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Abstract

Casualties in fires--and in particular, deaths--are tail events. The average fire does not cause deaths or injuries. There is increasing evidence that the people susceptible to dying in fires are a specific subset of the people in homes. It seems likely that the same holds true of the fire and the environment as well. That is, that it is a suite of circumstances that produce deaths (and to a lesser extent injuries) in fires. While there has been a lot of valuable work aimed at identifying characteristics associated with deaths in fire, there has been little aimed at identifying those suites of conditions that produce fire deaths. One that can be readily identified is a cigarette fire ignited on or in the immediate vicinity of a person who is frail. Other suites of circumstances are less clear.

People interact with fires rather than merely reacting to them, and the behaviors they engage in reflect that. This paper introduces a taxonomy of behaviors observed in people in home fires. Behaviors fall into five categories: Investigate, Discuss, Mitigate, Protective Action, and Reentry.

The typical engineering approach to fire design--ASET/RSET--does not effectively capture all observed behaviors in domestic fires. The basic assumption of the approach is that people react to a fire by evacuating, and that the time to evacuate is mostly independent of the fire. But these assumptions break down for domestic fires. A different approach is warranted for fire design for domestic spaces.

Key words

Fire; Home Fires; Human Behavior; RSET; ASET; PADM

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1. Introduction

Homes are where the vast majority of fire deaths and injuries occur. More than three-quarters of civilian fire deaths and almost three-quarters of reported civilian fire injuries occur in home structure fires, while about a quarter of the reported fires in 2014–2018 occurred in home environments[1]. Despite that, until recently there has been very little work looking at home fires. Homes differ from commercial and other public spaces on many dimensions. They tend to have different heat sources, different types of fuels, differences in the number and types of people present, and differences in behaviors. Home fires are important because, while they represent 28 % of all fires that fire departments respond to, they represent 77 % of injuries and deaths from fires. If one is interested in reducing fire deaths and injuries[2] (see Table 1), home fires are where the focus needs to be.

The paradigm of behavior in analyzing and modeling human behavior in fires (domestic and other) has tended to be that a fire starts, people are alerted to it in some way, and then they exit the building and call the fire department. With home fires in particular there is abundant evidence that this model is incomplete. People tend to interact with fire rather than merely reacting to it[3]. While it is clear that people's behavior is influenced by the presence of a fire, the fire's behavior is also influenced by the people around it. For example, when a fire occurs in a home, people commonly engage in behaviors intended to mitigate its effects, and in many cases successfully extinguish it[4]. Even when they do not extinguish the fire, there is often a great deal of activity in between discovering the fire and evacuating the home[5]. This paper sets out to describe what is known about this process.

In this paper domestic fires will be treated as having three components, the fire itself, the environment, and the people present. While these components are not mutually exclusive they will be a useful way of analyzing domestic fires. “Environment” includes escape routes, type of dwelling, state of doors, and fuel load. It will also include the larger environment like the neighborhood, size of the city the dwelling is in and distance to the nearest fire station, among other things. “Fire” includes heat source, and to some extent fuel types and availability. At its simplest, a fire is a growth curve. There is clearly overlap between the fire and the environment since fuel is a component of the fire as well as a characteristic of the environment. Oxygen is a component of the fire, but its availability is dependent on the environment. “People” includes things like their condition (able-bodied, frail, disabled, etc.) state (awake, alert, asleep, intoxicated, etc.) number and locations. Their behavior will also be considered as well as how it affects and is affected by the fire in considerable detail. A taxonomy of behaviors will also be introduced.

To the extent that our concern is the prevention of deaths and injuries, it is important to remember that deaths and injuries are tail events. Around two percent of reported domestic fires result in injuries and fewer than half a percent of reported domestic fires result in deaths. Therefore the average fire is likely not representative of conditions for fires that involve deaths—and vice versa.

This paper starts by looking at each of our components in turn: Sec. 2 looks at the fire component, Sec. 3 at the environment, and Sec. 4 at people. Sec. 5 examines human behavior in detail, and introduces a taxonomy for the behaviors that people involved in home fires

engage in. Sec. 6 discusses models of human behavior that have been used and proposed. Sec. 7 discusses mitigation measures and their effectiveness. Finally, Sec. 8 concludes by making some observations and recommendations for future research.

2. Fire

Most fires are never reported to the fire department. Fires not reported to fire department are generally referred to as “unattended” fires because they are not attended by the fire department. Greene and Andres[4][6] conducted a survey of households and estimated (among other things) the number of fires per hundred households per year and the percentage of those fires that are unattended by the fire department. They found that there were 6.56 fires per hundred households per year of which 96.7 % are not attended by the fire department. Similar results have been found for the United Kingdom[7] and Australia[8][9][10][11]. The results from[7]-[10] were that 75 % of fires are unattended by the fire service, while[11] found that 85 % of injury-inducing fires were unattended by the fire service.

Note that Greene and Andres' results differ in the magnitude of unattended fires from the others, although whether this difference is real or an artifact of sampling and analytic methodologies is not clear. One possible explanation for this difference is this. Greene and Andres ask about fires during the previous three months while the other sources ask about fires over the previous year. Greene and Andres discuss at length the issue of recall—where people forget about incidents as time passes[6]. They show that the longer ago the incident was the less likely people were to remember it, and spend a great deal of time and effort correcting for the recall issue. They also show that people are less likely to forget high-severity incidents than low-severity ones. It seems likely that fire-department attendance by itself would make an incident “high-severity.” That coupled with the likelihood that fire-department attendance is strongly correlated with fire severity suggests that fires where the fire department is present will be better remembered than ones where the fire department is not. That suggests that unattended fires are undercounted relative to attended fires. In addition, the UK and Australian surveys have longer recall periods (one year versus three months) which will tend to exacerbate the recall issue and likely amplify the relative undercounting of unattended fires.

According to [4], 80 % of unattended fires are put out by someone present in the house, and 18 % of fires self extinguish. Similar results apply to the United Kingdom where 70 % of fires are put out by someone in the house[7]. That reinforces the observation that people interact with fire rather than react to it[3]. In particular, a fire's growth is in part determined by the behavior of the people around it rather than being independent of the people around it. Fires during the early morning hours are more deadly than at other times[12]. That is likely due to an increased time to react to fire cues thus allowing the fire to grow further before people react.

Rate of growth of a fire clearly matters to both human behavior and outcome of the fire (e.g.,[3]). A number of other factors are known to impact the risk that a fire represents. Cooking fires, for example, are the most common fires[4] whether reported or unreported. However, they are among the least deadly fires. Fires that start in the living room or bedroom are among the deadliest (based on reported fires)[13], as are fires that start in upholstered

furniture or mattresses[12] (although[14] suggests that new standards have significantly reduced the likelihood of deaths from fires starting in mattresses). In both of those cases fires are starting in large and highly flammable fuel packets. Fires started by smoking materials are also among the deadliest [13][12][1] although likely for very different reasons. Here the reason is likely that the person is often intimate with the fire when it starts.

From this we conclude that speed of growth will matter, which in turn will depend on the fuel the fire starts in as well as the fuel load. Where the fire starts relative to the people in the house will determine how quickly the fire is detected as well as how much time the people have to respond. Whether a the fire starts as a flaming fire or smoldering fire also matters since it influences rate of growth as well as time to detection. Similarly, smoke alarms reduce the risk of reported fires[15][16]. They likely operate by reducing the amount of time to detection, reducing the amount of time a fire has to grow, and thus increasing the likelihood that a fire is extinguished without being reported to the fire department. They do not reduce the risk of casualties conditional on there being a reported fire[15]. One possible explanation is that the fires smoke alarms prevent from being reported are the less aggressive ones.

Other factors associated with fire risk include age and condition of a property[16][13] (although see [17]).

2.1. Detection

Fires in home environments are detected a number of ways. In some cases the person is present when the fire started. Sometimes a fire is detected directly: by seeing or hearing flame, seeing or smelling smoke, or feeling heat. Some fires are detected by detection systems, typically smoke alarms. Finally, a number of fires are not detected until they have gone out. Greene and Andres[4] report that for all fires--including those that were not reported to the fire department--some 22 % are detected because the person was present when the fire started. Another 53 % of respondents reported detecting the fire directly. Only 12 % of fires were detected by the sounding of a smoke alarm. Conditional on being home, the likelihood of detecting a fire by a smoke alarm was higher for attended fires compared to unattended fires. That is what one would expect. If a fire is detected by some means other than the sounding of a smoke alarm (and assuming a smoke alarm is present and functioning) then the fire must have been detected before the smoke alarm could sound. That suggests that fires detected through the sounding of a smoke alarm are detected later than other fires and thus tend to be larger, which in turn would be associated with a higher rate of reporting to the fire department.

Thompson and Wales [18] report on interviews with ten people who were involved in home fires in Kent UK. In all of the fires someone was injured. They reported that in five of the ten cases people first realized something was amiss by some form of direct detection, usually observing smoke. In four of the ten cases they realized something was amiss because a smoke alarm sounded. In the final case, the person was notified by someone else in the home. It is interesting to note that people did not automatically think there was a fire. Generally, it was not until they investigated and actually saw the fire that they realized that there was a fire.

Even though Greene and Andres[4] say that only 12 % of fires are detected by smoke alarms, smoke alarms still have a major impact. First, they found that homes with smoke alarms have

Table 1: Number of fires, injuries and deaths for different types of fires, structures and residences[2].

Type	Fires		Deaths		Injuries		Loss ($Millions)	
All Fires	1291 500	100 %	3704	100 %	16 600	100 %	14 820	100 %
Structure	481 500	37 %	2980	80 %	13 900	84 %	12 287	83 %
Residential	361 500	28 %	2870	77 %	12 700	77 %	7976	54 %
Single-Family	264 500	20 %	2390	65 %	8800	53 %	6428	43 %
Multi-Family	75 000	6 %	380	10 %	3400	20 %	1339	9 %
Other	22 000	2 %	100	3 %	500	3 %	209	1 %

fewer ignitions than homes without. There are a couple of possible explanations. It is possible that the people who install smoke alarms are *a priori* less likely to have fires. But is also seems likely smoke alarms detect a certain number of "almost fires" [19] that people are able to address before they become fires. Thus smoke alarms may well help prevent a significant number of fires. Further Gilbert[15] found that smoke alarms reduce the fraction of fires that get reported to the fire department by about 75 %. His result is consistent with a body of work on the effect of smoke alarms. Istre et al. [20] conducted a smoke-alarm give-away program in conjunction with the Dallas Fire Department and found a 68 % reduction in fire-related deaths and injuries compared to non-program homes, while Mallonee et al. found a decrease of 80 % in the number of fire-related injuries in a similar program in Oklahoma City [21]. Rohde [22] observed that "evidence suggests that smoke alarms play a key role in reducing the number of deaths and injuries associated with household fires each year."

3. Environment

Residential structures are typically divided into single-family homes, multi-family dwellings (including both apartments and condominiums), high-rise dwellings, mobile homes, and other residential structures including in particular group homes and hotels. While high-rise dwellings have characteristics that make separate analysis desirable (and some of the analysis below will treat them separately), they are difficult to separate out from other multifamily dwellings in the data, so they will usually be lumped in with other multifamily dwellings. Other residential structures--like mobile homes, group dwellings, and hotels--are minor contributors to the fire problem. Reported fires and injuries are relatively more common in multifamily dwellings, but deaths are more common in single-family dwellings (see Table 1). It is worth noting that the CPSC survey[4] found that fires (both reported and unreported) were more common in single-family detached residences than in any others (although the differences were not statistically significant). Taking those results at face value, that suggests that fires in multifamily residences are more likely to be reported to the fire department than those in single-family residences. One possible explanation would be that multifamily dwellings are more likely to have alarms that automatically notify the fire department. Other environmental factors that affect fire include renting[4] and vacancy rates [23] which are associated with increased fire risk.

The type and usage of the structure matters to how people behave in a fire. Much of the research on human behavior in fire over the years has focused on commercial occupancies

and other public spaces, but much of those results do not apply to domestic occupancies. For example, in commercial occupancies task attachment--the tendency to keep doing what one was doing and delay response to the fire signal--is common, while it is much less common in domestic settings. Other differences include differences in types of people who tend to be present, less in the way of formal procedures and structure to constrain behavior, increased likelihood of tackling or mitigating a fire, and more instances of reentry[5]. The differences are likely due to differences in the socio-physical environment. Specifically, public and commercial spaces are what are termed “closed” environments while domestic spaces are “open” environments [24]. In “closed” environments, activities--and in particular activities related to fire response--are formalized and managed. In contrast in open environments like domestic spaces activities are not normalized and managed. Thus in the closed environment people are placed in specific roles with specific behavioral expectations, while in open environments such role assignments and behavioral expectations are less formal. In addition, people in the space tend to have a sense of ownership responsibility and control in the space, and often they have loved ones present in the space. These factors all contribute to people being more proactive in dealing with the possibility of a fire in domestic spaces.

Multifamily dwellings represent a mix of open and closed environments. As such behavior will be a mix of both. The interiors of the private dwellings will be largely open environments with the characteristics represented by open environments in general, while the common spaces, hallways, stairwells etc. all represent closed spaces over which the residents have no specific ownership interest[5]. As such behavior in multifamily dwellings will be a hybrid of the behaviors of single-family residential environments and public spaces. High-rise multifamily dwellings have the characteristics of multifamily dwellings generally with the additional characteristics and limitations that being a high rise imposes.

Nilson and Bonander [25] looked at neighborhood-level factors influencing fire fatalities rates in neighborhoods in Sweden. They found that the factors split into two groups: a population vulnerability group (including those over 65, share living alone, share living in nursing homes, among others) and an urbanization and fire-service efficiency group (including Gross Regional Product, urbanization level, fire service response time, among other factors). They found that, accounting for population vulnerability, urbanization and fire-service efficiency decrease the risk of death from fire.

4. People

Much of the risk to human welfare in home fires depends on who is present in the home at the time of the fire. There are three different risks to account for: the risk of fire, the risk of injury and the risk of death. The risks differ depending on who is present, and the risks do not necessarily move together[5]. For example, for older people, fire risk is reduced[4], but risk of death is elevated[1]. Thompson et al.[5] argue that the “conveyor-belt theory”--the idea that fires lead inexorably to injury and then death unless interrupted by some outside force--is questionable at best, and that the risks of fire injury and death need to be treated independently.

Casualties are tail events. Only 1.9 % of fires result in injuries, and only 0.4 % of fires result in deaths. A 95 % confidence interval around the average fire could easily exclude all injury-

causing fires and a 99 % confidence interval around the average fire could easily exclude all fatal fires.

Fire risk is associated with people under the age of 18 [17][16], and in particular with people under the age of 5[16]. Fire risk is negatively associated with people over the age of 65 [17][16]. Number of residents in a household correlated positively with fire risk[16], as does number of smokers [17][16]. Being foreign-born is associated with increased fire risk [26]. Some studies find that income is negatively associated with fire risk [13][16] [27], although income (or rather poverty) is not the direct cause of the increased fire risk, rather other factors that correlate with low income[5]. Risk of fire is associated with larger households, and in particular, more people in the household under 18. On the other hand people in the household over 65 are negatively associated with fire risk. Somewhat surprisingly, households in which the respondent has higher education level is associated with increased fire risk [17] [26].

Risk of death is associated with people who are older (greater than 65 years) or very young (less than 5 years of age)[1][16]. It is also associated with disability. Risk of death is negatively associated with being married[16]. Living alone--and in particular being elderly and living alone--is associated with risk of death in a fire [25] [28]. Low income and socio-economic status has typically been associated with risk of death in fire[16]. Smoking is associated with risk of death as well[16]: fires started by smoking materials are among the deadliest[12] [27].

Jonsson et al. [29] ran a cluster analysis on deaths in fires and found six clusters. The first cluster consisted of deaths caused by burns after the ignition of clothing or paper. They were often smoking fires, often small, typically occurred during the day, and involved elderly female victims. Intoxication was rare. Cluster 2 consisted mainly of smoking-caused furniture fires originating in the living room or bedroom of an apartment. The victim was typically between 45 and 65, male, died of toxic effects, and often intoxicated. Cluster 3 mainly consisted of fires in houses originating in fireplaces or due to various types of electrical fires. The fires tended to be large, and victims were typically either old (80 or over) or young (less than 20). Victims were less likely than usual to be intoxicated. Cluster 4 consisted of kitchen fires. Victims typically died of toxic effects, and were more likely than average to be intoxicated. Cluster 5 consisted of fires occurring on weekday nights. They typically occurred in small communities and in communities with below-average income and education level, and in communities with declining populations. Victims were typically between 45 and 65 and were more likely than average to be intoxicated. Cluster 6 consisted of fires set intentionally.

It has become increasingly clear that deaths and injuries are different[5]. It has been common to think of deaths as extreme injuries: there are processes and circumstances the produce injuries and the stopping time of those processes determines whether a person was injured or killed. However Gilbert and Butry [30] showed that deaths affect different people than those affected by injuries--they termed the people susceptible to death in fire as “frail.” They also showed that the increased susceptibility to fire deaths as a function of age could be completely explained by “frailty.” That is, it is not age that makes a person susceptible to death in fire but “frailty.” They did not attempt to identify what frailty was, but Eggert and Huss [31] evaluated the medical factors that contribute to death in fire. They found that

cardiovascular and cardiopulmonary diseases increase susceptibility to carbon monoxide--the primary toxic gas in home fires--and was the most prominent factor that they identified. Also as people get older their ability to recover from burns decreases, although the reason for this is not clear.

While there is no research on the subject it seems likely that deadly fires will differ from other fires on other dimensions as well. It is likely that the fire characteristics will be different from non-deadly fires and the fire environment will often differ as well. One specific example that is clear is the association between fire started by smoking materials and deadliness. The association is likely the person being intimate with the fire in many cases. In general, though, the deadliness of a fire is correlated with its size[12], while recent research[11] suggests that most injury-inducing fires are not reported to the fire department, which in turn suggests that most injuries occur in relatively small fires.

Given that circumstances--both people present and physical conditions--that produce injuries differ from those that produce deaths in fires, it is entirely possible for a mitigation measure to simultaneously reduce deaths and increase in injuries. For example, a measure that reduces the risk of death may make people feel safer fighting fires and result in an increase in injuries. Behavioral studies make it clear that people are willing to risk injury by fighting and mitigating fires to protect people, pets and property (see discussion in Sec. 5). Even after suffering injury, people often express the willingness take the same risks [18].

There has been a lot of work over the decades devoted to identifying causes and indicators of death in fires, and the results have been relatively consistent. Some of those are causal in that they directly contribute to deaths in fires. Smoking and frailty are examples. Other of the characteristics identified are merely indicative. Poverty, for example, does not cause fires or deaths in fire, but rather tends to correlate with conditions that do. Nevertheless we are only beginning to understand the suite of circumstances that tend to produce deaths. Deaths are tail events, and likely typically involve multiple failures to produce conditions that can produce deaths, and understanding how those conditions go together is only beginning. One example of a suite of circumstances that tend to produce death that is consistent with all the work done to date would be a smoker who is frail (and thus has limited ability to deal with fire) who ignites a fire either their clothing or in their immediate vicinity. The work by Jonsson et al. [29] is an example of examining fatal fires from a systems perspective.

The greater incidence of vulnerable groups in homes--in particular the frail and the very young--is an important factor in understanding behavior in home fires. When such people are present their actions will reflect their vulnerability and will also affect the behavior of others present in the home. Much of the activity during a fire is directly or indirectly intended to ensure the safety of the people present, and the presence of frail and vulnerable persons (and pets) will certainly impact the behavior others present.

5. Human Behavior

As discussed before, the research on human behavior in commercial occupancies and other public spaces is of limited use in domestic environments. For example, in commercial occupancies task attachment is common, while it is much less common in domestic settings.

One thing is clear from the research on human behavior in home fires: that is that people are not passive victims of home fires but are quite active when a fire is discovered (e.g., [18][32][33]). Wood[33] surveyed people's behavior during a fire, looking at cases in the UK. He found that people engaged in a large variety of tasks including (among others) investigating the fire, fighting the fire, some other action to mitigate the fire and its damage, evacuating self or others, preparing for evacuation in some form, warning others, or calling the fire department. Among other findings, he found a number of cases of reentry after evacuation. Bryan[32] conducted similar research in the United States and found similar results.

Thompson and Wales [18] interviewed ten people involved in fires in which a person was injured. Response by people in the house was rapid. People did not realize there was a fire until they actually saw the fire. That was in spite of the fact that they were alerted to something being wrong by seeing smoke or hearing a smoke alarm. There was extensive action taken by the people in the property mostly aimed at mitigating or fighting the fire and evacuating or preparing for evacuation of themselves, their family and pets. Half the interviewees reentered the house at some point after evacuating.

Generally behaviors in home fires fall into five categories: Investigate, Discuss, Mitigate, Protective Action, and Reenter. It is tempting to see these as progressing in order from the first to last--and to some extent they will be discussed as if that were they case--but that will often not be the case. For example, there are abundant cases where behavior goes from investigate directly to protective action. There are examples in [18] where protective action is followed by further mitigation. Reentry in some sense is a special case used to highlight that fact that protective action (usually evacuation) is not necessarily the end of the sequence of behaviors. Reentry is a stand-in for further investigation, mitigation or additional protective action. While this paper analyzes these behaviors as occurring in sequence, in practice people will periodically reassess the situation to decide what to do next. Based on that reevaluation, they may jump steps or back up and engage in behaviors further up the list. Each of these behaviors are evaluated in detail below.

There is an important additional category of behaviors that also has to be considered: Do Nothing. In public spaces (i.e., in “closed” environments) Do Nothing is a common behavior, while it appears to be much less common in the domestic environment, for reasons already discussed. Miller[3] discusses human behavior in 108 fatal residential fires in New Zealand. Out of the 45 fire incidents described in the report, there are only two cases where “Do Nothing” can reasonably describe the behaviors taken.

When the subject is human behavior in fires, panic is often discussed but rarely observed[34][35]. There are two basic problems with panic: it is ill-defined, and it is rare.

There are at least four different categories of definitions of panic in use by researchers and others--and note that the definitions used by researchers have little overlap with the ones used by others (see[34] for a detailed discussion). First, many researchers investigate panic as irrational behavior in fires. Second, panic is often used to refer to competitive flight in a fire--that is, everyone stampeding toward the exit heedless of the effect it has on the survival chances of those around them. Third, people in fires often refer to the expression of strong emotion in some form (mostly by other people) as “panic.” Fourth, people often refer to

stress-induced suboptimality in decisions (judged *ex post*) as a product of "panic." While such phenomena may (and in fact do) occur, investigating them under the heading of "panic" given the vagueness of the term is more likely to result in confusion than clarity.

Panic, by any definition, is rare. Numerous post-incident analyses of incidents of "panic" have found behavior to be rational under the circumstances (although see[3] for some examples of irrational behavior). Competitive flight does happen but is extremely rare, and it tends to occur in cases where death is imminent--that is, in cases where such flight is one of the few rational choices remaining. The remaining definitions, expressions of strong emotion and stress-induced suboptimality in judgment, do not appear to have been studied. There does not appear to have been much research into stress-induced suboptimality in judgment in any context, let alone that of fires. So it is unclear how common those behaviors are or what impact they have on people's behavior or choices in fires.

5.1. Investigate

When some cue alerts people in homes to the possibility of a fire, the first action people typically take is to investigate [18][5]. While the observation is based on limited data, Thompson and Wales [18] found that while people responded promptly to fire cues, they did not realize that there was a fire until they actually saw the fire.

The purpose of the Investigate behavior is to determine what produced the cues that prompt people to realize something may be wrong. As such, its purpose overlaps with that of the Discussion behavior. This behavior is distinguished from Discussion behavior in that investigating involves going to the source of the cues (e.g., going and seeing where the smoke is coming from). When people are precluded from investigating, or perceive themselves as being precluded from investigating, then the process of identifying the source of the cues largely gets taken up by the Discussion behavior.

That implies that in single-family homes the Investigate behavior predominates over the Discuss behavior. In Multifamily dwellings, that will depend on the circumstances. If the fire occurs within the family's space, then Investigate will still predominate. If it occurs somewhere else, then the Discuss behavior will predominate. This does not necessarily mean that either behavior goes away. There are people who investigate in cases where the Discuss behavior tends to predominate, and the Discuss behavior likely is still common in single-family homes (although it has not been documented to my knowledge).

5.2. Discuss

Other works often refer to this as a "milling" phase. This behavior fills two roles. First its objective is to understand what produced the cues that people are responding to. Second its objective is to aid in deciding what to do. As such it overlaps with the Investigation behavior. In many of the case studies where this behavior is observed, the situation is such that a preliminary investigation cannot determine unambiguously what produced the cues. That will be much less common in a home environment. Necessarily the Milling or Discussion behavior will tend to be much abbreviated in home environments where the Investigation behavior is capable of resolving unambiguously what produced the cues, and where the presence of a known fire makes prompt action desirable.

Table 2: Number of casualties by action taken and percent of those casualties that are injured or died by action taken. Data is from NFIRS for the years 2010 to 2016.

	Number	Injury	Death	Unknown
Unknown	39 222	68.8 %	26.4 %	4.8 %
Fire Control	13 267	97.7 %	1.1 %	1.3 %
Escape	10 095	84.3 %	13.6 %	2.1 %
Other	5106	88.2 %	10.1 %	1.8 %
Sleeping	4844	73.8 %	24.2 %	2.1 %
Reentry (excluding Rescue)	2668	94.0 %	4.5 %	1.5 %
Rescue	2382	93.7 %	4.5 %	1.8 %
Unable to Act	1961	64.9 %	33.5 %	1.6 %
Irrational Act	1658	79.3 %	18.3 %	2.4 %
Total	81 203	63 860	14 746	2597

Kuligowski [36][35] defines this as "a communication process whereby individuals in a collective attempt to define the situation..., propose and adopt new appropriate norms for behavior, and seek coordinated action to find a solution to the shared problem at hand...." She adds that the group asks three questions: 1) what happened? 2) what should be done? and 3) who should act first?. Such behaviors have been observed in both commercial settings (in particular with the 9/11 attack on the World Trade Center [36]) and in multifamily dwellings (for example see [37]).

Although observational evidence is lacking, much of this is likely to be less salient in the case of single-family dwellings, where direct investigation can typically answer the question of what happened. Nevertheless, identifying what should be done--developing a plan of action--is still likely to be a product of a (hurried) discussion process. In fact, in family settings the plan of action can have different members of the household performing different actions at the same time. This divide-and-conquer process could explain in part the sex differences in behavior identified by (for example) Wood[33] and Bryan[32]. In many cases a Discussion behavior may precede the Investigation behavior. This serves to emphasize the earlier observation that these behaviors are not sequential steps in a set process but behavior categories that can occur in any order and be repeated as often as needed.

5.3. Mitigate

An important subset of activities that fall into the Mitigation behavior is the process of notifying other occupants and calling the fire department. Again, this behavior is commonly reported among people in domestic fires[33][32] [18]. That said, the bulk of the discussion here focuses on activities that are more directly aimed at fire control in some form.

Mitigation behaviors are common in domestic fires (see for example[33][32] [18]).These include attempts to fight the fire--the vast majority of which are in fact successful [4][7]--removal of fuels, attempts to move the burning object, and closing the door to the fire area. One person reported using tea towels to plug holes to limit the spread of smoke [18]. Other actions, less directly associated with the fire itself, are also undertaken to mitigate the effect of the fire, including closing other doors in the house or turning off appliances or gas.

Fire fighting in particular can be dangerous. In the National Fire Incident Reporting System (NFIRS), from 2010 - 2016 some 32 % of casualties where the activity was identified were from fire control. Fire control was associated with more than 13 000 casualties and formed the single largest category of casualties where activity was identified (see Table 2). Yet, conditional on being a casualty, it was one of the safest activities a person could engage in since only about 1 % of casualties while engaged in fire control resulted in death. Note that this does not mean that fire control is safe. Putting oneself in the way of a fire is inherently less safe than avoiding it. There is no good data how many people engage in firefighting behavior--or, importantly, any way to control for the aggressiveness of the fire.

There are several reasons why fire control is less likely to result in death (compared to injury) than other behaviors. First, people engaged in fire control have excellent information on the state of the fire and are in a good position to judge just how dangerous it is. Second, as mentioned above, deaths and injuries are different. It seems likely that people who are susceptible to dying in fires are less likely to engage in risky behaviors like firefighting. In general, it should not be surprising that a behavior that risks injury would, for several reasons, be less likely to result in death.

The decision to fight a fire is a choice based on what people find when they investigate the cues that signal a fire. That decision is inherently a risk-reward judgment. Inherently people balance the risk of injury (or rarely, death) against the possibility of limiting loss--both in terms of property damage, injury or loss of life, and other hedonic losses associated with a fire. If the person judges the risk of injury or death too great from fighting the fire, they will not. The concern, of course, is that people do not have the expertise to judge the risks involved in fighting a fire, and as a result will take greater risks than they should (see [18] who note that in their case studies, firefighting behavior in part stemmed from a “lack of understanding and awareness of the potentially rapid development and effects of smoke”). However, it is also worth noting that in the study by Thompson and Wales [18], most of the people said that they would do the same thing again, even though all participants in the study suffered injury in the fires.

The fire service has traditionally discouraged people from taking their own mitigation actions, but there is no guarantee in general that that would produce better outcomes. First, the vast majority of fires are not reported to the fire department and 80 % of them are extinguished by people on the scene[4]. While not all those fires would grow to the point where they would be reported to the fire department, an order-of-magnitude increase in the number of fires reported to the fire department would not be unbelievable, and it is unlikely that fire departments could handle such an increase. A dramatic increase in the amount of property damage would also be expected. It could be credibly argued that life safety would improve by such a change in behavior, but while such an outcome is believable, it is not guaranteed. The mitigation behaviors people engage in serve to stop fires before they get large in the vast majority of cases. In many other cases the behaviors are aimed at limiting the spread and rate of growth of the fire (see [18][32][33] for examples). There may well be cases where such actions extinguish fires that would otherwise cause harm, or slow the rate of growth of a fire to the point where someone who would otherwise not have time to escape can do so.

5.4. Protective Action

Protective action usually means evacuation, however, there are many cases where the protective action taken is that of sheltering in place (for examples, see [36] [37][3]). In high-rise residences and office buildings it is often the recommended form of protective action and "US building codes have required features for many years ... to allow protect-in-place strategies" [38].

An important stage of protective action is preparation. People rarely if ever just leave. There is sometimes extensive preparation before leaving. In[33][32], and [37] actions taken on when a fire occurred included getting dressed and collecting personal property. In [37] they also included collecting pets. In [36] (in an office context) once the decision had been made to evacuate, people collected their personal belongings and gathered up work in anticipation of a long delay in getting back into the office.

While sheltering in place is sometimes the preferred action in multifamily dwellings [38] (see [37] for examples), the preferred choice of protective action for people in single-family dwellings is likely to be evacuation. Examples can be found in the literature of people choosing to shelter in place in single-family dwellings, but they are usually cases where the possibility of evacuation has been precluded by some other factor (see[3] for examples).

Evacuation is a complex process involving deciding what preparation needs to be done, completing the preparation, and selection of a destination and a route for evacuation. People will not typically evacuate alone, but will tend to make sure that others in the household--including pets--are evacuated as well. That especially applies to households with children or people with disabilities. If a route turns out to be impassible, people will revisit their plan, sometime even abandoning the decision to evacuate in favor of sheltering in place [36]. During evacuation people tend to cluster in groups. Proulx [37] observed evacuations during fire drills of multifamily dwellings and observed the tendency for people to travel in groups while evacuating, even to the point of slowing down to keep pace with the group.

Thompson and Wales [18] suggest that people will "take actions and risks to ensure pets' welfare that are comparable with the actions that would be undertaken to secure the safety of other (human) family members." They describe subjects who put in considerable effort and risk to rescue pets. In [37] preparatory actions people took prior to evacuating included collecting pets. In general, it can be expected that for pet owners, evacuation will involved not only getting the people in the house out, but also the pets. And people will put themselves at risk to do so.

Runefors [27] looked at circumstances that were associated with successful evacuation for people over the age of 65 in Sweden, and found that smaller fires, and fires starting outside or in the kitchen were more likely to be associated with successful evacuation, while smoking fires, fires started by candles or electrical appliances, or being over 80 were associated with a lower chance of successful evacuation.

There is abundant evidence that people are willing to move through smoke when evacuating [39][33][32]. At the same time there are abundant examples of people who are deterred by smoke and turn back (e.g., [36] [39]). Factors that influence people's willingness to move through smoke when evacuating include recollection of the location of an exit and perceived

ability to traverse the distance required to reach the exit, the density and severity of the smoke, and presence or absence of heat with the smoke [39].

There is a substantial literature on the amount of time it takes to complete evacuation much of which overlaps with the literature on pre-evacuation times briefly discussed in Sec. 6.2 below [40]. As a rule, movement times are small in comparison to pre-evacuation times, even in public and multi-family occupancies. Disabled persons, who are likely to be much more common in residences than in public occupancies, can take considerably longer. In experiments some movement-impaired people move nearly as quickly as those without disabilities but those who use walkers tend to move about a third the speed of those without disabilities [41].

5.5. Reentry

Reentry is common in domestic fires[33][32][5]. In [18] half the people interviewed reentered the property at some point. However, reentry is not carried out for its own sake, rather it is done for the purpose of carrying out some other behavior, whether that be further investigation, mitigation, to complete some aspect of preparation that had not been completed, or take additional protective action. In the examples described in [18] the people who reentered the house engaged in all of the these activities.

The idea that a person would reenter a burning building for the purpose of protective action seems counter-intuitive, but evacuation often occurs in stages, evacuating one group of people from the house and then reentering for the purpose of evacuating the next group. In the examples described in [18] actions described on reentry included evacuating additional members of the household (in one case a disabled mother) as well as pets.

6. Models

6.1. Psycho-Social Models

Psycho-social models focus on the decision-making processes involved in choosing what to do. Kuligowski describes two closely related models of decision-making in fires, and in disasters generally. Her first model [42] describes a decision-making which consists of four steps:

- Perceive Cues
- Interpret situation and risk
- Make decision about action
- Perform action

The process is repeated as often as needed. In the behavioral model described here people repeat this process before (and after) every action. In many cases the process is very short, in some cases taking only fractions of a second. Within this model different actions are intended to meet different purposes. The purpose of investigating is to seek information that makes it possible to better interpret the situation and risk, The purpose of discussing is to increase the efficiency and accuracy of decisions. Mitigation and protective action are directed and dealing with the risk.

In a different paper, Kuligowski expands on the middle two steps of this process by adapting the Protective Action Decision Model (PADM) [43] [36], originally developed by Lindell and Perry [44]. The first part of the PADM are the "Pre-Decisional" steps. These start when people receive cues indicative of something different. During this pre-decisional phase three things must happen. People must:

- perceive the cues,
- pay attention to the cues, and
- comprehend the cues.

Comprehension in particular refers to developing an accurate understanding of the environmental cues. Once the cues have been properly comprehended then the process that makes up the core of the PADM begins. That process consists of answering the following questions:

- Is there a real threat that I need to pay attention to (is something really wrong)?
- Do I need to take protective action (do I need to act)?
- What can be done to achieve protective action (what are my options)?
- What is the best method of protection (which option do I choose)?
- Does protective action need to be taken now (do I act now or wait)?

It is worth pointing out that comprehension does not necessarily mean that people interpret the cues as meaning that there is a fire. Rather, it means they understand that the cues are indicative of some hazard. In the World Trade Center on 9/11 (described in detail in [36]) people rapidly arrived at the point of comprehension, understanding that something had happened, and began the PADM process. But much of the time spent in the PADM process consisted of trying to understand what the hazard was (where the purpose was to determine whether there was a real threat), and in determining how immediate it was (where the purpose was to determine whether action needed to be taken). "Protective Action" in the PADM should be thought of broadly as any action that serves to mitigate or protect. Thus any of the behaviors described above could be considered protective action under the PADM.

This process is not a linear one-way process. People engage in information seeking behaviors at all stages of this process and as new information becomes available the may move back or forward in the process. If credible information is presented, a person may skip stages in the process. If a person decides that there is no risk they may terminate the process altogether. In the case of the World Trade Center, there were instances where people in Tower 2 (the second tower hit) had decided to take protective action (specifically, to evacuate), but when an announcement was made advising people to return to their offices, they reconsidered their protective action [36].

Not strictly part of the PADM, but extensively discussed in the papers above, is the observation that this process has a strong social component. That is, the PADM is often carried out in a social setting, that is while milling (or sensemaking as it is often called, or

"Discussing" as it is called further above). That does not mean that there is a "group mind" [35]. People make up their own minds what to do. But they often do so while in consultation with others, and there is a strong imitative component to their decisions. If they see others engaging in some behavior (be it evacuation, sheltering in place, or acting as if there is nothing wrong) they are likely to (but not guaranteed to) do the same thing. When decisions are made in a group setting, there is often a division of labor or roles as well [35].

There have been some work aimed at understanding how to implement the PADM in evacuation models. These include [45] who builds a model for estimating pre-evacuation time based on the PADM. Gwynne [46] and Gwynne et al. [47] extensively discuss the process of designing an evacuation model that implements the PADM.

The PADM overlaps with and complements the behavioral model described in this paper. The PADM is focused on the decision process while the model described in this paper is focused on describing and understanding the possible actions taken. The models overlap in other ways as well. In order decide how serious the threat is, people may decide to investigate. The Discussion behavior often is the environment in which the PADM is carried out. Once any behavior is completed, there is typically a reevaluation, and the PADM process is carried out again.

6.2. ASET/RSET

Design and analysis for fire have traditionally revolved around the concepts of Available Safe Evacuation Time (ASET) and Required Safe Evacuation Time (RSET). The ASET is the amount of time between when ignition occurs and the time at which the fire has grown to the point of limiting the possibility of safe exit. The RSET is the amount of time required for people to become aware of the fire and safely evacuate. The ASET depends on the nature of the fire, fuels and environment, while the RSET includes the time till people become aware of the fire, the pre-evacuation time (sometime called pre-movement time) and the movement time. The intent of this approach is to be able to estimate ASET independent of the actions of the people (except, possibly for their initial locations) and to estimate RSET independent of the fire. The ASET/RSET model was developed with public spaces in mind and does not fit domestic occupancies particularly well. However, the following paragraphs will evaluate it in the domestic environment.

ASET is a function of the fire and environment. It will depend on the heat source, availability of fuels and air, location relative to escape routes, state of doors, and other environmental factors. For this discussion there are two special cases that deserve special mention: fires with ASET of zero and fires with ASET that is essentially infinite. Fires with ASET of zero are fires that start on the person or in their immediate vicinity. Such fires form a significant fraction of fatal fires [48] [49] (see[3] for examples). Fires with ASET that is essentially infinite include fires where the conditions are such that they will never grow to the point of impeding escape. Such fires will eventually self-extinguish (typically by running out of fuels to burn) before they grow too large. They will likely include a large number of the fires that are confined to the object of origin and kitchen or cooking fires.

RSET is typically broken down into the time required to be notified of the fire (including any investigation time required), pre-evacuation time, and movement time. Notification time will depend on a number of factors including (among others) time of day, whether the person is

asleep, presence or absence of smoke alarms, and location of the fire (see Sec. 2.1). Pre-evacuation time includes all the time and activities from the time the fire is confirmed (that is, as soon as the Investigate activity is completed, or at the point when the people believe there is a fire) until people begin the evacuation process. In the domestic environment this includes the time required for mitigation activities as well as the preparation time required before people begin to move toward the exit. There is a growing literature measuring pre-evacuation time and movement time in a number of occupancies [50], [37] [51] [52]. The bulk of these papers are devoted to commercial occupancies, but some look at multifamily occupancies and other occupancies as well. While these papers can provide insight into behavior in multifamily occupancies, for reasons discussed below they are likely to be less applicable to single-family dwellings.

Movement time is the amount of time it takes from when people start moving toward the exit until everyone is fully evacuated. Note that this includes reentry when reentry is performed for the purpose of furthering evacuation. Evacuation is considered complete when the people involved consider it complete. Thus, while outside observers may consider evacuation complete when all the people are out of the house, the people involved may not consider it complete until all the pets are out of the house as well. Since we are concerned with human behavior as it is rather than as it should be, we consider evacuation complete when the people involved consider it complete.

RSET is where the traditional modeling approach breaks down with domestic fires. The assumption is that people react to a fire by evacuating, and that the time required is mostly independent of the fire. But the former is definitely not true of domestic fires, and the latter is likely not true. To the extent that people engage in mitigation measures before starting evacuation--as the evidence strongly suggests--the pre-evacuation time will depend on the value of the ASET. That is, mitigation activities will tend to continue until the fire reaches a state that the person engaged in the activity considers unsafe, and then evacuation activities will commence. Furthermore, the experimental literature and modeling approaches for RSET tend to assume that movement is one-way. They do not contemplate reentry or staged evacuations, both of which appear to be common. These all tend to suggest that a different approach may be appropriate in domestic fires.

7. Mitigation Measures

The most common mitigation measure is smoke alarms. More than 90 % of homes have smoke alarms [19][6][15]. They are widely considered to be one of the most effective measures for preventing harm from fires [22] [19][1] [53]. Interestingly, smoke alarms also appear to fill a fire-prevention role[4] [19]. They likely fill that role by detecting what Ahrens [19] calls “almost fires,” which are then successfully “extinguished” before they actually become fires.

Gilbert[15] attempts to estimate the impact of smoke detectors on reported fires and casualties. He found that smoke alarms reduced reported fires by 70 to 80 % and reported casualties by 60 to 70 %. Clare et al. [54] examined the relationship between smoke alarms, fire department response time (as determined by the last unit on scene), and likelihood of a fire growing beyond the room of origin. They found that when smoke alarms were present, the likelihood of a fire growing beyond the room of origin grew by about 4 % per minute, but

when no smoke alarms were present likelihood of a fire growing beyond the room of origin remained relatively constant at around 80 %. That indicates that smoke alarms have a relatively large effect on limiting the spread of fires.

There have been a number of analyses of the impacts of smoke-alarm distribution programs [20] [21]. A smoke-alarm give-away program in Dallas, TX found that casualties decreased by 63 % in treatment houses over the course of five years after installation of the alarms [20]. A smoke-alarm give-away program in Oklahoma City, OK in the late 80's found an 80 % decrease in injuries in the treatment area over the course of the study [21]. Yelman et al. [55] evaluated the cost effectiveness of the Dallas program and found that, after accounting for lost productivity among victims, and not accounting for fire-prevention effects, the cost per injury prevented of the program was negative. That suggests that smoke-alarm give-away programs are highly cost-effective.

In 2008, the City of Surrey, BC, implemented the HomeSafe program that included, among other things, a phased smoke-alarm give-away program [56]. Over 12 years of the program they found that smoke-alarm usage increased from less that 30 % to about 60 %, while fires decreased from an average of more than 200 per 100 000 residential units to about 60.

Smoke alarms are known to have trouble awakening certain groups of people [39] including the young, older persons and those who are hearing impaired.

Sprinklers show signs of being highly effective for fire and casualty prevention. Warda and Ballesteros [53] considered the evidence on sprinklers to be inconclusive, but more recent evidence has found the them to be effective[1] [57]. Studies to evaluate their cost-effectiveness have found them to be a cost-effective means of fire and injury prevention [58] [59].

Warda and Ballesteros [53] in their review of possible interventions listed child-resistant lighters as an effective strategy, and fire-safe cigarettes and ignition-resistant household items as promising strategies. A recent report by Gilbert et al.[14] found ignition-resistant mattresses to be highly effective at preventing reported fires and fire deaths.

Intriguingly, there is evidence of behavioral change with regard to smoking which indicates that household rules prohibiting smoking inside the house have become more common [60]. This shift has been accompanied by a shift in the percentage of smoking fires that start outside [61]. The impact on reported fires and life-safety has not to date been measured, but it seems likely that this behavioral change has had an impact.

Runefors et al. [48][49] reviewed fire investigation reports for 144 fatal fires in Sweden with the purpose of identifying measures that would have prevented the fatalities. The most effective measures differed depending on whether the fire was smoking-caused or not. For all fires, the most effective measures were thermal- or smoke-activated suppression systems, smoke alarms, or flame-resistant bed-clothes. Since many of the smoking-related fatalities involve the smoker being intimate with the fire, several of the measures that were effective generally were much less effective for smoking-related fatalities. For smoking-related fatalities the most effective measures were smoke-activated suppression systems (thermal-activated suppression systems would have been much less effective) and flame-resistant bed-

clothes. Flame-resistant clothing would have been more effective for the smokers, while smoke alarms would have been much less effective.

8. Conclusions

Casualties in fires--and in particular, deaths--are tail events. The average fire does not cause deaths or injuries. There is increasing evidence that the people susceptible to dying in fires are a specific subset of the people in homes. It seems likely that the same holds true of the fire and the environment as well. That is, that it is a suite of circumstances that produce deaths (and to a lesser extent injuries) in fires. While there has been a lot of valuable work aimed at identifying characteristics of people, fires and environments associated with deaths in fire, there has been little aimed at identifying those suites of situational conditions that produce fire deaths. One that can be readily identified is a cigarette fire ignited on or in the immediate vicinity of a person who is frail. Other suites of circumstances are less clear.

There are a number of observations that can be made based on the research regarding fire in domestic environments. The large majority of fires are not reported to the fire department, and evidence suggests that the majority of those fires are put out by the people on site. This occurs in spite of the frequent admonition to “Get out, Stay out....” [18]. It is a reminder that people do not necessarily always act in accordance with fire-safety messaging.

This paper introduces a taxonomy of behavior in home fires. Behaviors are grouped into five categories: Investigate, Discuss, Mitigate, Protective Action, and Reentry. Evidence suggests that the first indications of a fire--things like smoke or the sounding of a smoke alarm--are not sufficient for people to realize that there is a fire. So on detecting those indications people's first action is typically to investigate. The discuss behavior, while it has not been documented in home fires, is well-documented in other types of fires as well as disasters in general. It also serves to emphasize the social nature of the response to domestic fires. Mitigation behaviors are typically aimed at fighting the fire, reducing its rate or extent of spread, or limiting its damage. Protective action, whether evacuating or sheltering in place, is specifically directed toward life-safety. People will often spend as much effort on protecting pets as they do on protecting the other human members of their household. Reentry in some sense is a special case used to highlight that fact that protective action (usually evacuation) is not necessarily the end of the sequence of behaviors. Reentry is a stand-in for further investigation, mitigation or additional protective action.

The typical engineering approach to fire design--ASET/RSET--does not explicitly capture all observed behaviors in domestic fires. The basic assumption of the approach is that people react to a fire by evacuating, and that the time to evacuate is mostly independent of the fire. But these assumptions break down for domestic fires. A different approach is warranted for fire design for domestic spaces.

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