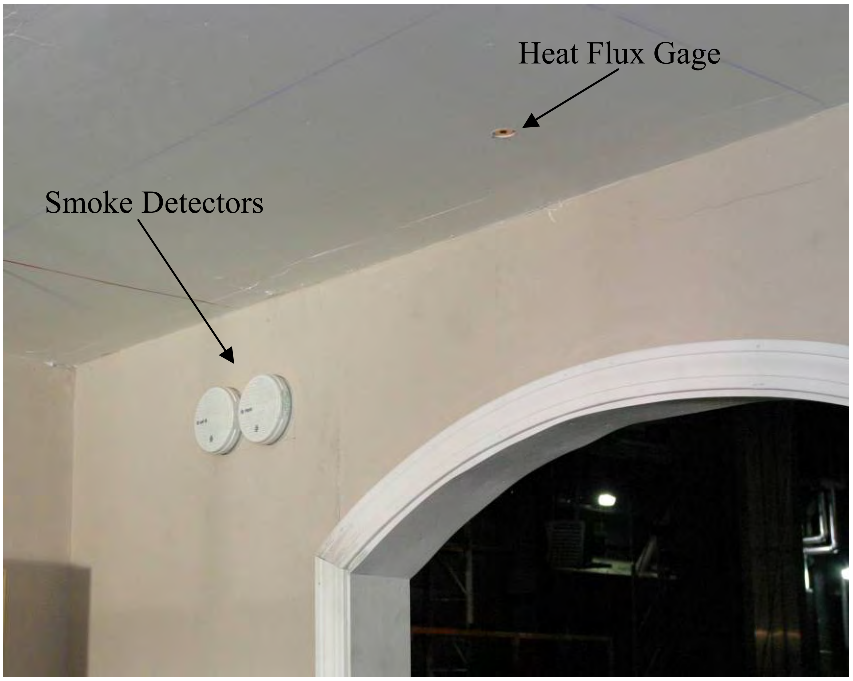

Figure 17: Smoke detector and ceiling heat flux gage locations.

2.4.6 Water Collection System

A special water collection system was constructed to collect the portion of the water exiting the living room via the archway. The system generally consisted of a stainless steel collection pan fastened to the base of the archway. Two sump pumps were located within the pan to transfer

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[**] FM Approved units were not used for these tests since battery operated residential detectors were required and FM Approvals does not approve these types of detectors.

the water to a 1040 L (275 gal.) intermediate bulk container (IBC). Depending on the volume of water flowing through the archway, either a ⅓ HP Goulds model SP035M or 1/16 HP Simer model 2310-03 sump pump was turned on to keep the collection pan from overflowing. Each test used a new IBC, and the stainless steel collection pan was scrubbed and triple rinsed with distilled water between tests to ensure there was no cross contamination. The collection pan was also covered in plastic wrap until immediately before the start of each test.

For the non-sprinklered test this system consisted of a 1.85 m long x 0.3 m wide x 0.36 m tall (6 ft. 1 in. x 1 ft. x 1 ft. 2 in.) stainless steel pan connected to the IBC with plastic tubing. However, the heat output from the fire exiting the archway was sufficient to damage the pumps and burn the plastic tubing. This resulted in an unknown amount of contamination to the collected water. Consequently, the collection system was redesigned to minimize the heat flux to the pumping system for the sprinklered test and the demonstration test (referred to as non-sprinklered test (b)). The revisions to the system included increasing the length of the collection pan to 2.46 m (8 ft. 1 in.) and moving the pumps to the pan edge away from the archway, Figure 18. Additional revisions to the system for non-sprinklered test (b) included changing all tubing to stainless steel and surrounding the pumps with a stainless steel baffle, Figure 19.

Figure 18: Revised water collection pan setup for sprinklered test.

Figure 19: Baffled water collection pan setup for non-sprinklered test (b).

2.4.7 Water Quality Analysis

The services of Woodard and Curran were retained to evaluate the quality of the wastewater generated in each test and to determine the potential environmental impacts on groundwater and surface water. Analysis of the water samples included general chemistry parameters, heavy metals, cyanide, volatile organic compounds, and semi-volatile organic compounds. The complete list of analysis and appropriate test methods is provided in Table 11. Full details of the water analysis are reported in Reference 38.

Table 11: Wastewater Analysis Taken from Reference 38

Analysis	Test Method
Volatile Organic Compounds (VOCs)	USEPA 624
Semi-Volatile Organic Compounds (SVOCs)	USEPA 625
pH	USEPA 150.1
Chemical Oxygen Demand – COD	SM 5220
Specific Conductance	SM 2510
Ammonia Nitrogen	SM 4500
Nitrate Nitrogen	SM 4500
Total Cyanide	SM 4500
Total Suspended and Dissolved Solids	SM 2540
Total Organic Carbon (TOC)	SM 5310
Total Phosphorous	SM-4500P-E(M)
Total and Dissolved Priority Pollutant 13 Metals*	USEPA 6010B/7470

*Antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, and zinc.

2.4.8 Solid Waste Analysis

The services of Woodard and Curran were retained to evaluate the solid waste generated in each test to determine if the debris exhibited the hazardous waste characteristics of toxicity. Samples of ash and/or charred materials were collected after each test and analyzed per the United States Environmental Protection Agency's (USEPA) Toxicity Characteristic Leaching Procedure (TCLP), Method 1311. Details of the solid waste analysis are reported in Reference 38.

2.4.9 Video and Photography Details

Each test was documented via video and still photography. Video documentation consisted of five cameras in total: two cameras viewing inside the living room (Panasonic Color CCTV, Model # WV-CP504) and three cameras, including a standard definition (Sony DSR-PD170) and two high definition (Sony HVR-Z1U), positioned around the exterior of the room. The standard definition camera was positioned to view the east wall of the room, while the two high definition cameras were positioned to look at the north-west and south-west corners of the room. The cameras viewing the interior of the room were installed in the west and north walls. The camera positions relative to the room are shown in Figure 20. In addition to the video images, still photography was taken before, during, and after each test, via two digital 35-mm cameras.

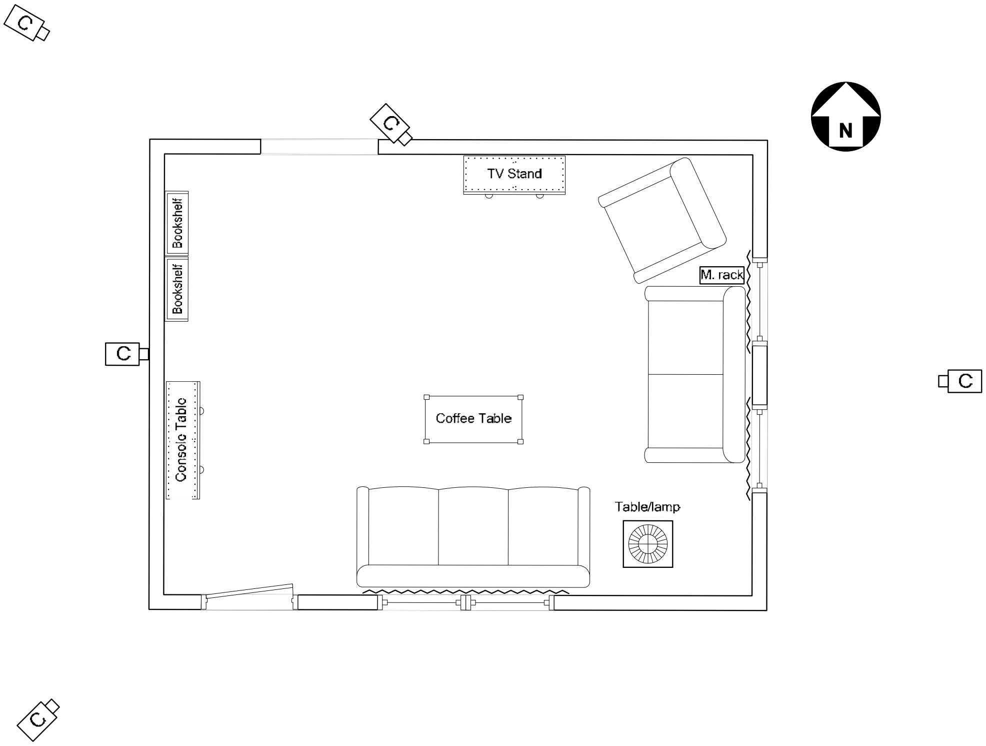


Figure 20: Video camera positions relative to the room.

3 EXPERIMENTAL RESULTS

3.1 FIRE TEST CHRONOLOGIES

On September 17, 2009, the first fully instrumented, non-sprinklered test was conducted. The comparison burn, a fully instrumented sprinklered test was conducted on October 1, 2009; in addition, a second non-sprinklered test was conducted as a demonstration test for the visitors present on that day. The test setup and conditions for the demonstration test were identical to the previous two tests. Very limited data was collected during the demonstration test and it is not included in the main analysis. The fire test chronologies for the two fully instrumented tests are provided in Table 12.

Table 12: Fire Test Chronologies

Event	Sprinklered Test (min:s)	Non-Sprinklered Test (min:s)
Ignition	0	0
Smoke Detector Activation (Ionization)	0:25	0:25
Flames Reach the Ceiling 2.4 m (8 ft.)	0:35	1:55
Sprinkler Activation	0:44	---
Smoke Detector Activation (Photoelectric)	1:10	0:33
Window 1 Breaks	---	4:00
Window 2 Breaks	---	4:42
Flames Extend Out of Archway	---	4:48
Window 4 Breaks	---	5:12
Window 3 Breaks	---	5:32
Flames Exit Around Exterior Door Seam	---	5:42
Window in Exterior Door Falls Out	---	6:18
Fire Service Pries Open Door	10:30	---
Fire Service Applies Hose Stream	10:38	10:30
Fire Service Enters Room	10:58	11:42
Fire Out	13:40	24:44

Note: Windows are numbered as East Wall, North (#1), East Wall, South (#2), South Wall, East (#3), and South Wall, West (#4).

In the non-sprinklered test, fire spread from the magazine rack to the curtains and loveseat and was noticeably slower compared to the sprinklered test, as seen in the time for the flames to reach the ceiling. This longer incipient period is reflected in the ceiling thermocouple measurements reported in Section 3.5; however, the slower fire development does not impact any of the final results and conclusions. It should be noted that in the demonstration test, non-sprinklered (b), the fire development from ignition until 44 seconds was very similar to the sprinklered test. The difference between the two non-sprinklered tests reflects the inherent variability of large-scale fires.

3.2 SPECIES MEASUREMENTS WITHIN THE DUCT

A limited number of species was measured by both FM Global and APCC within the 20-MW exhaust duct. The time resolved concentrations of carbon monoxide, carbon dioxide, and unburned hydrocarbons are presented for the non-sprinklered and sprinklered tests in Figure 21 and Figure 22, respectively. In Figure 21 and Figure 22 the FM Global data are one-second samples and the APCC data are 30-second grab samples.

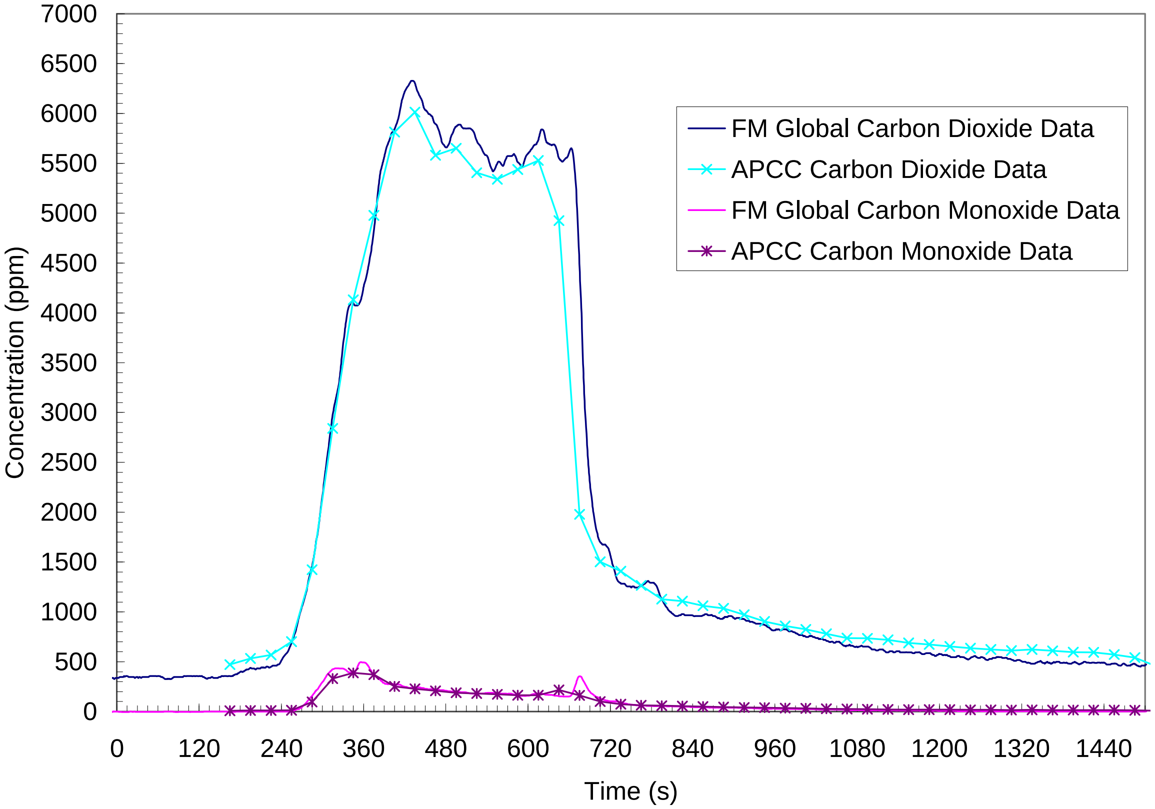


Figure 21: Duct concentrations of CO_2 and CO for the non-sprinklered test.

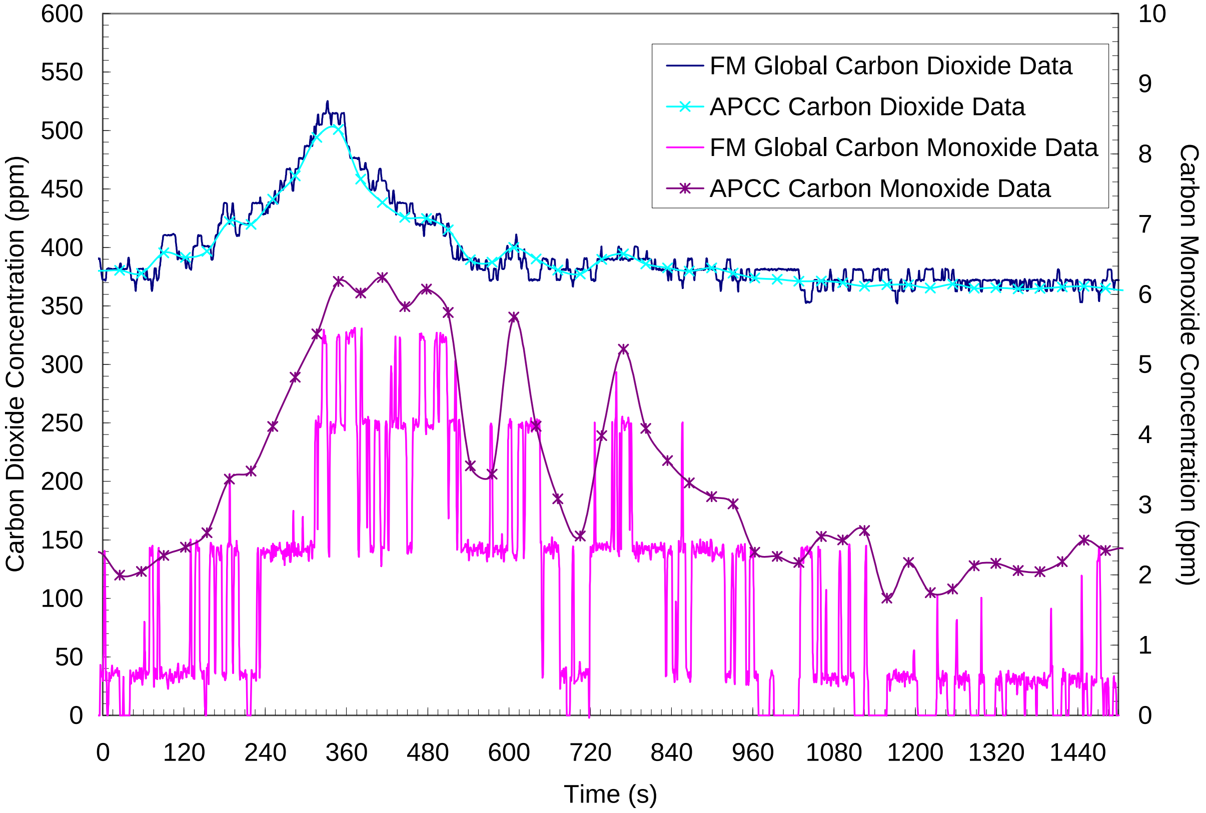


Figure 22: Duct concentrations of CO_2 and CO for the sprinklered test.

Excellent agreement is seen between the two independent data sets. The slight deviation between the FM Global data and the APCC data for the carbon monoxide levels in the sprinklered test is attributed to the very low concentrations, i.e., less than 7 ppm, and the dynamic range of the FM Global analyzer. In the following sections, the FM Global data are used to calculate the heat release rate and the total energy generated during each test, and the APCC data are used to evaluate the environmental impact.

3.3 HEAT RELEASE RATE AND TOTAL ENERGY

The chemical heat release rate (HRR) of each fire was calculated from calorimetry techniques based on carbon monoxide and carbon dioxide generation. The total chemical energy released during each fire was determined by integrating the time-resolved heat release rate data.

The chemical heat release rates as a function of time for the sprinklered and non-sprinklered tests are shown in Figure 23; the peak heat release rates were 300 kW and 13,200 kW respectively. The total energy released in the non-sprinklered test was 5,169 MJ, 76 times greater than that of the sprinklered test, which was 68 MJ. The calculated total energy released as a function of time is shown in Figure 24.

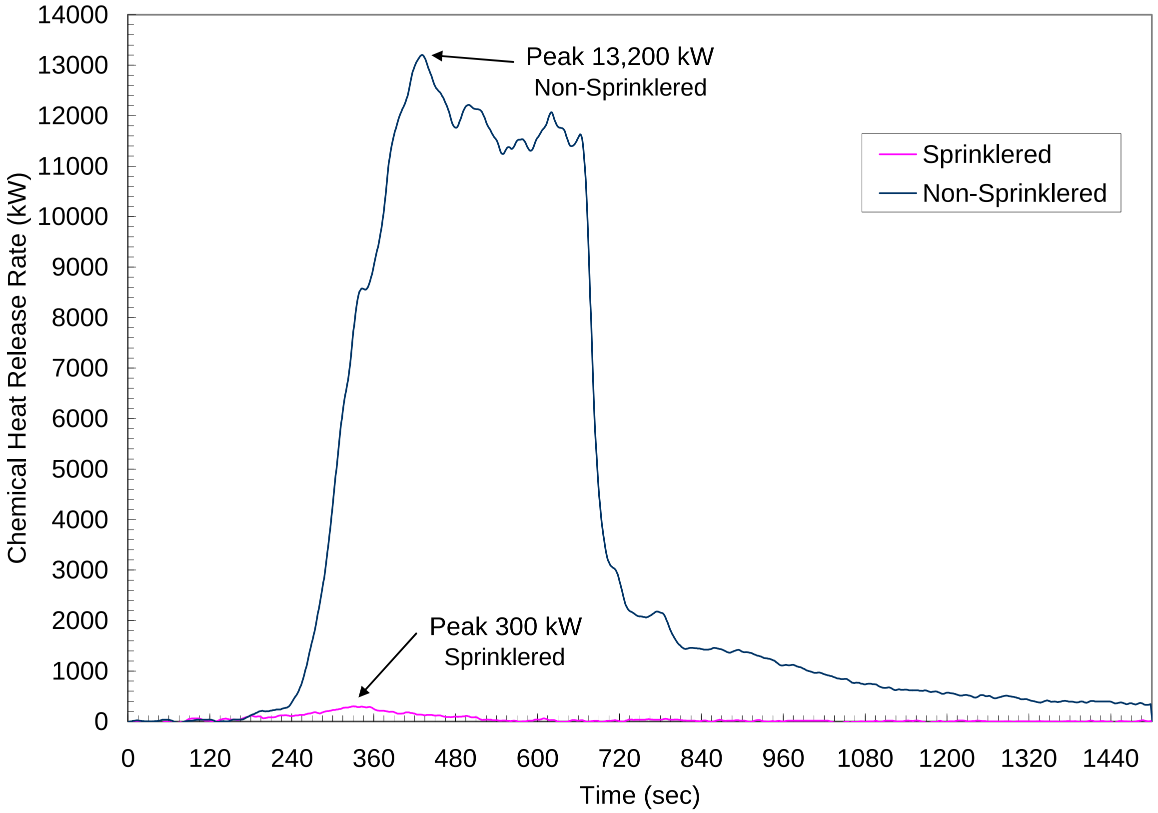


Figure 23: Chemical heat release rate as a function of time for the sprinklered and non-sprinklered tests.

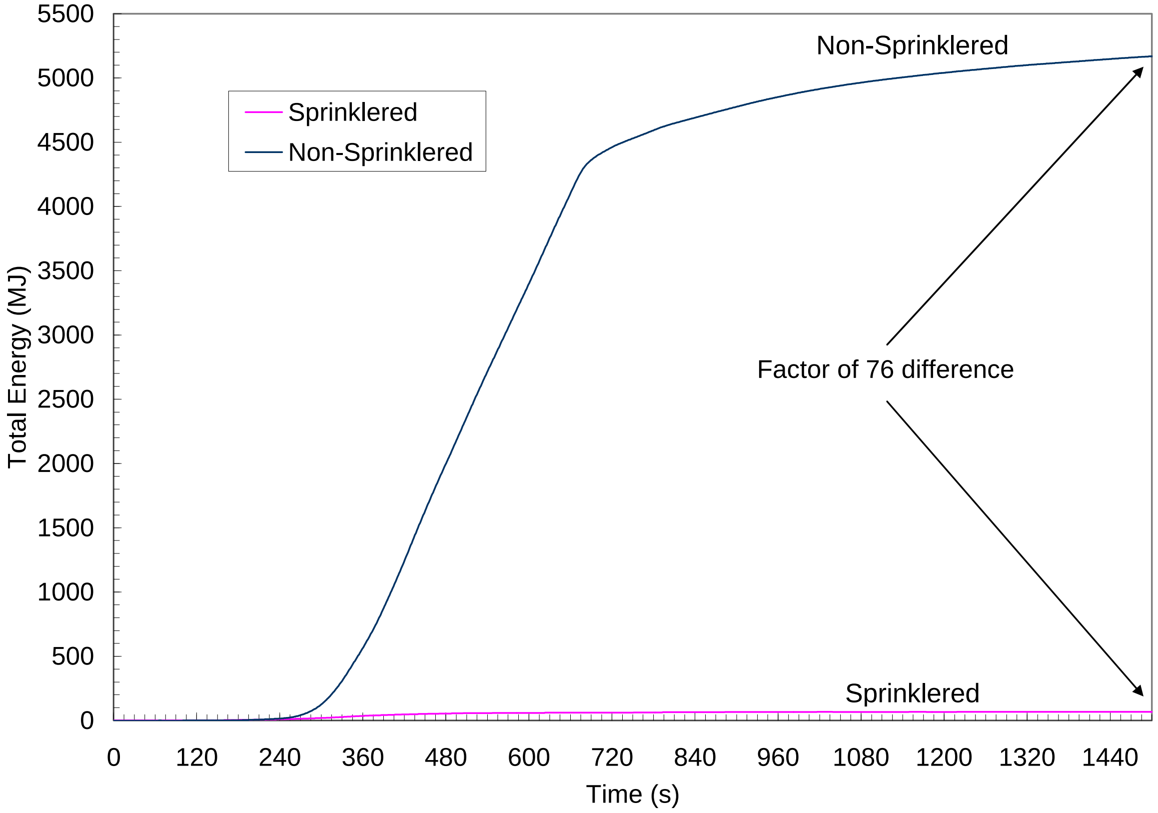
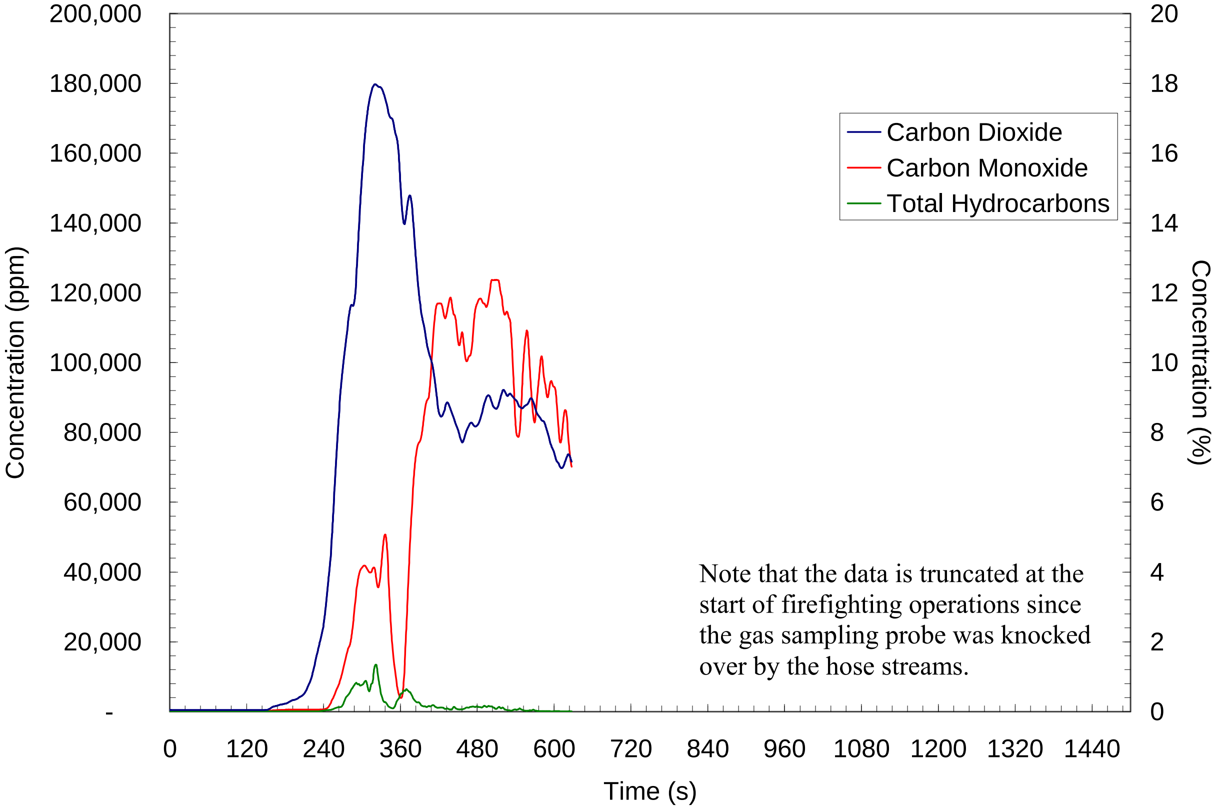


Figure 24: Total chemical energy as a function of time for the sprinklered and non-sprinklered tests.

3.4 ROOM GAS MEASUREMENTS

Gas measurements including the generated carbon dioxide, carbon monoxide, and total hydrocarbons, and the depleted oxygen levels within the rooms were monitored at a 1.5 m (5 ft.) elevation in the center of the room as described in Section 2.4.2. The generated species are plotted as a function of time in Figure 25 and Figure 26, for the non-sprinklered and sprinklered tests respectively.



Note that the data is truncated at the start of firefighting operations since the gas sampling probe was knocked over by the hose streams.

Figure 25: Carbon dioxide, carbon monoxide, and unburned hydrocarbon concentrations as a function of time within the room for the non-sprinklered test.

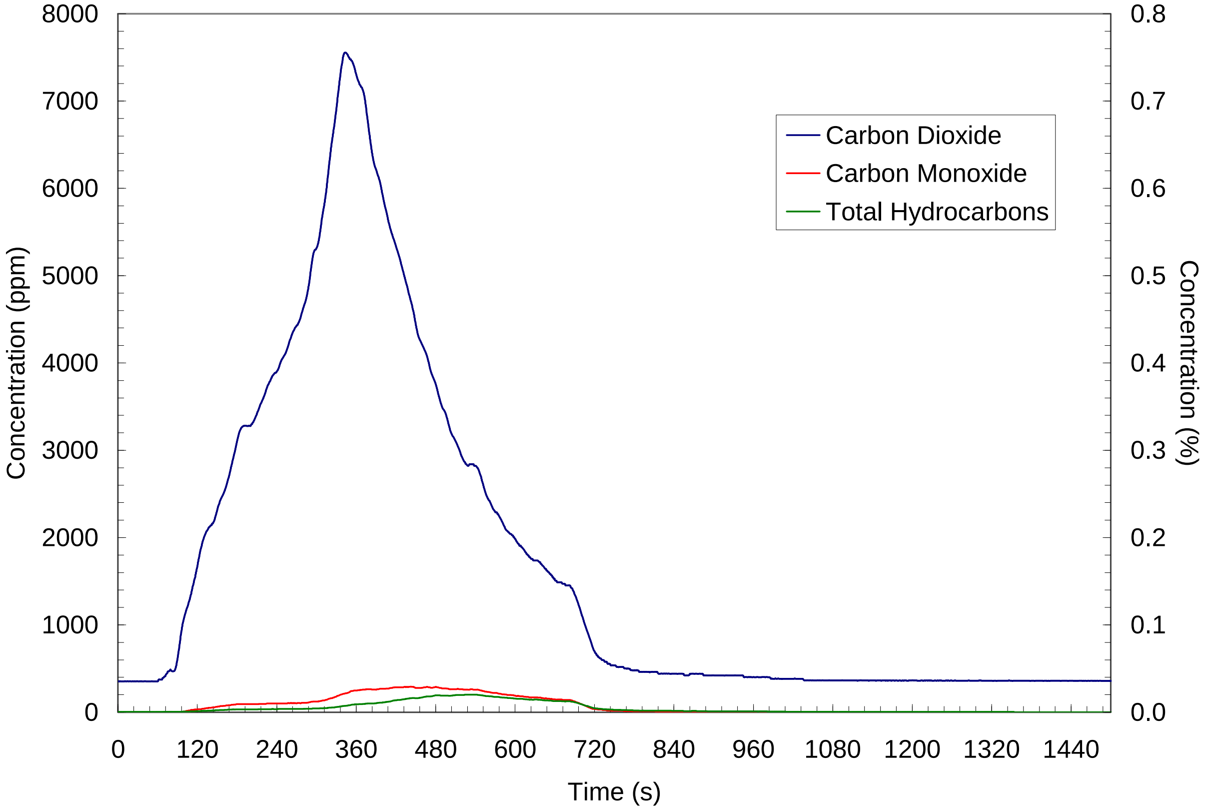
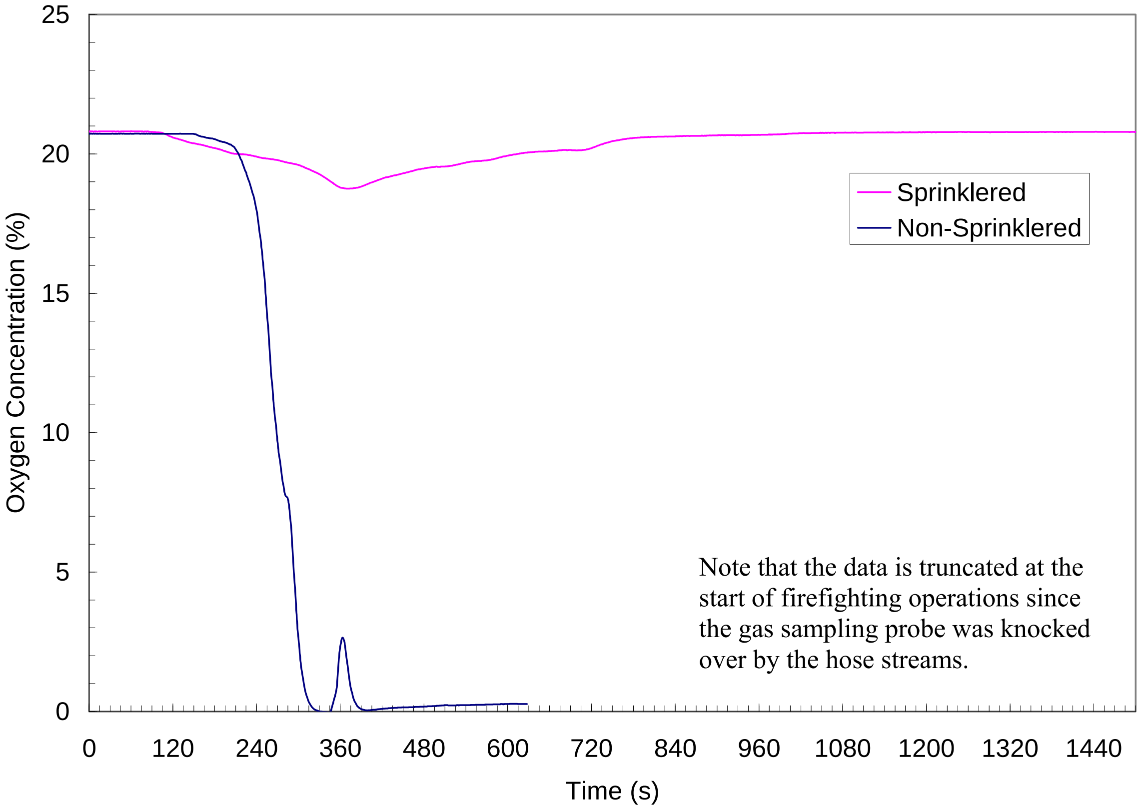


Figure 26: Carbon dioxide, carbon monoxide, and unburned hydrocarbon concentrations as a function of time within the room for the sprinklered test.

It should be noted that the maximum calibrated gas analyzer range for the carbon monoxide, in the non-sprinklered test, was 100,000 ppm (10%); measured concentrations above the maximum range should be viewed with caution. Furthermore, in the non-sprinklered test, at some point after the initiation of firefighting activities the gas sampling probe was knocked over by the hose streams; therefore, all of the data is truncated at the initiation of firefighting activities for this test.

Significantly higher levels of carbon dioxide, carbon monoxide, and total hydrocarbons were measured in the non-sprinklered test than in the sprinklered test. Maximum carbon monoxide levels differed by a factor of 420, while maximum carbon dioxide and total hydrocarbons levels differed by a factor of 24 and 67 respectively.

The oxygen concentrations as a function of time for the sprinklered and non-sprinklered tests are plotted in Figure 27. In the sprinklered test the oxygen level did not decrease below 18.8%; however, in the non-sprinklered test the oxygen level decreased to zero.



Note that the data is truncated at the start of firefighting operations since the gas sampling probe was knocked over by the hose streams.

Figure 27: Oxygen concentrations as a function of time within the room for the sprinklered and non-sprinklered tests.

3.5 CEILING TEMPERATURES

Thermocouple measurements near the ceiling were taken at 13 locations as described in Section 2.4.3. The time resolved temperature measurements for the non-sprinklered and sprinklered tests are plotted in Figure 28 and Figure 29 respectively. In the non-sprinklered test a temperature rise across the ceiling is observed at approximately 120 s. The thermocouple reading directly over ignition, i.e., Tclg10NE, reached 530°C (986°F) as the flames spread up the curtain and reached the ceiling. The decrease in temperatures observed at 150 s is attributed to the curtain burning and falling to the floor, thus momentarily decreasing the flame height. As the fire developed and spread, the temperatures near the ceiling rose rapidly and thermocouple readings in excess of 900°C (1650°F) were recorded throughout the room up to the initiation of firefighting activities at 630 s. The maximum readings at several locations approached the upper calibrated limit of a Type K thermocouple, i.e., 1250°C (2282°F) and should be viewed with caution.

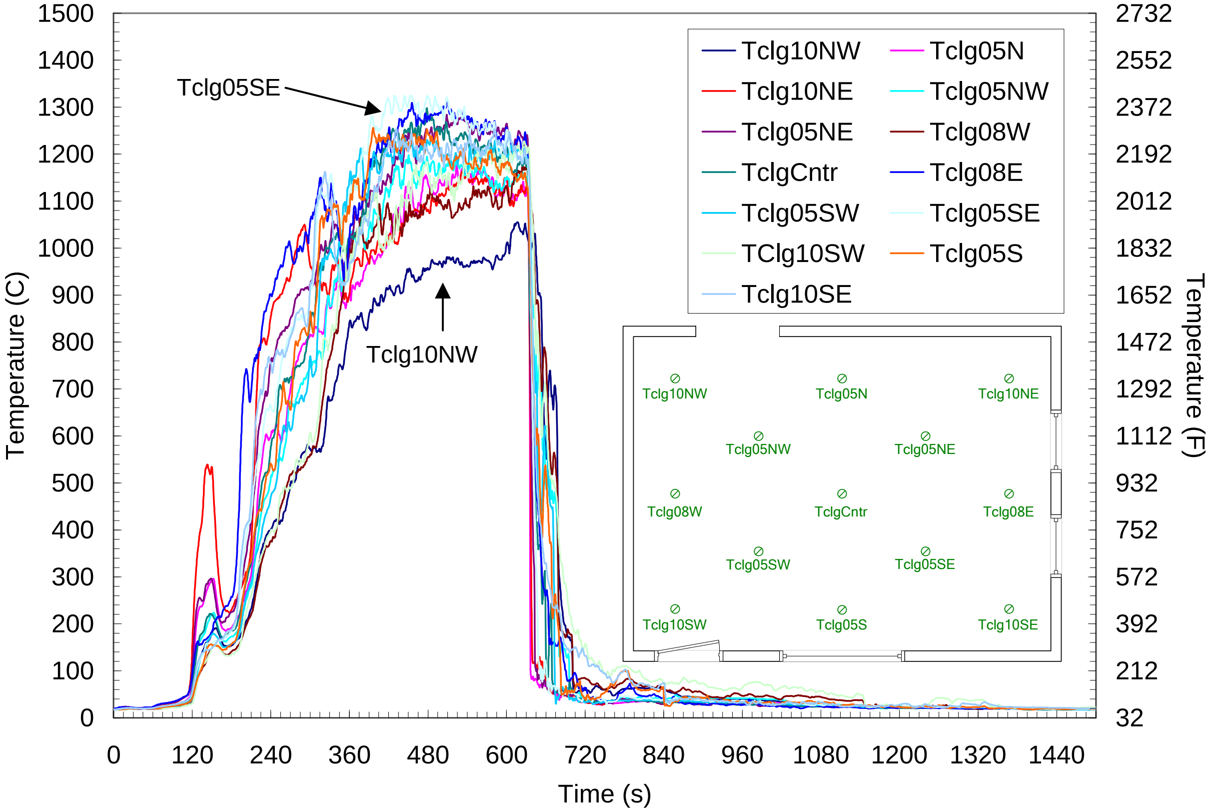


Figure 28: Near-ceiling thermocouple measurements for the non-sprinklered test.

In the sprinklered test, fire propagation from the magazine rack to the curtain and loveseat was more rapid and is reflected in the rapid temperature rise recorded directly over ignition. Upon sprinkler operation, at 44 seconds, the temperatures decrease and for the remaining duration of the test the temperatures near the ceiling do not exceed 260°C (500°F).

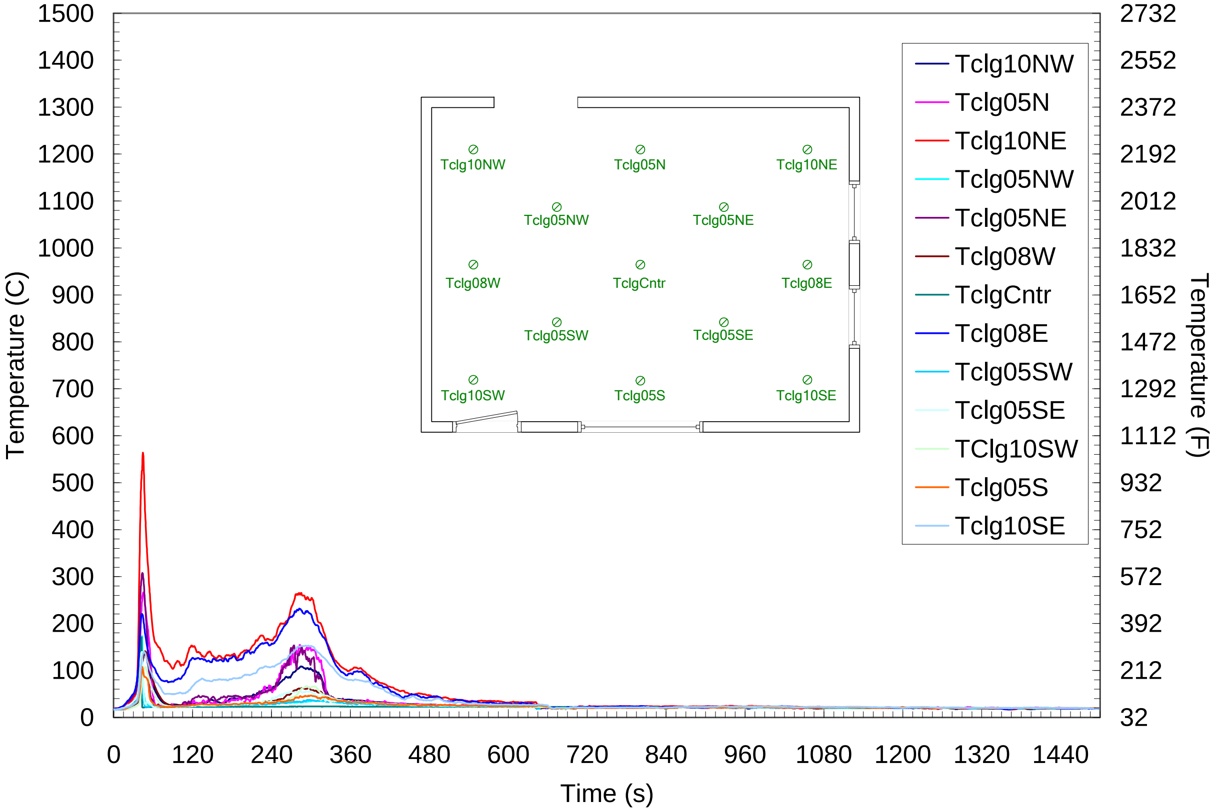


Figure 29: Near-ceiling thermocouple measurements for the sprinklered test.

3.6 FLASHOVER

Flashover is defined by the International Standards Organization as “the rapid transition to a state of total surface involvement in a fire of combustible material within an enclosure” [39]. Although not precise, the typical quantitative criteria for flashover are room temperatures between 500°C (932°F) and 600°C (1112°F), or radiation to the floor of the compartment from the gas layer between 15 and 20 kW/m^2 (1.3 to 1.8 BTU/ft^{2}s). A more subjective demarcation of flashover is the visual observation of flames external to the enclosure.

Using these criteria, the time to flashover in the non-sprinklered test was determined to be between 271 seconds and 327 seconds (see Figure 30). The embedded images in Figure 30 are of the archway taken at the two defining boundaries, i.e., ceiling temperature of 500°C (932°F) and a floor heat flux of 20 kW/m^2 (1.8 BTU/ft^{2}s). The dashed line indicates the visual observation of flames extending to the floor within the enclosure and extending out of the archway.

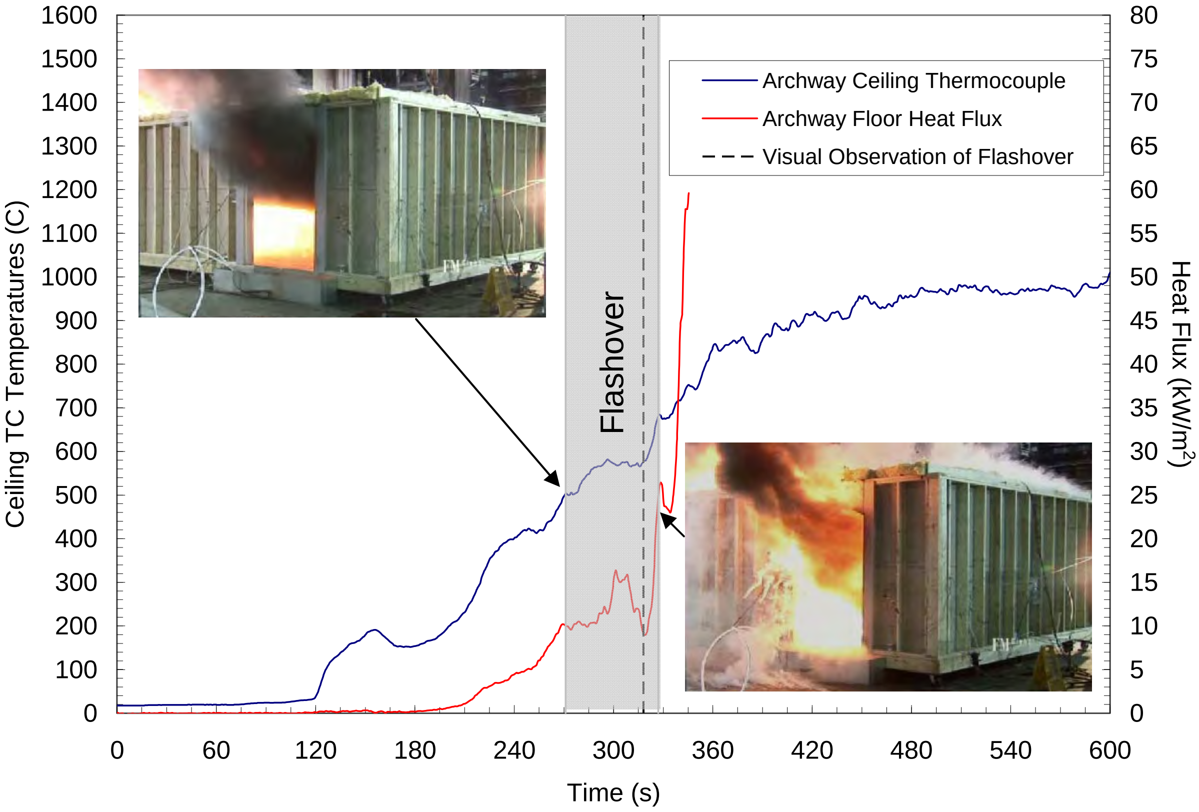


Figure 30: Flashover analysis of non-sprinklered test.

The occurrence of flashover prior to fire service response is an indication that the fire would have progressed to adjoining rooms, thus increasing the volume of materials consumed by the fire and the quantity of water required to extinguish the fire. In the sprinklered test the temperature near the ceiling at the archway did not exceed 136°C (277°F), the heat flux at the floor did not exceed 0.3 kW/m^2 (0.03 BTU/ft^{2}s), and no flames were observed exiting the enclosure. All of the data indicate that flashover did not occur in this case and the fire was contained completely to the room of origin.

3.7 WATER USAGE

As noted previously, the water sample from the first non-sprinklered test was potentially contaminated due to the melted plastic tubing and sump pumps within the water collection pan; therefore, water flow measurements and water samples for quality analysis were also taken during the demonstration test. Data from the demonstration test are labeled non-sprinklered (b). It should be noted that a more aggressive firefighting approach was also implemented in the demonstration test to better represent typical fire service response.

The volume of water discharged as a function of time in each of the three tests is plotted in Figure 31 and the results are tabulated in Table 13.

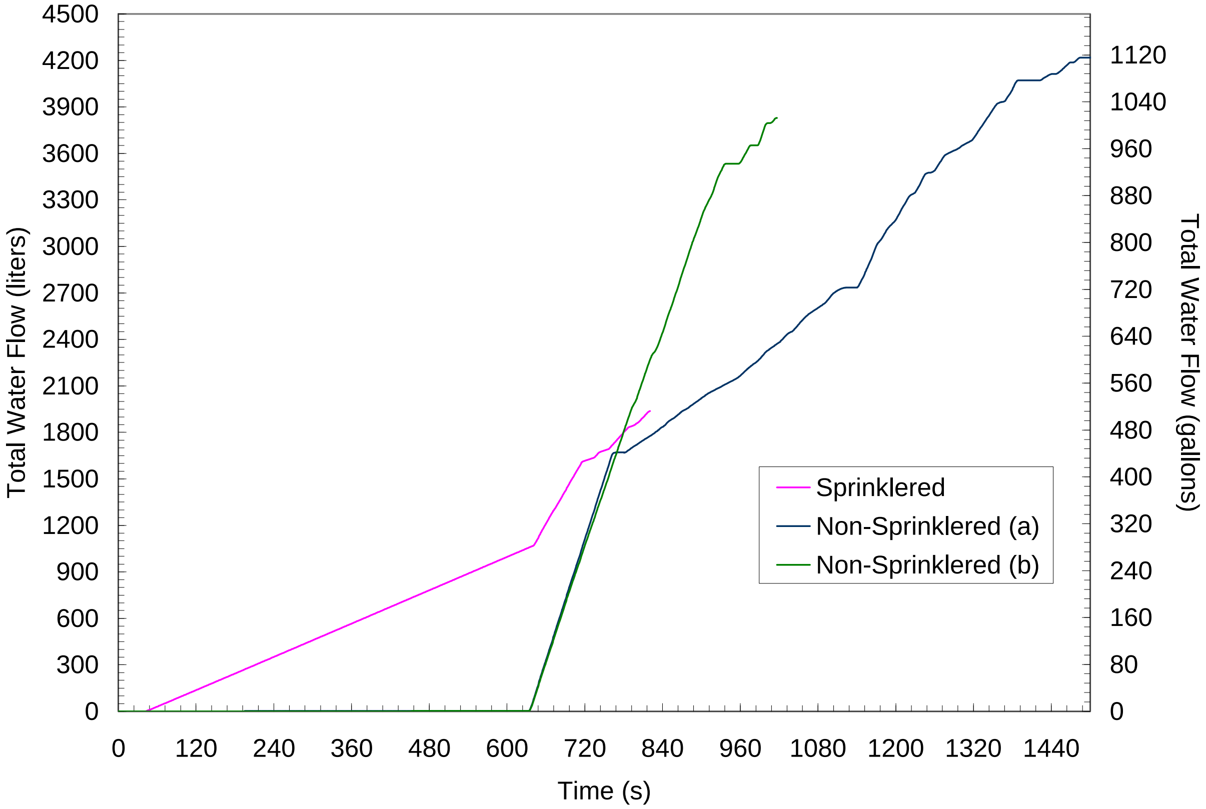


Figure 31: Total volume of water used as a function of time.

Comparing the water usage between non-sprinklered test (a) and (b), the difference in the total quantity of water discharged was not significant, i.e., ~379 L (100 gal.); however, the more aggressive firefighting tactic resulted in extinguishment of the fire 7 minutes and 46 seconds faster. Taking the lower water discharge volume as the representative volume of water for the non-sprinklered tests and comparing it to the total combined sprinkler and hose stream volume, for the sprinklered test, it is seen that 50% less water was used in the sprinklered test compared to the non-sprinklered test. Furthermore, the fire with the sprinkler was extinguished 3 minutes and 17 seconds faster than the non-sprinklered fire. This comparison is conservative, i.e., expected values for the non-sprinklered case will be larger, for two reasons, 1) the time to extinguishment and the volume of water used with the more aggressive firefighting tactics was used for the calculations; and more importantly, 2) in the non-sprinklered tests the fire would have propagated to adjacent rooms, if not the entire house, requiring more time and water to extinguish the fire. Conversely, the fire was contained to the ignition area in the sprinklered room making the results independent of any additional rooms. Extrapolation of the water usage data to larger occupancies will be made in Section 4.2.

Table 13: Water Usage Results

	Sprinklered	Non-Sprinklered (a)	Non-Sprinklered (b)
Sprinkler [L (gal.)]	1393 (368)	0	0
Hose Stream [L (gal.)]	545 (144)	4221 (1115)	3835 (1013)
Total [L (gal.)]	1938 (512)	4221 (1115)	3835 (1013)
Time to Extinguishment [s]	820	1484	1017

3.8 AIR EMISSION RESULTS

The following table, labeled Table 14, has been extracted directly from Reference 38. In the original report the table is labeled *Table 3-1: Controlled Burn Air Emissions* and the results are reported in pounds.[††] In addition to the mass of each species, the ratio between the non-sprinklered and sprinklered values is reported for each species. Of the 123 species analyzed, only 76 were detected in either the sprinklered or non-sprinklered test. There were 24 species detected at ratios in excess of 10:1, of which 11 were detected at ratios in excess of 50:1, and of those six were detected at ratios in excess of 100:1. Four species, NH_3, 1,2,3-trichloropropane, carbon tetrachloride, and o(rtho)-xylene, were detected in the non-sprinklered test but not in the sprinklered test. Similarly, four species, ethanol, hydrogen chloride (HCl), isopropyl alcohol (IPA), and bromoform, were detected in the sprinklered test but not the non-sprinklered test. The data indicate that “The total emissions from the Sprinkler controlled burn were lower than the emissions from the No Sprinkler controlled burn” [38].

[††] Note: Woodard and Curran used the terms “No Sprinkler” for the non-sprinklered test, and “Sprinkler” for the sprinklered test.

Table 14: Controlled Burn Air Emissions (Table 3-1 extracted from Reference 38)

Criteria Pollutants	Emissions (lbs/burn)		Ratio of Emissions, No Sprinkler vs. Sprinkler
	17 September No Sprinkler	1 October Sprinkler	
CO	26.42	0.23	113
NO_2	0.14	0.14	1
SO_2	0.48	0.20	2.4
Total VOC - THC (as CH_4)	3.77	0.02	184
Particulate	17.76	1.39	13
Greenhouse Gases	**Emissions (lbs/burn)**		**Ratio of Emissions, No Sprinkler vs. Sprinkler**
	17 September No Sprinkler	**1 October Sprinkler**	
CO_2	793.95	12.98	61
Methane	1.80	0.01	130
Nitrous Oxide (N_2O)	0.17	0.02	7
Metals	**Emissions (lbs/burn)**		**Ratio of Emissions, No Sprinkler vs. Sprinkler**
	17 September No Sprinkler	**1 October Sprinkler**	
Antimony (Sb)	0.017	0.00056	30
Arsenic (As)	0.00056	0.00023	2.5
Barium (Ba)	0.012	0.012	1
Beryllium (Be)	0.0014	0.000056	25
Cadmium (Cd)	0.0014	0.00012	12
Total chromium (Cr)	0.050	0.015	3.3
Copper (Cu)	0.016	0.0091	1.8
Mercury (Hg)	0.0082	0.0048	1.7
Lead (Pb)	0.013	0.0087	1.5
Manganese (Mn)	0.081	0.010	8.3
Nickel (Ni)	0.043	0.0095	4.6
Phosphorous (P)	0.012	0.0084	1.5
Selenium (Se)	0.012	0.00063	19
Silver (Ag)	0.00052	0.00026	2
Thallium (Tl)	0.00070	0.00028	2.5
Zinc (Zn	0.147	0.018	8.4

Table 14: Controlled Burn Air Emissions (Table 3-1 extracted from Reference 38) (cont'd)

Air Toxics and Other Pollutants	**Emissions (lbs/burn)** 17 September No Sprinkler	1 October Sprinkler	**Ratio of Emissions, No Sprinkler vs. Sprinkler**
Acetaldehyde	0.32	0.0016	200
Acrolein	0.21	0.35	0.6
Benzene	0.69	2.06	0.3
Ethanol	0	1.44	0
Ethylene	0.51	0.012	43
Formaldehyde	0.15	0.0092	17
Hydrogen Fluoride (HF)	0.0026	0.0045	0.6
Hydrogen Chloride (HCl)	0	0.016	0
Isopropyl Alcohol (IPA)	0	0.35	0
Methanol	0.20	0.037	5.5
NH_3	0.0026	0	---
NO	0.91	0.021	44
Toluene	0.58	0.084	6.9
Hydrogen Cyanide (HCN)	0.07	0.013	5.4
1,1,1-Trichloroethane	0.46	0.56	0.8
Bromoform	0	0.0011	0
Carbon Disulfide	25.15	0.037	678
Chloroform	0.046	0.012	3.8
Methyl Ethyl Ketone (MEK)	3.52	0.053	67
Iodo-methane	1.042	0.077	14
1,2,3-Trichloropropane	28.31	0	---
Carbon Tetrachloride	0.13	0	---
m(eta)-Xylene	0.057	0.016	3.5
o(rtho)-Xylene	2.97	0	---
p(ara)-Xylene	7.22	0.90	8
Total Xylenes	10.24	0.91	11
Methyl Isobutyl Ketone (MIBK)	3.16	0.032	98

Table 14: Controlled Burn Air Emissions (Table 3-1 extracted from Reference 38) (cont'd)

	Emissions (lbs/burn)		
	17 September	1 October	
Semi-Volatile Organic Air Toxics	No Sprinkler	Sprinkler	Ratio of Emissions, No Sprinkler vs. Sprinkler
1,2,4-Trichlorobenzene	0	0	---
1,2-Dichlorobenzene	0	0	---
1,3-Dichlorobenzene	0	0	---
1,4-Dichlorobenzene	0	0	---
1-Chloronaphthalene	0	0	---
1-Methylnaphthalene	0.0056	0.0017	3.3
2,4,5-Trichlorophenol	0	0	---
2,4,6-Trichlorophenol	0	0	---
2,4-Dichlorophenol	0	0	---
2,4-Dimethylphenol	0	0	---
2,4-Dinitrophenol	0	0	---
2,4-Dinitrotoluene	0	0	---
2,6-Dinitrotoluene	0	0	---
2-Chloronaphthalene	0	0	---
2-Chlorophenol	0	0	---
2-Methylnaphthalene	0.0065	0.0011	5.7
2-Methylphenol	0.0095	0.0017	5.5
2-Nitroaniline	0	0	---
2-Nitrophenol	0	0	---
3 & 4-methylphenol	0.015	0.0020	7.6
3,3'-Dichlorobenzidine	0	0	---
3-Nitroaniline	0	0	---
4,6-Dinitro-2-methylphenol	0	0	---
4-Bromophenyl phenyl ether	0	0	---
4-Chloro-3-Methylphenol	0	0	---
4-Chloroaniline	0	0	---
4-Chlorophenyl phenyl ether	0	0	---
4-Nitroaniline	0	0	---

Table 14: Controlled Burn Air Emissions (Table 3-1 extracted from Reference 38) (cont'd)

Semi-Volatile Organic Air Toxics (con't)	Emissions (lbs/burn) 17 September No Sprinkler	Emissions (lbs/burn) 1 October Sprinkler	Ratio of Emissions, No Sprinkler vs. Sprinkler
4-Nitrophenol	0	0	---
Acenaphthene	0	0	---
Acenaphthylene	0.021	0.00029	75
Aniline	0	0	---
Anthracene	0.0032	0.00023	14
Benzidine	0	0	---
Benzo(a)anthracene	0.0017	0.00023	7.4
Benzo(a)pyrene	0.0018	0.00029	6.1
Benzo(b)fluoranthene	0.0029	0.00023	13
Benzo(g,h,i)perylene	0.0021	0.00023	9
Benzo(k)fluoranthene	0.00088	0.00029	3.1
Benzoic Acid	0.15	0.0011	130
Benzyl Alcohol	0.0011	0.00029	3.7
Benzyl butyl phthalate	0.00026	0.0044	0.1
Biphenyl	0.013	0.0011	12
Bis(2-chloroethoxy)methane	0	0	---
Bis(2-chloroethyl)ether	0	0	---
Bis(2-chloroisopropyl)ether	0	0	---
Bis(2-ethylhexyl)phthalate	0.15	0.061	2.5
Carbazole	0	0	---
Chrysene	0.0013	0.00023	5.5
Dibenz(a,h)anthracene	0.00042	0.00023	1.8
Dibenzofuran	0	0	---
Diethyl phthalate	0	0	---
Dimethyl phthalate	0	0	---
Di-N-butyl phthalate	0	0	---
Di-N-octyl phthalate	0	0	---
Fluoranthene	0.0085	0.00061	14
Fluorene	0.0035	0.00023	15
Hexachlorobenzene	0	0	---
Hexachlorobutadiene	0	0	---
Hexachlorocyclopentadiene	0	0	---
Hexachloroethane	0	0	---
Indeno(1,2,3-cd)pyrene	0.0019	0.00029	6.7
Isophorone	0	0	---
Naphthalene	0.092	0.0012	78
Nitrobenzene	0	0	---
N-Nitrosodimethylamine	0	0	---
N-Nitroso-di-n-propylamine	0	0	---

Table 14: Controlled Burn Air Emissions (Table 3-1 extracted from Reference 38) (cont'd)

Semi-Volatile Organic Air Toxics (con't)	Emissions (lbs/burn)		Ratio of Emissions, No Sprinkler vs. Sprinkler
	17 September No Sprinkler	1 October Sprinkler	
N-Nitrosodiphenylamine	0	0	---
Pentachlorophenol	0	0	---
Phenanthrene	0.024	0.00055	44
Phenol	0.075	0.00085	88
Pyrene	0.0067	0.00029	23

Note: Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are greenhouse gases that were measured during the controlled burns. A result of zero indicates that the constituent was either not detected or controlled burn test results were below the detection limit of the analysis. A dash (---) indicates that ratio was not calculated, because a constituent was not detected in the analysis.

3.9 WATER QUALITY RESULTS

The following results and discussion related to the wastewater analysis have been extracted directly from Reference 38. The section and table numbering of the original report have been maintained. The water analysis includes water samples from each of the fire tests. In addition, since FM Global uses a closed-loop recycled water system for firefighting purposes, samples of the recycled water on each day were also analyzed to establish a baseline.

4.2.1 Analytical Results

As discussed, one composite wastewater sample was collected from each controlled burn (i.e., with and without sprinkler) immediately following fire response activities. Samples were analyzed for general chemistry parameters, dissolved and total metals, VOCs, and SVOCs. Additionally, one recycled water sample was collected per controlled burn and analyzed for the same suite of parameters. Analytical results for all constituents detected at least once in wastewater samples are summarized in Table 4-2a and 4-2b. Recycled fire fighting water sample results are also reported on these tables. The laboratory analytical reports for these samples are provided in Appendix B. As discussed, there were potential sample contamination issues associated with the September 17, 2009 sampling event for the No sprinkler controlled burn. However, for comparative purposes, the analytical results for this wastewater sample and recycled water samples collected on this date are presented on Table 4-2a.

The values presented in the analytical results table show either a detected concentration, or a "non-detect" concentration, indicated by a qualifier of "U". The "U"-qualified value is the reporting limit (RL), which is the lowest concentration that an analytical instrument can accurately measure, within specified limits of precision and accuracy. The constituent may potentially be present at a level below the RL, but the instrument is not able to detect it at a concentration lower than the RL. Note that RLs are, in part, dependent on sample-specific *characteristics, such as the level of contaminant present or the sample dilution required for analysis, and thus, the RL for one analyte in one sample may vary considerably from the RL reported for the same constituent in another sample.*

Because various constituents were detected in the recycled fire fighting water samples, the tables below provide adjusted concentrations of constituents in each wastewater sample. This adjusted, or net, concentration represents the difference between the detected level of a constituent in wastewater and the corresponding detected level in the recycled water sample. Non-detect results were not included in calculation of the adjusted concentration. A positive net value indicates that the concentration of constituent in the wastewater sample was greater than that of the recycled water sample; conversely, a negative value indicates that the concentration in the recycled water sample was greater than that of the wastewater sample.

Table 4-2a: Summary of Analytical Results – Wastewater Samples, September 17, 2009

		September 17, 2009 Sampling Event				
LOCATION		**RW - 1** **Recycled Water**		**WW-1** **No Sprinkler**		**WW-1** **No Sprinkler**
SAMPLING DATE		**9/17/2009**		**9/17/2009**		**9/17/2009**
	Units	Result	Qual	Result	Qual	**Net Result***
General Chemistry						
pH (H)	SU	7.8		11.6		3.8
Specific Conductance	umhos/cm	2,100		5,100		3,000
Solids, Total Dissolved	ug/l	1,200,000		4,000,000		2,800,000
Solids, Total Suspended	ug/l	5,000	U	2,000,000		2,000,000
Cyanide, Total	ug/l	5	U	96		96
Nitrogen, Ammonia	ug/l	75	U	7,200		7,200
Nitrogen, Nitrate	ug/l	100	U	1,900		1,900
Phosphorus, Total	ug/l	19		337		318
Chemical Oxygen Demand	ug/l	220,000		850,000		630,000
Total Organic Carbon	ug/l	71,000		240,000		169,000
Volatile Organic Compounds						
Chloroform	ug/l	150		160		10
Benzene	ug/l	50	U	50	U	ND
Styrene	ug/l	50	U	50	U	ND
Acetone	ug/l	5,900		6,400		500
Semivolatile Organic Compounds						
Phenol	ug/l	7	U	230		230
2-Methylphenol	ug/l	6	U	100		100
3-Methylphenol/4-Methylphenol	ug/l	6	U	200		200
Benzoic Acid	ug/l	86		1,300		1,214
Total Metals						
Antimony, Total	ug/l	50	U	208		208
Arsenic, Total	ug/l	5	U	5	U	ND
Chromium, Total	ug/l	10	U	10	U	ND
Copper, Total	ug/l	45		35		-10
Lead, Total	ug/l	2	U	12		12
Mercury, Total	ug/l	0.2	U	1.3		1.3
Silver, Total	ug/l	0.8	U	0.8	U	ND
Zinc, Total	ug/l	82		188		106
Dissolved Metals						
Antimony, Dissolved	ug/l	50	U	210		210
Copper, Dissolved	ug/l	10	U	10	U	ND
Mercury, Dissolved	ug/l	0.2	U	1.5		1.5
Zinc, Dissolved	ug/l	50	U	50	U	ND

U = Constituent not detected at laboratory reporting limit
ug/L = micrograms per liter
SU = standard units
umhos/cm = micromhos per centimeter
Free CN- = Cyanide (CN-) criteria are available for free, or bioavailable, cyanide. Wastewater results are reported for total cyanide. Total cyanide concentrations are not necessarily indicative of free cyanide concentrations.

*Wastewater concentrations were corrected to account for the contribution of contamination from the recycled firefighting water used to extinguish the test burns. The net result shown above is the difference between the measured level of a constituent in the test burn sample and the corresponding recycled water sample.
Non-detect (ND) results were not included in calculating the difference (i.e., these results were assumed equivalent to zero).
A negative result indicates that the test burn sample level was lower than the recycled water concentration.

Table 4-2b: Summary of Analytical Results – Wastewater Samples, October 1, 2009

		October 1, 2009 Sampling Event							
LOCATION		**RW-1**		**WW-1**		**WW-1**	**WW-2**		**WW-2**
		Recycled Water		**Sprinkler**		**Sprinkler**	**No Sprinkler**		**No Sprinkler**
SAMPLING DATE		**10/1/2009**		**10/1/2009**		**10/1/2009**	**10/1/2009**		**10/1/2009**
	Units	Result	Qual	Result	Qual	**Net Result***	Result	Qual	**Net Result***
General Chemistry									
pH (H)	SU	8.1		7.9		-0.2	12.1		4
Specific Conductance	umhos/cm	2,200		2,300		100	7,300		5,100
Solids, Total Dissolved	ug/l	1,200,000		1,300,000		100,000	5,500,000		4,300,000
Solids, Total Suspended	ug/l	5,000	U	36,000		36,000	640,000		640,000
Cyanide, Total	ug/l	5	U	639		639	55		55
Nitrogen, Ammonia	ug/l	75	U	1,470		1,470	4,850		4,850
Nitrogen, Nitrate	ug/l	100	U	130		130	440		440
Phosphorus, Total	ug/l	16		500		484	401		385
Chemical Oxygen Demand	ug/l	160,000		420,000		260,000	810,000		650,000
Total Organic Carbon	ug/l	54,000		110,000		56,000	190,000		136,000
Volatile Organic Compounds									
Chloroform	ug/l	290		84		-206	82		-208
Benzene	ug/l	100	U	62		62	50	U	ND
Styrene	ug/l	100	U	50	U	ND	63		63
Acetone	ug/l	13,000		11,000		-2,000	8,000		-5,000
Semivolatile Organic Compounds									
Phenol	ug/l	6.8	U	280	U	ND	370		370
2-Methylphenol	ug/l	5.8	U	240	U	ND	180		180
3-Methylphenol/ 4-Methylphenol	ug/l	5.8	U	240	U	ND	290		290
Benzoic Acid	ug/l	80		2,000	U	ND	960	U	ND
Total Metals									
Antimony, Total	ug/l	50	U	50	U	ND	272		272
Arsenic, Total	ug/l	5	U	5	U	ND	7		7
Chromium, Total	ug/l	10	U	10	U	ND	10		10
Copper, Total	ug/l	40		61		21	46		6
Lead, Total	ug/l	2	U	2		2	18		18
Mercury, Total	ug/l	0.2	U	2.5		2.5	0.8		0.8
Silver, Total	ug/l	0.8	U	0.8	U	ND	1.8		1.8
Zinc, Total	ug/l	165		337		172	350		185
Dissolved Metals									
Antimony, Dissolved	ug/l	50	U	50	U	ND	150		150
Copper, Dissolved	ug/l	10	U	30		30	10	U	ND
Mercury, Dissolved	ug/l	0.2	U	1.1		1.1	0.6		0.6
Zinc, Dissolved	ug/l	128		182		54	50	U	ND

U = Constituent not detected at laboratory reporting limit
ug/L = micrograms per liter
SU = standard units
umhos/cm = micromhos per centimeter
Free CN- = Cyanide (CN-) criteria are available for free, or bioavailable, cyanide. Wastewater results are reported for total cyanide. Total cyanide concentrations are not necessarily indicative of free cyanide concentrations.

*Wastewater concentrations were corrected to account for the contribution of contamination from the recycled firefighting water used to extinguish the test burns. The net result shown above is the difference between the measured level of a constituent in the test burn sample and the corresponding recycled water sample.
Non-detect (ND) results were not included in calculating the difference (i.e., these results were assumed equivalent to zero).
A negative result indicates that the test burn sample level was lower than the recycled water concentration.

4.2.1.2 Pollutant Concentrations in Wastewater

Recycled Water Samples: *Analytical results for both of the recycled water samples indicate that total copper, total zinc, two VOCs (acetone and chloroform), and benzoic acid, a SVOC, are present at a level above the laboratory reporting limits. In general, the types of constituents detected in both September 17 and October 1 samples were similar, although concentrations of these constituents were variable. Of the metals, only zinc was detected in dissolved form, and only in the October 1, 2009 sample. General chemistry results showed that organic solids were also present in the water samples. These results indicate that a baseline level of chemical constituents is present in the recycled water system.*

Sprinkler controlled burn: *Acetone, benzene, and chloroform were detected in the sample obtained from the Sprinkler controlled burn, WW-1, on October 1, 2009. Both chloroform and acetone levels in the Sprinkler controlled burn sample were lower than those of the recycled water sample collected on the same sample date. No SVOCs were detected in the Sprinkler sample; however, reporting limits for several of the constituents were elevated in this sample compared to those in the recycled water sample (due to the high concentrations of several analytes present in the sample), thereby potentially "masking" the presence of these constituents. Total and dissolved copper, mercury, and zinc were detected in sample WW-1; lead was detected only in total form in this sample.*

No Sprinkler controlled burn: *Similar types of constituents were detected in the samples obtained from the No Sprinkler controlled burn (samples WW-1, on September 17, 2009 and WW-2, on October 1, 2009). Chloroform, styrene, acetone, and several phenolic compounds were detected; both acetone and chloroform levels were lower than those detected in the recycled water sample. Heavy metals, including antimony, arsenic, chromium, lead, mercury, and silver, were also detected. Of the metals, only antimony and mercury were detected in dissolved form, and in both samples, implying that most of the detected metals are likely associated with suspended particulate matter.*

During the October 1, 2009 event, both chloroform and acetone concentrations were highest in the recycled water sample compared to concentrations detected in the Sprinkler and No Sprinkler samples. Because both of these compounds are volatile, one would expect a higher degree of volatilization resulting from either controlled burn (because recycled fire fighting water is spread over a larger area and because the heat from the fire would increase volatilization), which may, in part, explain the difference in concentration for these contaminants.

Three SVOCs were detected in the No Sprinkler sample, whereas none was detected in the Sprinkler sample; however, the reporting limits for SVOCs in the Sprinkler sample were similar to or higher than those of the No Sprinkler sample. It is therefore unclear whether SVOCs in the Sprinkler sample are not actually present or are present but at levels below the reporting limits.

Relative to the recycled water samples, the Sprinkler and No Sprinkler samples contained higher levels of both total suspended and dissolved solids, organic carbon, and nutrients (nitrogen and phosphorous). In general, the No Sprinkler water samples contained the highest levels of solids and TOC, and a higher pH. This is expected, considering the high generation of ash resulting *from the No Sprinkler controlled burn compared to the Sprinkler controlled burn. Of all of the wastewater samples, the total cyanide concentration was highest in the October 1, 2009 Sprinkler sample. Cyanide gas can be generated from burning synthetic polymers in building materials and furnishings, as well as natural materials such as wood.*

Metals concentrations were variable between the Sprinkler and No-Sprinkler controlled burn samples, with no clear bias shown by either sample. In general, however, the differences in concentration between the two controlled burns were less than an order of magnitude. Of the eight metals analyzed (as total metals), six metals were detected in the No Sprinkler sample at concentrations higher than that of the Sprinkler sample. However, dissolved copper, mercury, and zinc concentrations were highest in the Sprinkler controlled burn. Dissolved antimony concentrations were highest in the No Sprinkler sample.

The pH of the composite wastewater samples from the two No Sprinkler controlled burns were 11.6 and 12.1 vs. pH of 7.9 for the wastewater sample from the Sprinkler controlled burn. Thus, the wastewater from the No Sprinkler controlled burns was approximately four orders of magnitude higher in alkalinity than the wastewater from the Sprinkler controlled burn. The discharge of any wastewater with pH values of higher than 10 would be a serious environmental concern. Wastewaters exhibiting pH values of greater than 9.0 would be exceeding the allowable discharge range of pH 5.5-9.0 required by most environmental regulatory agencies.

3.10 SOLID WASTE ANALYSIS

Solid waste from each of the tests, including non-sprinklered test (b) was analyzed as described in Section 2.4.8. The results of the analysis indicate that all three samples “would not be considered ‘hazardous waste’ under USEPA regulations”. Furthermore, “the wastes are not anticipated to significantly leach once landfilled” [38].

4 DISCUSSION

In the following sections, the reduction in the environmental impact due to the use of automatic fire sprinklers in a fire will be discussed. Quantification of the environmental impact will be based on analysis of greenhouse gases, water usage, potential environmental impacts of wastewater runoff, fire damage, and solid waste material disposed in landfills. In addition, the benefits of automatic fire sprinklers from a life safety perspective will be presented.

4.1 IMPACT ON GREENHOUSE GASES

This section discusses the impact of sprinkler protection on the generation of greenhouse gases. The measured greenhouse gases reported in Section 3.8 can be converted to an equivalent mass of carbon dioxide:

$$CO_{2,equivalent} = GWP_{gas} \cdot m_{gas} \tag{9}$$

Where:

$CO_{2,equivalent}$ - equivalent mass of carbon dioxide for a gas

m_{gas} - mass of the greenhouse gas

GWP_{gas} - global warming potential of the gas

The global warming potentials (GWP) "are a measure of the relative radiative effect of a given substance compared to another, integrated over a chosen time horizon. [40]" A common time horizon used by regulators is 100 years.

The global warming potential, measured masses of greenhouse gases, and calculated equivalent carbon dioxide levels are listed in Table 15. The equivalent mass of CO_2 generated in the non-sprinklered test was 404.4 kg (890.7 lb.) versus 8.7 kg (19.2 lb.) generated in the sprinklered test. This indicates that in the event of a fire, the use of sprinklers can reduce the greenhouse gas emissions by 97.8%. It should be noted that this is a conservative value, i.e., the expected values will be larger, since in the non-sprinklered test the fire would have propagated to adjacent rooms, if not the entire house, before firefighting intervention commenced.

Table 15: Equivalent Carbon Dioxide Values for Measured Greenhouse Gases

Gas	GWP*	Measured Mass		Equivalent CO_2	
		(Non-Sprinklered) kg (lb.)	(Sprinklered) kg (lb.)	(Non-Sprinklered) kg (lb.)	(Sprinklered) kg (lb.)
CO_2	1	360.1 (794)	5.9 (13.0)	360.1 (794)	5.9 (13.0)
CH_4	25	0.82 (1.8)	0.004 (0.019)	20.5 (45.2)	0.1 (0.22)
N_2O	298	0.08 (0.17)	0.009 (0.02)	23.8 (52.5)	2.7 (6.0)
			Total	**404.4 (890.7)**	**8.7 (19.2)**

* Based on a 100-year time interval

These results can be extrapolated to estimate the total greenhouse gas production resulting for all residential fires within the U.S. between 1999 and 2008. As discussed previously in Sections 1.2.3 and 1.2.4, the average size of a single-family home during that time period was 164 m^2 (1,765 ft^2) and the estimated average damage, per NFPA statistics, was 14%. Furthermore, data from NFPA indicate that the total number of residential fires in one- and two-family homes (including manufactured homes) between 1999 and 2008 was 2,943,500. Assuming a direct proportionality between the greenhouse gas emissions and the area of the room, it is estimated that 14.5 kg/m^2 (3.0 lbs/ft^2) of equivalent carbon dioxide was generated. Based on these values, the total amount of greenhouse gases generated between 1999 and 2008, as a result of residential fires, was 979,950,020 kg (2,160,419,982 lb.) If sprinklers had been used, the total mass of greenhouse gases, over the 10-year period, would have been reduced by 97.8% to 21,558,900 kg (47,529,240 lb.) On a yearly basis the values are reduced by a factor of 10.

As a reference, the EPA reports that "In the United States, approximately 4 metric tons of carbon dioxide (CO_2) equivalent (almost 9,000 pounds) per person per year (about 17% of total U.S. emissions) are emitted from people's homes. The three main sources of greenhouse gas emissions from homes are electricity use, heating and waste."

4.2 WATER USE EXTRAPOLATION

In this section, the quantity of water needed to extinguish a fire in structures larger than the one used in this study will be estimated. The key assumption in this analysis is that the quantity of water needed to extinguish the fire is directly proportional to the area of the room. It is reported in Section 3.7 that the quantity of water used in non-sprinklered test (b) was 3,835 L (1,013 gal.). Based on the area of the room used in this study the quantity of water per unit area needed to extinguish the fire without a sprinkler was 138 L/m^2 (3.4 gal/ft^2).

Assuming various percentages of damage to a typical sized residence, the projected quantity of water required by firefighters can be determined and the percent reduction achieved by using a sprinkler can be estimated. The experimental data reported in Section 3.7 and the estimates in Table 16 indicate that, in the event of a fire, for an average sized home of 164 m^2 (1,765 ft^2) using sprinklers can reduce the water usage between 50% and 91%.

Table 16: Water Usage Estimates

Percentage Damaged	**Area Damaged m^2 (ft^2)**	**Estimated Water Usage by Firefighters L (gal.)**	**Reduction Achieved by Using Sprinklers (%)**
25	41 (441)	5,644 (1,491)	66
50	82 (883)	11,292 (2,983)	83
75	123 (1,324)	16,936 (4,474)	89
100	164 (1,765)	22,584 (5,966)	91

4.3 FIRE DAMAGE

The combustible loading within each living room consisted of the primary and secondary fuel items, decorative items, and ignition package comprising a combined mass of 309.8 kg (683.0 lb.). The carpet, carpet padding, and plastic window frames are also considered part of the combustible loading, adding an additional 130 kg (287 lb.) of combustible material. Therefore, the total mass of combustible material in each living room was 440 kg (970 lb.).

In the sprinklered test, the items that sustained fire damage included the recliner, loveseat, magazine rack, carpet, and carpet padding. The initial and final mass of each of these items is listed in Table 17. The final mass of the magazine rack, carpet, and carpet padding was not recorded; however, based on the post test images, it is assumed that 80% of the magazine rack was consumed in the fire, and a 457 mm x 457 mm (1.5 ft. by 1.5 ft.) area, or 0.75%, of carpet and carpet padding was damaged in the fire.

Table 17: Mass of Combustibles Consumed in Sprinklered Test

Item	Initial Weight kg (lb.)	Final Weight kg (lb.)	Mass Consumed kg (lb.)
Big Easy Recliner	44.5 (98.1)	40.8 (90)	3.7 (8.1)
Kick Back Loveseat	56.9 (125.5)	49.9 (110)	7.0 (15.4)
Carpet + Carpet Padding	94.0 (207)	93.3 (205.7)	0.7 (1.3)
Magazine Rack	1.7 (3.75)	0.34 (0.75)	1.4 (3.0)
Total	**197.1 (434.5)**	**184.3 (406.4)**	**12.8 (28.5)**

Based on the values listed in Table 17, and the initial weight of all the combustibles in the room, the fraction of material burned in the sprinklered test was 3.0%.

In the non-sprinklered test, following the fire extinguishment, none of the items within the room were recognizable and the final mass of individual items could not be determined directly. The mass of materials consumed is, therefore, estimated based on the total energy released and an assumption for the chemical heat of combustion. In Section 3.3, the total energy released from the fire was calculated to be 5,169 MJ. Using the chemical heat of combustion for pine, i.e., 12,400 kJ/kg, as the lower bound and that of flexible polyurethane foam, i.e., 19,000 kJ/kg, as the upper bound, it is calculated that the mass of material consumed in the fire was between 272 kg (600 lb.) and 417 kg (919 lb.), or 62% to 95% of the total room fuel load. For the fire scenario used in this study, in an actual home, the fire would likely have propagated to adjacent rooms increasing the mass of materials damaged.

The increased fire damage, in the non-sprinklered test, will have a direct impact on a building's sustainability via the embodied carbon associated with materials necessary for reconstruction. As stated previously, Norman *et al.* [24] estimated that the average equivalent annual embodied greenhouse gases per unit area for construction materials associated with residential dwellings is $7.4\ kg_{CO_2} / \left(m^2 - year\right)$. Estimates of the embodied carbon associated with furnishings, contents, and carpet are beyond the scope of this study.

4.4 POTENTIAL ENVIRONMENTAL IMPACTS OF WASTEWATER RUNOFF

The following results and discussion related to the wastewater analysis have been extracted directly from Reference 38. The section and table numbering of the original report have been maintained.

4.3 POTENTIAL ENVIRONMENTAL IMPACTS OF FIRE WATER RUNOFF

Fire water runoff carries with it numerous contaminants and solids that may enter soil, groundwater, or a waterbody and potentially pose a health risk or cause ecological harm. There are numerous examples of large industrial fires where fire fighting water runoff resulted in both short- and long-term devastating environmental impacts, such as fish kills [41]. However, even relatively small-scale fires have the potential to affect the local environment as a result of wastewater runoff[‡‡]*.*

During and after fire-fighting activities, there are several major pathways that the resultant fire wastewater can take to enter the environment:

- *Runoff can enter soil, where contaminants in the runoff may adsorb onto soil particles;*
- *Contaminants bound to soil may eventually leach into groundwater;*
- *Runoff may directly discharge into a nearby pond, wetland, or stream; and*
- *Runoff can enter a stormwater system and eventually discharge into a waterbody.*

Both human and ecological receptors may then contact contaminants adsorbed to soils, may ingest or contact contaminated groundwater or surface water, or may ingest contaminants that have accumulated in food items such as home-grown produce or fish. Pollutant loading to the environment will be directly influenced by the volume of water generated from fire fighting activities and associated wastewater runoff. By reducing the volume of fire wastewater, the potential hazard to the environment may be reduced.

To evaluate the difference in pollutant loading and associated environmental hazards between the Sprinkler and No Sprinkler controlled burns, wastewater results generated from the controlled burns conducted on October 1, 2009 were compared to two types of federal water quality standards: Maximum Contaminant Levels (MCLs) and National Recommended Water Quality Criteria (WQC). Although MCLs and WQC are not directly applicable to wastewater, these criteria can be used as tools to assess potential environmental impacts that may be associated with fire wastewater runoff.

MCLs (USEPA 2006) are criteria applicable to ground and surface waters and are relevant to all potable water supplies (both surface and ground) in the United States. MCLs are not available for each constituent detected in the wastewater samples; in such instances, wastewater

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[‡‡] Air and particulate emissions from fires are also significant pathways with respect to potential environment impacts; however, this section evaluates only the wastewater pathway. Air emissions from the controlled burn scenarios are discussed in Section 3 of this report.

data lacking MCLs were compared to USEPA Secondary Drinking Water Standards, Action Levels or Health Advisories, when available. These drinking water standards are generally designed to be protective of human health. Note that drinking water standards are not available for several of the detected organic constituents or general chemistry parameters. Drinking water standards are presented on Table 4-4.

WQC (USEPA 2009) are numeric limits on the amounts of chemicals that can be present in a river, lake, wetland, or stream and are designed to be protective of both human health and aquatic life. Altogether, there are six separate sets of WQC. Those protective of human health are applicable to waters that can be used as not only a source of potable water but also for fish or shellfish consumption. There are separate human health criteria for potable and non-potable waters. The "water + organism" WQC (for potable water supplies) are equivalent to or lower (i.e., more conservative) than the "organism only" WQC (for non-potable waters). Aquatic life WQC are available for fresh water and saltwater environments, as well as short- and long-term exposures. Of the aquatic life WQC, the Criterion Maximum Concentration (CMC) represents acute exposures in water, whereas the Criterion Continuous Concentration (CCC) represents chronic exposures. For a single fire event, CMCs are most relevant, since the discharge of fire wastewater to a waterway is expected to be a one-time event that occurs for a relatively short duration. Note that WQC are not available for the detected organic constituents and several of the general chemistry parameters. Water quality criteria are presented on Table 4-5.

For purposes of this evaluation, the net concentrations of constituents detected in the controlled burns conducted on October 1, 2009 were compared to these standards. As discussed, these standards are not applicable to wastewater, and this comparison is intended to be used only as a means to assess the relative impact to water quality of both types of controlled burns. The net concentrations in the wastewater represent a worst-case estimate of ground or surface water contamination. Under a more typical scenario, one would expect that only a portion of the total fire wastewater volume would percolate through the ground into an underlying aquifer or migrate overland and discharge into a waterbody. In all likelihood, the concentrations of pollutants in wastewater could be substantially reduced by the time the wastewater enters the receiving waterbody, or the volume of wastewater may never reach a waterbody.

Because there are a variety of environmental factors (such as soil type, volume of the receiving waterbody, depth to groundwater etc.) that could affect the extent of dilution of wastewater into either surface water or a groundwater aquifer, Woodard & Curran applied a generic ten-fold dilution factor to the net wastewater concentrations of constituents in order to estimate hypothetical surface or groundwater concentrations. This generic dilution factor represents the assumption that a ten-fold dilution of the levels of contaminants in wastewater would occur once the wastewater enters a receiving waterbody and is likely conservative for most situations where wastewater would percolate directly into the ground or discharge into a waterbody containing a relatively high volume of water. (Note that many states [e.g., Massachusetts, Connecticut] also use a generic 10-fold dilution factor to derive groundwater contaminant standards that are protective of groundwater migration to surface water bodies.) For smaller streams or wetlands, however, the ten-fold dilution factor may not necessarily be conservative. Estimated surface/groundwater concentrations were compared to drinking water standards and WQC, as shown on Tables 4-4 and 4-5, respectively.

Table 4-4: Comparison of Wastewater Results to USEPA Drinking Water Standards and Guidelines

Parameter	Units	Drinking Water Standard or Guideline		Analytical Results, 10/1/09			
				Sprinkler		No Sprinkler	
				WW-1	Diluted Concentration[1]	WW-2	Diluted Concentration[1]
		Value	Basis	Result	Estimated	Result	Estimated
General Chemistry							
pH	SU	6.5-8.5	SDWR	7.9	7.9	***12.1***	***12.1***
Specific Conductance	umhos/cm			100	10	5,100	510
Solids, Total Dissolved	ug/l	500,000	SDWR	100,000	10,000	***4,300,000***	430,000
Solids, Total Suspended	ug/l			36,000	3,600	640,000	64,000
Cyanide, Total	ug/l	200	MCL (free CN-)	***639***	63.9	55	5.5
Nitrogen, Ammonia	ug/l	30,000	Lifetime HA	1,470	147	4,850	485
Nitrogen, Nitrate	ug/l	10,000	MCL	130	13	440	44
Phosphorus, Total	ug/l			484	48.4	385	38.5
Chemical Oxygen Demand	ug/l			260,000	26,000	650,000	65,000
Total Organic Carbon	ug/l			56,000	5,600	136,000	13,600
Volatile Organic Compounds							
Benzene	ug/l	5	MCL	***62***	***6.2***	***50*** U	
Styrene	ug/l	100	MCL	50 U		63	6.3
Semivolatile Organic Compounds							
Phenol	ug/l	2,000	MCL	280 U		370	37
2-Methylphenol	ug/l			240 U		180	18
3-Methylphenol/ 4-Methylphenol	ug/l			240 U		290	29
Total Metals							
Antimony, Total	ug/l	6	MCL	***50*** U		***272***	***27.2***
Arsenic, Total	ug/l	10	MCL	5 U		7	0.7
Chromium, Total	ug/l	100	MCL	10 U		10	1
Copper, Total	ug/l	1,300	MCLG	21	2.1	6	0.6
Lead, Total	ug/l	15	Action Level	2	0.2	***18***	1.8
Mercury, Total	ug/l	2	MCL	***2.5***	0.25	0.8	0.08
Silver, Total	ug/l	100	SDWR	0.8 U		1.8	0.18
Zinc, Total	ug/l	5,000 / 2,000	SDWR/ Lifetime HA	172	17.2	185	18.5
Dissolved Metals							
Antimony, Dissolved	ug/l	6		***50*** U		***150***	***15***
Copper, Dissolved	ug/l	1,300	Action Level	30	3	10 U	
Mercury, Dissolved	ug/l	2		1.1	0.11	0.6	0.06
Zinc, Dissolved	ug/l	5,000	SDWR	54	5.4	50 U	

Notes:

U	= Constituent not detected at laboratory reporting limit	MCL	= Maximum Contaminant Level
ug/L	= micrograms per liter	MCLG	= Maximum Contaminant Level Goal
SU	= standard units	SDWR	= Safe Drinking Water Regulation
umhos/cm	= micromhos per centimeter	HA	= Health Advisory
Free CN-	The MCL is available for free cyanide. Results are available for total cyanide.	THM	= Total trihalomethanes (chloroform, bromoform, bromodichloromethane)

(1) Estimated surface or groundwater concentration based on wastewater analytical results, adjusted to account for baseline contamination from firefighting water. Estimated concentration assumes wastewater is diluted to one-tenth of the original concentration. pH level of sample was not adjusted.

Bold italicized font indicates that concentration or detection limit exceeds the drinking water standard or guideline.

(2) Results are presented for only the constituents detected at levels higher than those of the recycled firefighting water sample.

Table 4-5: Comparison of Wastewater Results to Federal Water Quality Criteria

Parameter	Units	National Recommended Water Quality Criteria						Analytical Results, 10/1/09			
		Aquatic Life Criteria				*Human Health Criteria*		Sprinkler		No Sprinkler	
		Freshwater		*Saltwater*		*Water + Organism*	*Organism Only*	WW-1 Concentration	Diluted Concentration[5]	WW-2 Concentration	Diluted Concentration[5]
		CMC	*CCC*	*CMC*	*CCC*			Result	Estimated	Result	Estimated
General Chemistry											
pH	SU		6.5-9		6.5-8.5	5-9		7.9	7.9	***12.1***	***12.1***
Specific Conductance	umhos/cm							100	10	5,100	510
Solids, Total Dissolved	ug/l					250,000		***100,000***	10,000	***4,300,000***	***430,000***
Solids, Total Suspended	ug/l							36,000	3,600	640,000	64,000
Cyanide, Total [1]	ug/l	22	5.2	1	1	140	140	***639***	***63.9***	***55***	***5.5***
Nitrogen, Ammonia	ug/l		100(4)					***1,470***	***147***	***4,850***	**485**
Nitrogen, Nitrate	ug/l		100(4)			10,000		***130***	13	***440***	44
Phosphorus, Total	ug/l		8(4)					***484***	**48.4**	***385***	***38.5***
Chemical Oxygen Demand	ug/l							260,000	26,000	650,000	65,000
Total Organic Carbon	ug/l							56,000	5,600	136,000	13,600
Volatile Organic Compounds											
Benzene	ug/l					2.2	51	***62***	***6.2***	***50*** U	
Styrene	ug/l							50 U		63	6.3
Semivolatile Organic Compounds											
Phenol	ug/l					10,000	860,000	280 U		370	37
2-Methylphenol	ug/l							240 U		180	18
3-Methylphenol/ 4-Methylphenol	ug/l							240 U		290	29
Total Metals[2]											
Antimony, Total	ug/l					5.6	640	***50*** U		***272***	***27.2***
Arsenic, Total	ug/l	340	150	69	36	0.018	0.14	***5*** U		***7***	***0.7***
Chromium, Total[3]	ug/l	16	11	1,100	50			10 U		10	1
Copper, Total	ug/l	13	9	4.8	3.1	1,300		***21***	2.1	***6***	0.6
Lead, Total	ug/l	65	2.5	210	8.1			2	0.2	***18***	1.8
Mercury, Total	ug/l	1.4	0.77	1.8	0.94			***2.5***	0.25	***0.8***	0.08
Silver, Total	ug/l	3.2		1.9				0.8 U		1.8	0.18
Zinc, Total	ug/l	120	120	90	81	7,400	26,000	***172***	17.2	***185***	18.5
Dissolved Metals											
Antimony, Dissolved	ug/l					5.6	640	***50*** U		***150***	***15***
Copper, Dissolved	ug/l	13	9	4.8	3.1	1,300		***30***	3	***10*** U	
Mercury, Dissolved	ug/l	1.4	0.77	1.8	0.94			***1.1***	0.11	0.6	0.06
Zinc, Dissolved	ug/l	120	120	90	81	7,400	26,000	54	5.4	50 U	

Notes:

U	= Constituent not detected at laboratory reporting limit
ug/L	= micrograms per liter
SU	= standard units
umhos/cm	= micromhos per centimeter
CMC	= No CCC available. Value is the Criterion Maximum Concentration
Free CN-	= Cyanide (CN-) criteria are available for free, or bioavailable, cyanide. Wastewater results are reported for total cyanide. Total cyanide concentrations are not necessarily indicative of free cyanide concentrations.

(1) Value is for free (physiologically available) cyanide. Note that wastewater samples were analyzed for total cyanide.
(2) Aquatic life criteria are expressed in terms of dissolved metals. Many of the metals criteria are also dependent on water hardness and/or other chemical properties of the waterbody.
The values presented on this table are those reported in the EPA 2009 criteria document and have not been adjusted.
(3) Criteria are presented for hexavalent chromium, the more toxic form of chromium. Note that wastewater samples were analyzed for total chromium.
(4) EPA Ecoregional criteria. Values are the lowest ecoregional criteria for rivers, streams, lakes and reservoirs. Nitrate value is for total nitrogen.
(5) Estimated surface or groundwater concentration based on wastewater analytical results, adjusted to account for baseline contamination from firefighting water.
Estimated concentration assumes wastewater is diluted to one-tenth of the original concentration. pH level of sample was not adjusted.
Bold italicized font indicates that concentration or detection limit exceeds the drinking water standard or guideline.
(6) Results are presented for only the constituents detected at levels higher than those of the recycled firefighting water sample.

Comparison to Drinking Water Standards

For this evaluation, wastewater net concentrations based on the October 1, 2009 results were compared to Federal drinking water standards and guidelines (i.e., MCLs and Health Advisories; USEPA 2006), assuming that ground- or surface water at a site could be used as a potential source of potable water. Drinking water standards and guidelines are presented in Table 4-4.

Under a worst-case scenario, where all of the wastewater from a fire runs off or percolates into a potable water source and assuming that there is no decrease in the concentration of contaminants (i.e., the drinking water source would contain 100% of the initial concentration of a contaminant present in the wastewater), the resultant concentrations of numerous contaminants could exceed drinking water standards for both Sprinkler and No Sprinkler *controlled burns, suggesting that wastewater could potentially pose a health risk to users of an impacted water supply. Under a more realistic scenario, assuming that a 10-fold dilution of contaminant concentrations in wastewater would occur once wastewater enters a drinking water supply, fewer constituents exceed the MCLs. The following table summarizes the parameters and constituents that exceed MCLs for each controlled burn.*

Table 4-6: Constituents in Wastewater Exceeding Federal Drinking Water Standards

Sprinkler Controlled Burn	No Sprinkler Controlled Burn
Benzene	pH Antimony

This comparison indicates that different classes of pollutants in wastewater generated from a fire in a structure may potentially be present at levels exceeding Federal drinking water standards.

Comparison to Water Quality Criteria

Detected concentrations and diluted concentrations of constituents in each wastewater sample were compared to WQC, as shown on Table 4-5. Exceedances are summarized in the following table for each controlled burn.

Table 4-7: Constituents in Wastewater Exceeding Federal Water Quality Criteria

Sprinkler Controlled Burn	No Sprinkler Controlled Burn
Total cyanide Nitrogen (ammonia) Phosphorous Benzene	pH Total dissolved solids Total cyanide Nitrogen (ammonia) Phosphorous Antimony Arsenic

As indicated above, more constituents detected in the No Sprinkler controlled burn sample (in particular, heavy metals) exceed WQC compared to the Sprinkler controlled burn sample. Again, assuming that a 10-fold dilution of pollutant concentrations would occur once the wastewater entered a waterbody, several constituents remain at levels exceeding WQC in the No Sprinkler controlled burn, whereas fewer constituents under the Sprinkler controlled burn exceed WQC.

4.5 LANDFILL IMPACTS

In this section the environmental impact associated with disposing solid waste materials in a landfill is discussed[§§] in terms of total lifetime carbon dioxide emissions.

[§§] Evaluating the impact associated with alternative disposal such as recycling or energy recovery is beyond the scope of this project.

In the sprinklered test, only a small portion of the room furnishings was damaged. However, any fire damaged items would need to be replaced. The total mass of materials needing to be disposed of is 184.3 kg (406 lb.); the final mass of each of the items is listed in Table 17. Additional materials damaged due to smoke and water may need to be disposed of and replaced; however, assessment of this part of the damage would be very subjective and beyond the scope of this analysis.

In the non-sprinklered test, the mass of materials within the enclosure requiring disposal is assumed to be the remaining 5.3% to 38.2% of material, or 23.2 kg to 168 kg (51.1 lb. to 370.4 lb.), as discussed in Section 4.3. Although not included in this study, the extensive damage to the entire enclosure would require complete demolition increasing the landfill contribution.

Decomposition rates of furniture and furnishings in landfills, and the associated greenhouse gas emissions, are not readily available; however, estimates can be made based on data for wood and forest products. Micales and Skog [42] state that only "0-3% of the carbon from wood are ever emitted as landfill gas. The remaining carbon . . . remains in the landfill indefinitely." The methane yield for wood in a landfill is reported as 0.000 – 0.013 $kg_{CH_4}/kg_{dry\ wood}$. To determine the equivalent mass of CO_2 the value is multiplied by the GWP of methane. The resulting equivalent carbon dioxide generated by furniture and furnishings in landfills is 0.000 - 0.325 $kg_{CO_2}/kg_{dry\ wood}$.

The EPA reports that "as with other inorganic materials…there are zero landfill methane emissions, landfill carbon storage, or avoided utility emissions associated with landfilling carpet" [43]. In other words, carpet in landfills does not contribute to greenhouse gas emissions and can be omitted from this analysis.

The amounts of materials disposed of in a landfill from the sprinklered and non-sprinklered test, based on the analysis in Section 4.3, are listed in Table 18. For the sprinklered test the mass of materials is divided into carpet and furniture. Since the carpet does not contribute to the landfill emissions, the total equivalent carbon dioxide emission of 33.5 kg (74 lb.) is based solely on the quantity of wood products. For the non-sprinklered test, due to the excessive damage, the mass of materials could not be separated. As such, the total equivalent carbon dioxide emission of 7.5 - 54.6 kg (16.5 - 120.4 lb.) is based on the total mass of disposed materials.

Table 18: Mass and Carbon Dioxide Emissions from Damaged Materials in a Landfill

	Mass of Materials [kg (lb.)]		**Carbon Dioxide Emissions [kg (lb.)]**	
	Carpet	**Wood Products**	**Carpet**	**Wood Products**
Sprinklered	94.0 (207)	103.1 (227.3)	0	33.5 (74)
Non-Sprinklered	---	23.2 – 168 (51.1 - 370.4)	---	7.5 – 54.6 (16.5 – 120.4)

The values presented represent a conservative estimate of the impact of a non-sprinklered fire on landfill greenhouse gas emissions. As noted previously, there was extensive damage to the entire enclosure in the non-sprinklered test that would require complete demolition and add to the mass of material sent to a landfill. Furthermore, if additional rooms had been present, the fire would have propagated and additional materials would have required disposal in a landfill.

4.6 ROOM TENABILITY

Although not the main focus of this project, a brief analysis on the tenability within the sprinklered and non-sprinklered rooms will be provided in this section.

Fires generate a variety of toxic gases that have a synergistic physiological effect on humans; however, carbon monoxide inhalation is considered the key factor in fire fatalities. The physiological effects from carbon monoxide exposure range from headaches to death depending on the level of carbon monoxide exposure and the duration; some examples are provided in Table 19 [44]. In addition to the maximum concentrations, Reference 45 states that a time integrated exposure of 43,000 ppm-minutes will result in incapacitation, while 120,000 ppm-minutes is lethal.

Table 19: Physiological Effects of Carbon Monoxide Exposure and the Times Critical Levels Were Reached in the Sprinklered and Non-Sprinklered Tests

Level of CO (ppm)	Physiological Effects	Non-Sprinklered (s)	Sprinklered (s)
0	Normal, fresh air	0	0
100	Slight headache after 1-2 hours	157	179
200	Possible mild headache after 2-3 hours	167	334
400	Headache and nausea after 1-2 hours	238	NA
800	Headache, nausea, and dizziness after 45 minutes; collapse and possible unconsciousness after 2 hours	246	NA
1,000	Loss of consciousness after 1 hour	247	NA
1,600	Headache, nausea, and dizziness after 20 minutes	249	NA
3,200	Headache and dizziness after 5-10 minutes; unconsciousness after 30 minutes	254	NA
6,400	Headache and dizziness after 1-2 minutes; unconsciousness and danger of death after 10-15 minutes	261	NA
12,800	Immediate physiological effects; unconsciousness and danger of death after 1-3 minutes	272	NA

Elevated temperatures can also impact survivability. Purser states that “a victim exposed for more than a few minutes to high temperatures and heat fluxes (exceeding 120°C) in a fire is likely to suffer burns and die either during or immediately after exposure, due principally to hyperthermia” [46].

For the sake of this analysis, tenability within the rooms will be assessed based on the following three criteria measured at the 1.5 m (5 ft.) elevation within the center of the room:

- Maximum carbon monoxide level
- Time integrated carbon monoxide exposure
- Air temperature

The measured carbon monoxide levels at a 1.5 m (5 ft.) elevation in the center of the room are shown in Figure 32 and Figure 33, for the sprinklered and non-sprinklered rooms respectively.

In addition to the time resolved carbon monoxide concentrations, the integrated carbon monoxide is also plotted for each test.

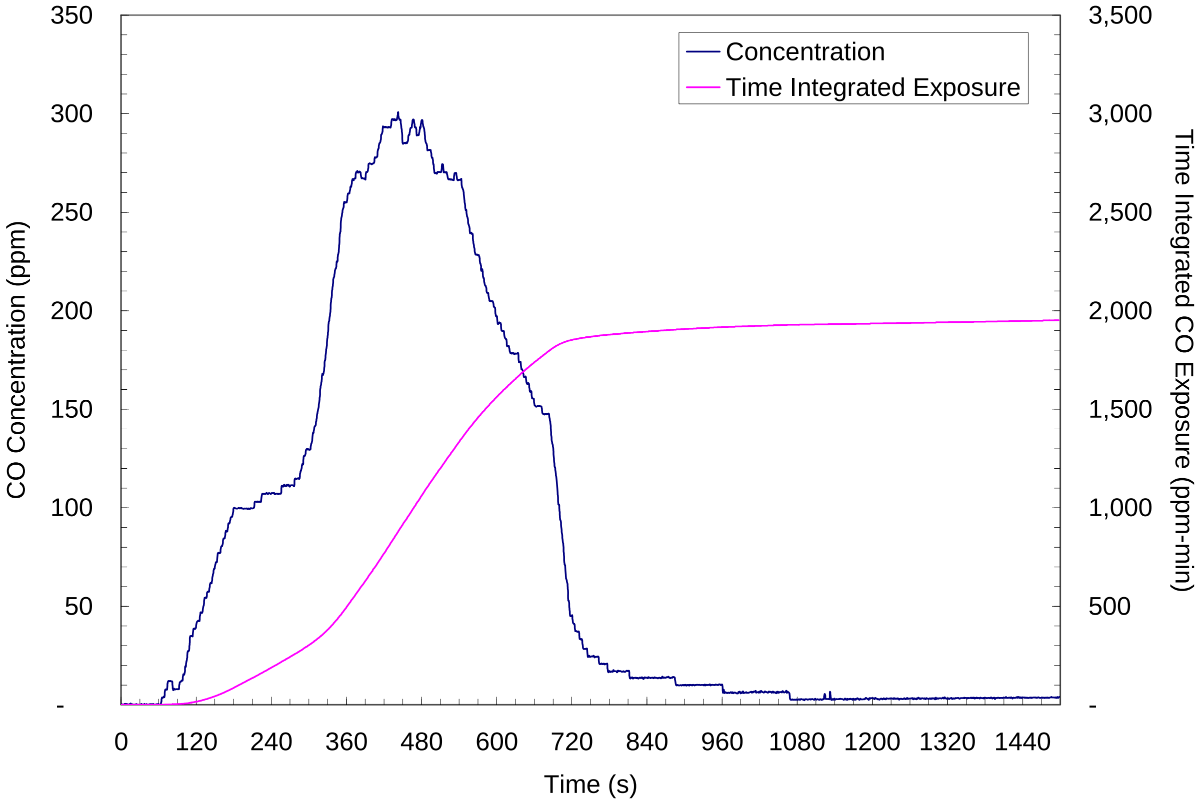

Figure 32: Carbon monoxide concentrations and integrated values as a function of time for the sprinklered test.

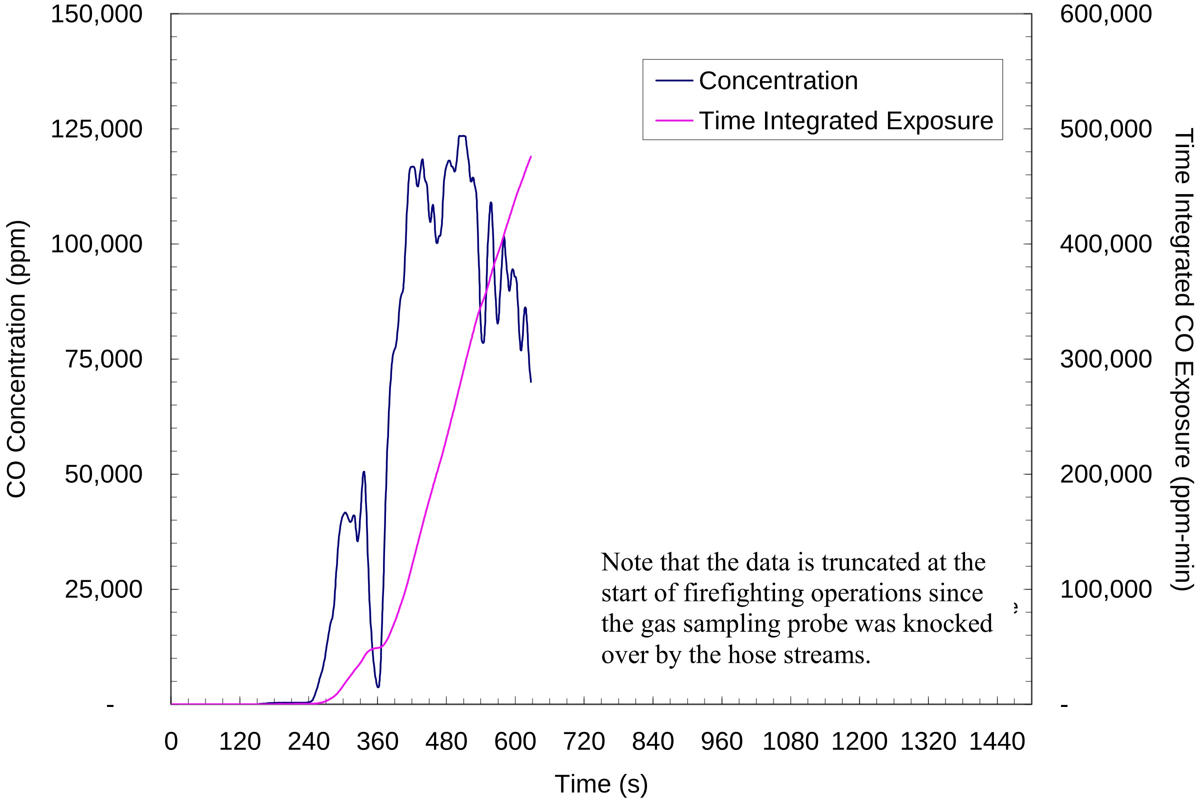

Figure 33: Carbon monoxide concentrations and integrated values as a function of time for the non-sprinklered test.

In the non-sprinklered test the maximum carbon monoxide concentration was in excess of 12% (120,000), an order of magnitude greater than that associated with immediate physiological effects and death. Conversely, in the sprinklered test the maximum carbon monoxide level was 300 ppm, which, based on the data in Table 19, would result in a headache and possibly nausea after one to three hours of exposure.

The integrated carbon monoxide levels in the sprinklered test did not reach either the incapacitation or lethal levels. The maximum value was 1,952 ppm-minutes, more than 20 times lower than the value associated with incapacitation. In the non-sprinklered test, the incapacitation level of 43,000 ppm-minutes was reached 339 seconds after ignition, while the lethal level of 120,000 ppm-minutes was reached 420 seconds after ignition.

The measured air temperatures at the 1.5 m (5 ft.) elevation in the center of the room as a function of time for the sprinklered and non-sprinklered tests are shown in Figure 34.

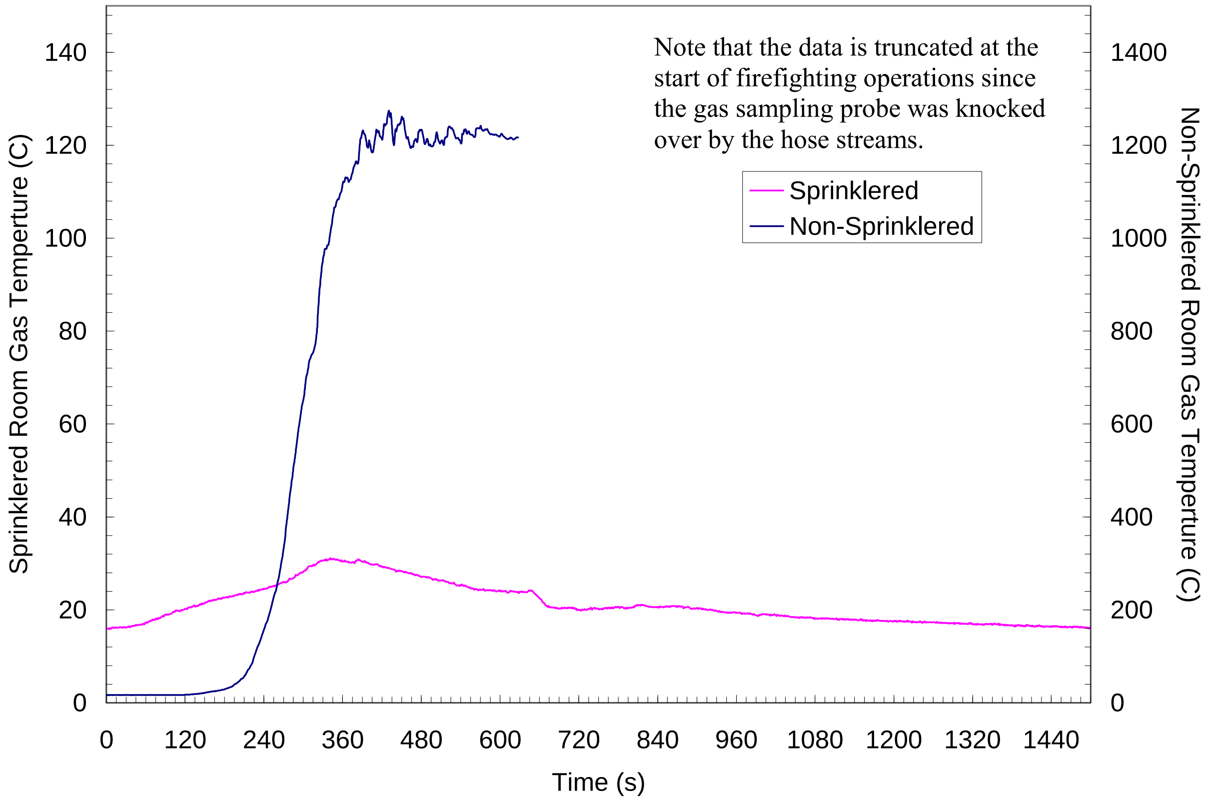

Figure 34: Air temperature as a function of time for the sprinklered and non-sprinklered test at 1.5 m (5 ft.) elevation within the center of the room.

In the non-sprinklered test the critical air temperature of 120°C (248°F) was reached at 230 seconds after ignition and reached a maximum level of 1274°C (2325°F). In the sprinklered test the maximum air temperature at the 1.5 m (5 ft.) elevation was 31°C (88°F).

The results clearly indicate that, in addition to the environmental benefits of using sprinklers, the use of sprinklers also results in maintaining safe, tenable conditions within the room.

5 CONCLUSIONS

The research presented in this report has demonstrated that automatic fire sprinklers protect the environment while further verifying that they reduce property damage and protect lives. The work included an analysis of the contribution of risk factors, such as fire, on the total lifecycle carbon emissions of a home and the reduction to that contribution achieved via the use of automatic fire sprinklers.

In support of the theoretical analysis, large-scale fire tests were conducted to quantify the reduction in the environmental impact via the use of sprinklers. Quantification of the environmental benefit achieved by using automatic fire sprinklers was based on comparisons of measurements between a sprinklered and non-sprinklered test and included total greenhouse gas production, quantity of water required to extinguish the fire, quality of water run-off, potential impact of wastewater runoff on groundwater and surface water, and mass of materials requiring disposal. Key conclusions from the experimental portion of the project are:

- In the event of a fire, the use of sprinklers reduces greenhouse gas emissions by 97.8%.
- In the event of a fire, the use of sprinklers reduces water usage between 50% and 91%.
- In the event of a fire, the use of sprinklers reduces fire damage.
- In the sprinklered test, flashover did not occur and the fire was contained to the room of origin.
- In the non-sprinklered test, flashover occurred prior to fire service intervention; therefore, additional materials would have been damaged, a greater mass of greenhouse gases would have been emitted, and additional materials would have been disposed of in a landfill.
- The total air emissions generated during the sprinklered test were significantly lower than the total air emissions generated during the non-sprinklered test.
- Of the 123 species of greenhouse gas and criteria pollutants, volatile and semi-volatile organic and inorganic compounds, heavy metals, and particulate matter analyzed, only 76 were detected in the air emissions in either the sprinklered or non-sprinklered tests.

- Of the 76 species detected, the ratio of non-sprinklered to sprinklered levels for 24 of the species was in excess of 10:1. Eleven were detected at a ratio in excess of 50:1, and of those six were detected at a ratio in excess of 100:1. The remaining species were detected at the same order of magnitude.
- Fewer persistent pollutants, such as heavy metals, and fewer solids were detected in the wastewater sample from the sprinklered test compared to those found in the non-sprinklered test.
- More constituents were detected in the non-sprinklered test that exceeded both federal drinking water standards and water quality standards than in the sprinklered test.
- The pH value of the non-sprinklered wastewater was between 11.6 and 12.1 versus the pH of 7.9 for the sprinklered test. Wastewater exhibiting pH values greater than 9.0 exceed the allowable discharge range of 5.5 to 9.0 required by environmental regulatory agencies. Wastewater exhibiting pH values greater than 10.0 represent a serious environmental concern.
- Wastewater generated from a fire in a structure not equipped with a sprinkler system may potentially have a greater impact on a water supply, due to the higher pollutant load that is carried with the wastewater stream.
- Analysis of the solid waste samples indicated that the ash/charred materials from neither the sprinklered nor the non-sprinklered test would be considered “hazardous waste,” and that the wastes are not anticipated to significantly leach once landfilled.

6 REFERENCES

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