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RSET/ASET, a flawed concept for fire safety assessment

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SUMMARY

For the evaluation of occupant safety in the case of building fires, the Required Safe Egress Time/Available Safe Egress Time (RSET/ASET) concept has become widespread and is now commonly used in the fire safety engineering profession. It has also become commonly used by smoke detector (smoke alarm) manufacturers in assessing whether a particular detector technology is adequate. It is shown in this paper that the concept is intrinsically flawed and its use promotes the diminishment of fire safety available to building occupants. The concept innately ignores the wide variations in capabilities and physical condition of persons involved in fire. It is based on implicitly assuming that, after a brief period where they assess the situation and mobilize themselves, occupants will proceed to the best exit in a robotic manner. This assumption completely fails to recognize that there are very few fires, especially in residential occupancies, where occupants perished or were seriously injured who had endeavored to exit in this robotic manner. Instead, in the vast majority of fire death and serious injury cases, the occupants did not move in such a manner and their evacuation took longer than anticipated on the basis of robotic movement. There is a wide variety of reasons for this, and these are well known in the profession. The concept also ignores that there can be a wide variation in fire scenarios. The same building and the same fire protection features can be evaluated, but both RSET and ASET can change drastically, depending on the scenario used. The consequence of using the RSET/ASET concept for fire safety engineering or product design purposes is that fire deaths and injuries are permitted to occur, which are preventable. Copyright © 2010 John Wiley & Sons, Ltd.

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INTRODUCTION

Most fires will become lethal to a building occupant, if the occupant remains exposed to the products of combustion for a long enough time period. Since early and successful extinguishment cannot be

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ensured for all cases, fire safety strategies for buildings are generally based on timely evacuation of occupants‡. Since a fire may not be obvious to the occupant, especially when sleeping, warning of the occupants by a smoke detector§ is a necessary feature of fire safety.

The mother was woken by a smoke detector, which sounded, but sounded late. She found one of her children and brought the child out of the burning building. She then went back in to get her other child. But she was overcome by smoke while inside and perished. The second child, meanwhile, had exited by himself through another exit and was no longer in the house. In another family, children were being taken care by a babysitter. A fire started on the first floor of a house. There was a smoke detector response, but it was late. The babysitter brought one child out successfully. Then she went to look for the second child. The other child meanwhile had attempted to escape herself, but made the wrong choice of going upstairs, instead of heading for the front door. By the time the babysitter reentered, the stairs were impassable and the child died.

In another fire, the family was in one part of the house, while electrical wiring started a smoldering fire in the living room. Eventually, the fire ignited the Christmas tree, which started burning rapidly. The smoke detector sounded, but too late. The father thought that he could taken the tree outside, but enough of it had come alight that he got badly burned in the process. A smoldering fire started in the sofa. After a very long time, the smoke detector sounded and the mother was woken. She rounded up her two children and attempted to escape through the back door. Unfortunately, the back door had an inside-key deadbolt and she could not get the key to work, despite fiddling with it. Eventually, she decided to exit through a window and get a neighbor's help to break the door down and rescue the children, who had meanwhile run away from her. But when the neighbor arrived, he had to restrain her from reentering, since the fire would have been lethal to anybody reentering. The two children perished. Fire histories of this type are exceedingly common and are known to most fire safety practitioners. The common thread in all of them is that the occupants were notified of the fire when the fire was at a late enough stage so that there would probably have been enough time to move robotically to an exit, but not enough time to have an intervening activity take place.

Another category of slow occupant responses is those where the occupants are moderately slowed down due to their physical condition. Obviously, if occupants are bed-ridden and immobile, or so intoxicated that waking is precluded, it is not expected that a smoke detector's warning will benefit them, even if a very early alarm was sounded. But when occupants are only modestly infirm, the fire safety profession should not dismiss the potential for them to be saved. Examples here would be a person with a leg cast, or one who has taken a tranquilizer, but is still able to wake to an alarm sound, albeit not to move rapidly thereafter.

A number of specific cases have also been documented in the files of the Consumer Product Safety Commission (CPSC). During the night, a student at the University of Miami of Ohio [1] was awoken by the sound of a smoke detector. According to fire reports, the fire was started by smoking materials igniting furniture. When he opened the door of his bedroom, the smoke was so thick that he had to jump out of the window to escape. He was joined by the two students in the adjacent

‡This concept applies only to normal buildings. In some situations, evacuation is impossible and different fire protection strategies are needed. Such exceptions include submarines, aircraft in flight, and other specialized situations.

§We shall use the term smoke detector for all types of devices that are designed to cause an audible alarm to be sounded upon the detection of smoke. Some authors distinguish between central-panel-connected 'smoke detectors' and single-station 'smoke alarms'. For the purposes of this paper, we do not distinguish between these types of devices and will apply the term 'smoke detector' to either type of device.

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bedroom, as well as several students on the second floor, all of whom also jumped out of windows. Three students died who did not jump out of windows. Newspaper stories blamed the students for possibly being impaired, suggesting that they took an especially long time to respond to the alarm and then commenced exiting inefficiently. But according to official reports, the student who first awoke to the smoke detector was not impaired, yet at the time that he awoke the egress paths were already blocked. The tragedy could have been avoided had the smoke detector sounded earlier.

In a fire in Georgia [2], a 57 year old woman and her 96 year old mother died in a fire, thought to be electrical in nature, that smoldered for a period of time. Initial reports from fire investigators stated that 'smoke detectors were operational but were not in the area where the fire started', implying a delayed detection time. Investigators also noted that 'the 57 year old did not know the layout of the home and was not able to break a window', implying a slow egress time. Both assumptions were attempts by the investigators to explain why two people died despite of the working of smoke alarms. However, after further analysis, investigators came to the conclusion that the smoke had plenty of time to reach to the detector and that the most likely reason for the occupants being trapped was the delayed response of the smoke alarm.

Around 6:00 a.m., two adults awoke to the sound of a smoke alarm and realized that it was coming from the apartment next door [3]. Despite heroic attempts, thick smoke prevented them from rescuing the 23 year old mother and her small child. According to investigators, this was an electrical fire that started adjacent to the mother's bed. The child was trapped because she was incapable of self-rescue; yet, she could have been evacuated had her mother been able to act. But the mother was likely incapacitated by high levels of CO; yet, high levels of concomitant smoke did not activate the smoke alarm.

DEVELOPMENT OF THE RSET/ASET CONCEPT

In the evaluation of fire safety for buildings or other places of human occupancy, the modern trend has been to seek to establish quantitative performance metrics. Quantification is always desirable, but especially so when a comparison of two or more alternative strategies is to be made. The most important area where this has been of issue is the provision for adequate escape potential for the occupants of a place where a fire has started. Over the last few decades, a metric has arisen where adequate consideration has not been given to its correctness, since superficially it seems to be a sensible concept. The concept is that occupants of a place undergoing a fire will require a fixed, calculable (or prescribable by *fiat*) time to make their escape. This time is called RSET, the **R**equired **S**afe **E**gress **T**ime. A parallel calculation is then made of ASET, the **A**vailable **S**afe **E**gress **T**ime. If the simple relation ASET $>$ RSET is fulfilled, then it is deemed that the building's fire safety is fully adequate, at least in regards to the safety of escaping occupants. The calculations involved are usually simple to make and the arithmetic relationship is trivially easy to evaluate.

The first significant example of use of the RSET/ASET was the 1975 'Indiana Dunes I' smoke detector study sponsored by NIST [4]. At that time, the terms RSET and ASET were not yet developed, but the evaluation of occupant fire safety in this research study was done using the concept, albeit without the explicit nomenclature.

In the first phase of the Indiana Dunes I study, there was surprisingly no account taken of the time the occupants will consume to make their ultimate escape. The authors simply assumed that, if there was any time, regardless how slight, after the alarm was sounded and before untenable conditions were reached on the escape route, 'success' was achieved. In other words, the assumption

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was made that the occupant will need zero time to make the escape. In 1976, Phase 2 of Indiana Dunes I testing was reported [5], and the analysis was also identical. In 1983, Waterman, one of the authors of the Indiana Dunes I studies, published a follow-on paper [6] that stated that, of course, people will need more than zero time to make their escape, but he did not reanalyze the data with that in mind. Instead, he referred to an unpublished study by Rexford Wilson, who had reanalyzed the data on the basis that it would take the occupants 1, 2, 3, 4, or 5 min to effectuate their escape. Wilson then recommended that, of these choices, 3 min should be selected. This was taken to be conservative, since tests conducted by the City of Los Angeles Fire Department showed that, in a staged exercise, all occupants would escape in less than 1 min. The staged exercise involved persons who were woken from sleep by a simulated fire alarm and were to make their exit upon being woken.

In fairness, it must be pointed out that, while it is obvious today that, in many cases, people perish in fires since they do not move robotically toward a viable exit, this was not necessarily widely known in the mid-1970s. In 1977, Stahl and Archea [7] published a state-of-the-art review of the literature on the emergency evacuation of buildings. The paper discusses the fact that occupants may not proceed to an exit upon being notified by an alarm signal, if they perceive that this is unlikely to be a real fire. It also establishes that it was already known in the mid-70s that an occupant is likely to 'investigate' the status of the fire before commencing the escape. But the authors only make reference to only a single, unpublished paper that discusses the possibility that an occupant may reenter a burning building, and no references to any other behaviors that would cause a significant delay in the person's exiting the building. No instances of attempts to fight a fire that have gone badly wrong are cited. Furthermore, the majority of studies to that date focused on commercial or institutional occupancies and on high-rise buildings, rather than single-family homes, even though the latter are where the overwhelming majority of fire deaths occur. It is the view of the present authors that evacuation studies of institutional buildings should not be used as the basis for assessing fire safety in residences. Apart from the basic fact that fire deaths in commercial/institutional occupancies are comparatively rare, human behavior in private homes tends to be different than in public occupancies. It is extremely unlikely, for example, that a person would delay the escape from an office building due to searching for their pet dog. More important, people are rarely asleep in a commercial building when a fire occurs. Even studies on high-rise housing tend not be helpful towards understanding fires in single-family homes. In 1981, a more comprehensive review paper [8] was able to identify three studies where reentry of buildings was mentioned. But it again demonstrated that the published studies on human behavior in fires remained highly focused on commercial, institutional, and high-rise buildings, devoting but little effort to examine common behavioral aspects associated with fire deaths in single-family houses.

The first important study to focus on non-robotic behavior of people was not available until 1987. In that year, Levin [9] described his EXITT evacuation model, which was the first computer model to consider that human movements in fire are different from water flowing through a channel or marbles sliding downhill[¶]. It explicitly described that the first action of a person becoming aware of a fire is to 'investigate' the fire, which will usually involve moving towards the fire, and not away from it. It also considered that in residences (unlike in public occupancies), upon learning

[¶]Even today, it is rare to find any evacuation model which considers the actual behavior of the occupants and is not simply a mechanistic exercise in mathematics.

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of a fire, a person is likely to first look for, and attempt to rescue family members. Once these preliminaries are completed, however, the occupant was not allowed further counterproductive actions in Levin's model.

The actual RSET/ASET terminology itself and the mathematic relationship 'ASET > RSET' were first explicitly set forth by NIST's Cooper in 1983 [10]. Interestingly, Cooper was a fluid mechanics specialist and did no work on the RSET part of the equation. For ASET, he proposed a fluid-mechanical program that calculates when the upper gas layer descends down to a person's head, at which point the ASET time period is terminated. The calculation of RSET he left to others.

ADOPTION OF THE RSET/ASET CONCEPT

The early history of the RSET/ASET concept was a NIST development. In more recent times, the concept has become widespread, not only throughout the US design community, but also internationally. Barely two years after NIST proposed the concept, the late Jonathan Sime, who was a specialist on human behavior in fires, proposed a revised RSET scheme [11]. Instead of assuming that the only time the individual will need is to react to the alarm signal and march robotically to the optimal exit, he set forth that RSET must consist of three components: RSET $= T_r + T_c + T_e$, where T_r = recognition phase, which includes acts such as investigating; T_c = coping phase, which includes acts such as fire fighting; and T_e, = escape phase, which involves all activities that transpire thereafter, until the occupant actually exits the building. Conceptually, Sime's scheme would be perfectly satisfactory, since the defined periods are elastic enough to accommodate the activities that realistically may transpire. Practically, however, the scheme is unsound, since it implies that a fixed, specified amount of available time is 'good enough.' By contrast, a safety-oriented methodology should deliver the maximum escape time that can be physically and economically provided.

It is also common to find the RSET/ASET concept used as an integral part of the performance-based option in the NFPA 101 Life Safety Code [12], although the latter is not widely used in connection with single-family housing. NFPA's Fire Alarm Code, NFPA 72 [13], also contains a performance-based option but, again, this option is generally used for occupancies other than single-family housing. The Society of Fire Protection Engineers has issued a Guide [14] on human behavior in fire, where they recommend the use of the RSET/ASET concept. The Guide briefly refers to some studies documenting counterproductive activities, but then SFPE makes no recommendation that time be allowed for such activities in doing calculations.

Interestingly, not long ago NFPA's John Hall published a paper entitled 'How many people can be saved from home fires if given more time to escape?' [15]. Hall endeavors to use existing statistics to answer this question, although he recognizes that these are problematic. In the course of analyzing the statistics, Hall makes some decisions that are inexplicable. He considers that some victims are described as 'acting irrationally' and these are unlikely to benefit from having additional escape time. He cites as an example of irrational activity the common situation where a victim ends up in a closet and perishes there. These are invariably either small children, or else adults who got lost due to thick smoke. Thus, in fact, the opposite is true: these victims would almost assuredly have been saved had there been enough warning. With enough warning, escaping occupants will not encounter smoke that is extremely thick and will see the correct egress path. Small children will need adults' help in any case to exit. But if time is sufficient, there will be time for adults to round up and escort the children and there will be no reason for them to meander off by themselves into a closet. It is also generally considered an irrational activity to go back into a burning house to remove possessions or search for pets. But, again, if there is sufficient time provided between when an individual is first warned of a fire and when conditions get terminally bad, the likelihood is increased that individuals performing such counterproductive acts will still be saved. Hall also does not adequately address the reality that some 'irrational' behavior is caused by the loss of mental and decision-making capacities due to CO and toxic gas exposure.

Hall also considers that individuals who are 'unable to act,' since they are too young or are physically impaired, are unlikely to benefit from having additional escape time. This is an over-generalization. If such individuals are alone in the house, then this is likely to be true. But in many cases there are competent adults in the same household. It will take much more time to assist an impaired individual, but if a competent adult is available, there is no reason to believe 'unable to act' individuals will not benefit from having increased escape time. It is important to note that, despite these problems with the approach, Hall concluded that, for individuals capable of reacting to an alarm sound, roughly half of the deaths and $\frac{2}{3}$ of the injuries could be prevented if more time was available between alarm and the point when conditions become untenable. This ultimate conclusion, of course, precisely supports our thesis. Curiously, despite emphasizing agreement [16] with Hall's conclusion, NIST remains [17] an advocate of the kind of RSET/ASET methodology, which is detrimental toward saving lives.

The National Research Council Canada (NRCC), where much valuable research on human behavior in fires has been done, recently published a study [18] where the authors accede to the RSET/ASET concept. Yet, at the same time, they point out[‖] that, for normal, healthy individuals in a Canadian single-family house at night, as much as 11 min can be required after sounding of the alarm before the occupant has finally exited the premises. This is a helpful antidote to Wilson's notion that 3 min should be perfectly adequate.

In recent years, the International Organization for Standardization (ISO) has taken the lead in promoting the RSET/ASET concept. The first-generation ISO document on this topic was ISO 13387-8 [19]. It instructs the reader to use the RSET/ASET concept, but without giving any details how to do it. Functionally, the document espouses Sime's rewrite of the RSET concept, except that 'recognition phase' and 'coping phase' are lumped into a single 'pre-movement time'. This term is unfortunately misleading, however, since 'pre-movement time' actually includes the time when the occupant is in motion, but not yet on the ultimate path toward the exit. Even more confusingly, Cooper, Sime and the earlier researchers assumed that, for RSET and ASET, $t = 0$ corresponds to the time of the sounding of the alarm. ISO redefined these times to begin at ignition, and not at the time of the alarm. Thus, at the present time, if RSET and ASET terms are used, the start time is ambiguous, unless the author makes this explicitly clear. ISO 13571 [20] explicitly instructs the reader to make use of the RSET/ASET concept, although it fails to give any useful guidance for actually doing it. ISO 19706 [21] mandates the use of the RSET/ASET concept, but refers to other ISO standards for the actual details. Finally, ISO is in the process of developing ISO 16738 [22], which is devoted solely to giving guidance on doing RSET/ASET calculations. The current draft discusses at length various human factors, but in the final analysis, ends up wholeheartedly recommending RSET/ASET calculations as a mathematical exercise in physics. The concept that as much escape time as physically and economically viable should be provided does not enter

[‖]The NRCC report states that an RSET up to 16 min can be needed, of which 5 min is the time between the ignition and the sounding of the alarm, whereas 11 min is the post-alarm time.

into it, and it continues the RSET/ASET orthodoxy that the minimum calculated RSET is sufficient, and the benefits of providing more are not considered. Disappointingly, the document explicitly points out that counterproductive, time-consuming behavior may be encountered in a fire, but then illogically assumes that the analyst can successfully do some mathematical calculation to account for all that. This document keeps the ISO 13387-8 notion that there will be some time elapsed prior to movement, but the 'pre-movement time' is renamed 'pre-travel activity'. Following ISO's lead, various countries have subsequently taken on the RSET/ASET concept. For instance, a recent paper from the Peoples' Republic of China [23] explains that Chinese fire evacuation provisions for subway trains are based on RSET/ASET.

USING RSET/ASET

Despite the use of quantitative variables, the evaluation of both RSET and ASET is highly subjective. To calculate ASET, one must quantify the conditions (and therefore, the time) when occupants will no longer be able to move safely through the exit path and into the outdoors or similar safe area. This is a two-part problem: setting 'tenability' or 'incapacitation' criteria, and then assessing the results of experimental fires or computer calculations against these criteria. With criteria in hand, the assessment is trivial, but the criteria themselves are not amenable to any sort of rigorous study. The basic problem is that there is a complex interaction between physical and psychological variables and these are not suitable for experimental study (one generally cannot perform experiments that would endanger human volunteers, while animals do not constitute a suitable surrogate where human intelligence is involved). Thus, various criteria have been proposed (e.g. [20]), but they are highly arbitrary and have little basis in either physics or physiology. There is even no agreement in the profession as to the nature of the population to be protected: should it be the average individual? or should it be a deliberately selected case of infirmity? or should it be based on a normal population distribution, but taken at some level much below the mean? if so, how much?

Although ASET has been ill-defined and lacking objectivity, the problems are much worse with RSET. The basic RSET concept is that human beings act like robots and will proceed to march to the correct exit in a linear and straightforward manner. The time to accomplish this has acquired the name 'movement time' and represents simply extrapolations primarily from fire drills. Some actual fire evacuations have been studied, but these invariably have been of successful evacuations, i.e. dead victims were not studied. To this robot-like 'movement time' is added a 'pre-movement time', with the sum of the two comprising RSET. The pre-movement time attempts to take into account the psychological fact that victims are not athletes waiting for the starter's signal, but rather will require a certain time before they proceed to move anywhere, and an even further time before they decide to go toward the exit. As mentioned above, the latest Canadian study pointed out that up to 11 min might be invested in different actions by the occupants, once the alarm sounds. This finding appears to have been totally ignored, presumably either due to conflict with preconceptions or possibly due to a refusal to recognize the facts of human behavior. We can find no other papers espousing the need for realistic times to be used. Instead, in the latest NIST study on this topic [24], pre-movement times in the range of 0–80 s (this is not a misprint) were used. NIST further elaborated that the maximum 80 s pre-movement time should pertain only to occupants identified as 'elderly', whereas the remaining population was expected to not consume more than 50 s. Neither the elderly nor the non-elderly were presumed to be consuming time to

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search for or assist others. In actual fact, a mother with four small children would be expected to be able to safely rescue each and every one of them, despite the fact that this is a four-fold burden.

The RSET concept is fundamentally flawed because both the movement and the pre-movement times are viewed as fixed numbers that can be adequately obtained and that will provide adequate safety for the intended occupants. As explained above, reality is very different from this mechanistic view and an individual may require what somebody unacquainted with the circumstances might judge to be an 'unreasonable' amount of time. Even individuals who are normal and without the responsibilities of caring for others may take a long time if they had taken some medicine that made them sleepy and slow to react. Thus, RSET is innately a stochastic distribution and it is improper to reduce it to a single number, and flagrantly improper if the chosen number is not at the high-end tail of the distribution.

The solution to this situation does not lie in re-computing movement and pre-movement times on a more realistic basis. This is because the basic RSET/ASET concept converts a quantitative question into a categorical one. The correct question to ask when comparing fire safety strategies is: 'What is the available safe egress time with Strategy B, compared with Strategy A?' This is to be answered quantitatively. If Strategy B offers significantly more egress time than Strategy A, then it is the one that should be chosen, assuming that the implementation is affordable. The RSET/ASET scheme, however, converts this pivotal safety problem into a triviality: If RSET = 100 s, ASET for Strategy A = 105 s, whereas ASET for Strategy B = 1000 s, then both strategies fulfill the requirement that ASET > RSET and, consequently, both are deemed to be equally acceptable. In actual practice, no fire safety strategy can be 100% successful, since for some individuals $RSET \rightarrow \infty$. But the likelihood of saving lives will be increased if the assessment strategy used recognizes that as ASET is progressively increased, more and more lives will be saved.

SMOKE DETECTORS AS A CASE EXAMPLE

The RSET/ASET analysis originated with research on smoke detectors. Not surprisingly, this is the area where the use of the concept has led to the greatest problems in its application. The use of the RSET/ASET concept has formed the basis for various published studies giving the conclusion that photoelectric and ionization smoke detectors are 'equally' competent at saving lives. But examination of the actual test data then shows that the conclusions would be very different if the RSET/ASET concept had not been used. Both types of detectors 'save lives', but a proper analysis of the large body of collected data very clearly indicates that these technologies are not equivalent, and that use of photoelectric smoke detectors in the home would result in a notable increase in 'saving lives'. Extensive performance testing of photoelectric and ionization detectors by Texas A&M University in full-scale house fires revealed very delayed response of ionization detectors to certain fires although conditions were rapidly becoming untenable. RSET/ASET analysis of such data for an 'average' detector response gives a false conclusion that photoelectric and ionization detectors are both adequate when, in reality, ionization detectors frequently only sounded so late as to be ineffective [25].

NIST's latest series of tests (sometimes called 'Indiana Dunes II' to indicate that it is a modern revisitation of the original 1970s work) [24] can perhaps be the best used to illustrate why the RSET/ASET concept is inimical to life safety. The NIST Press Release [26] on the study stated that: 'Smoke alarms are of two types—ionization and photoelectric. Some combination models are sold. According to the two-year NIST home smoke alarm performance study, ionization smoke

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Table I. Average ASET times, along with their standard deviations, as compiled by NIST [27].

	ASET (s)	
	Photoelectric	Ionization
Smoldering fires	2136 ± 1001	276 ± 331
Flaming fires*	129 ± 74	177 ± 69
Cooking fires†	739 ± 148	796 ± 241

*Fast/ultra-fast fires.
†Medium/fast fires.

alarms respond faster to flaming fires, whereas photoelectric smoke alarms respond quicker to smoldering fires. The report concluded that, despite these differences, the placement of either alarm type on every level of the house provided the necessary escape time for the different types of fires examined. The researchers determined the necessary escape times (i.e. RSET) by considering the time that the alarms sounded in various locations and the development of untenable (unsurvivable) conditions (i.e. ASET)'.

The problem with this NIST conclusion is that it is not supported by the data obtained in the study. Table I is a part of the analysis of the data that NIST published [27] in response to questions [28] regarding the study. But such a simple RSET/ASET analysis using averages fails to bring out several important findings:

(1) In the smoldering scenarios, the ionization detectors often did not provide the necessary escape time.
(2) In the most common flaming scenario (cooking fires), the photoelectric detectors, although a little slower, provided at least 8–9 min for most fires.
(3) In the Fast/Ultrafast Flaming scenario, neither type of smoke detector may provide sufficient warning if the occupants are asleep.
(4) These results have to be put in the context that most flaming fires occur while occupants are awake (very small RSETs), whereas the vast majority of smoldering fires occur while occupants are asleep (potentially long RSETs).

In the Report [24] itself, NIST provides a more accurate statement, 'Both common residential smoke alarm technologies (ionization and photoelectric) provided *positive escape times* in *most* fire scenarios'. NIST is correct in stating that there were positive escape times in most scenarios ($\frac{57}{64}$), but they fail to point out that the most common smoke detector in use, i.e. the ionization type, fails to provide a positive escape time in a large fraction of the smoldering fires that could be the most common type of fatal fire that occurs while people are sleeping (Table II).

Focusing now specifically on smoldering fires, Table III gives the ASET results for the smoldering fire tests, as reported by NIST [29]. For the 30 cases (10 tests, 3 variants) considered (tests where data were not successfully collected for both detector types are excluded here), the average ASET = 1794 s for the photoelectric detectors and 160 s for the ionization. It can easily be seen that $1794 \gg 160$ and that, consequently, the photoelectric technology is the one that is more likely to save lives. This, however, is not how NIST's interpretation was made. Again, it should also be noted that NIST's conclusions were based on 'average' smoke detector performance, although in certain test fires, ionization detectors failed to sound at all.

Table II. Tests with positive ASET results.

	Number of tests with 'positive escape times'	
	Photoelectric	Ionization
Smoldering (12 fires)	$\frac{12}{12}$	$\frac{7}{12}$ (est.)
Flaming (16 fires)	$\frac{15}{16}$	$\frac{16}{16}$
Cooking (4 fires)	$\frac{4}{4}$	$\frac{4}{4}$
Totals	$\frac{31}{32}$	$\frac{27}{32}$
	$\frac{58}{64}$	

Table III. Available Safe Egress Time, ASET (s) for smoldering fires in the NIST Indiana Dunes II tests.

		Photoelectric			Ionization		
Test	Type	Every level	Every level + bedrooms	Every room	Every level	Every level + bedrooms	Every room
SDC01	Smoldering chair in living room	1015	1015	2865	190	190	1085
SDC04	Smoldering mattress in bedroom	2290	2290	2290	95	105	105
SDC06	Smoldering mattress in bedroom	2650	2650	2650	65	70	70
SDC08	Smoldering mattress in bedroom	18	1432	1432	22	74	74
SDC11	Smoldering chair in living room	92	92	3458	100	100	378
SDC23	Smoldering chair in living room	3298	3298	3298	16	16	16
SDC27	Smoldering chair in living room (air conditioning)	2772	2800	2800	−54	−54	−54
SDC31	Smoldering chair in living room	270	270	1076	230	230	416
SDC34	Smoldering chair in living room	26	26	2254	26	26	374
SDC37	Smoldering mattress in bedroom	568	568	568	298	298	298

In 2000, Fleming [30] proposed a way of restructuring the RSET/ASET concept for smoke detectors so that it would no longer be inimical to life safety. It requires defining

$$\text{Margin of Safety} = \text{ASET} - \text{RSET}$$

The Margin of Safety variable, which is a quantitative variable, is to be maximized in order to improve life safety. By comparison, the RSET/ASET scheme is a categorical assignment:

$$\text{Margin of Safety} \geqslant 0 \;\rightarrow\; \text{Pass}$$

$$\text{Margin of Safety} < 0 \;\rightarrow\; \text{Fail}$$

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Table IV. Margin of Safety (s) for smoldering fires in the NIST Indiana Dunes II tests.

Test	Type	Photoelectric			Ionization		
		Every level	Every level + bedrooms	Every room	Every level	Every level + bedrooms	Every room
SDC01	Smoldering chair in living room	950	950	2800	125	125	1020
SDC04	Smoldering mattress in bedroom	2225	2225	2225	30	40	40
SDC06	Smoldering mattress in bedroom	2585	2585	2585	0	5	5
SDC08	Smoldering mattress in bedroom	−47	1367	1367	−43	9	9
SDC11	Smoldering chair in living room	27	27	3393	35	35	313
SDC23	Smoldering chair in living room	3233	3233	3233	−49	−49	−49
SDC27	Smoldering chair in living room (air conditioning)	2707	2735	2735	−119	−119	−119
SDC31	Smoldering chair in living room	205	205	1011	165	165	351
SDC34	Smoldering chair in living room	−39	−39	2189	−39	−39	309
SDC37	Smoldering mattress in bedroom	503	503	503	233	233	233

As explained above, one of the major faults of the RSET/ASET scheme is that RSET values, far from being some simple calculation or measurement, are actually a poorly defined stochastic distribution. But by using Fleming's Margin of Safety variable, this would be less of an obstacle. For the purpose of making a comparative design, one could fairly arbitrarily select an RSET value, and it would still be clear which of two alternate designs provides better life safety. It bears emphasizing that only comparative, not absolute, designs can ever be rationally made. Since RSET is a stochastic distribution, it has neither a design value nor a fixed upper limit. Thus, one cannot ever conclude that a design is 'good', but only that design A is 'safer' than design B. However, it should be clear that such a solution is practical and is not an obstacle to competent design.

Table IV shows the values for the Margin of Safety in the NIST tests considered above. These correspond to RSET = 65 s, which is the value specified in NIST's spreadsheet [29]; the published NIST report considered RSET values ranging from 5 to 140 s without adopting a unique value. Using the categorical RSET/ASET concept, 'success' is found for 27 out of 30 cases for the photoelectric detectors and for 21 out of 30 cases for the ionization detectors. But using *Margin of Safety*, it can be seen that the average margin of safety is 1606 s for photoelectric detectors, and 95 s for ionization detectors. Again, we emphasize that an unrealistic RSET = 65 s value was specified. If Wilson's 3 min value was used, the margins of safety would become 1491 s for the photoelectric detectors and −19 s (i.e. occupants became incapacitated and failed to exit) for the ionization detectors. It must be emphasized that this stark conclusion of 'occupants got incapacitated and failed to exit' applies now to the average result for the ionization detectors, and not just a few unfortunate cases. But, as described above, NRCC's 11 min value is a much more realistic example to consider, if saving occupants is the objective. In such case, the average margin of safety becomes 1011 s for the photoelectric detectors and −500 s for the ionization. The evidence is clear about which is the preferred solution, and which is a failure.

The results of Table IV can be used to illustrate two main points: (1) in smoldering fires, photoelectric detectors provide vastly more escape time than ionization detectors; and (2) ionization detectors often are not providing even minimally sufficient ASET for the occupants. The NIST data (as opposed to the NIST conclusions) generally agree with previous research (e.g. [31]) where long-smoldering synthetic materials were tested. However, some of the results of this study are confusing or misleading and were not resolved despite specific notification [28]:

(1) For various bedroom fires (SDC04, SDC06, SDC23, etc.), the ASET did not change when a detector is located in the room of origin, as opposed to in the hallway. This is probably due to the fact that NIST did not have a smoke detector located in the room itself.
(2) For some fires (e.g. SDC34), the difference between the photoelectric and the ionization detectors in the burn room was only a few seconds, whereas the difference in the hallway right outside the room was more than 1000 s. No other researcher studies (e.g. [32]) found this type of variance.
(3) For one living room fire (SDC23) the detectors on the second floor landing responded several thousand seconds before the detectors in the foyer on the first floor, directly outside the living room.

It is disturbing that the NFPA 72 Technical Committee [33] had a task group that considered the RSET/ASET concept in great detail, as propounded in the latest NIST study, and ended up wholeheartedly endorsing both the RSET/ASET concept and the fallacious notion that photoelectric and ionization detectors are equally suited for residential fire detection purposes. The Committee explicitly considered the various factors involved in defining the ASET, but peremptorily accepted NIST's unrealistic RSET values and did not in any way consider the life safety of individuals who behave in a non-robotic fashion. It may be noted that the only two fire service personnel assigned to the task group—individuals who would most likely be most familiar with occupant behavior in residential fires—recorded their dissent from the endorsement.

SUMMARY AND CONCLUSIONS

Human behavior in fires is not mechanistic or robotic. It is common to find that individuals engage in actions that are counterproductive, unsafe, or seemingly unreasonable. A robot could evacuate a house in a very short time. Yet people encountering fires in their homes often behave much less efficiently and become trapped in a fire. Consequently, engineering strategies that ignore these realities are flawed and will necessarily give misleading conclusions.

The RSET/ASET concept was originally developed in 1975/76, although it did not acquire the terminology until somewhat later. Most of the early literature on evacuation was focused solely on fire drills, and none of it involved single-family houses. During the 1970s, a few research studies

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began to be done where single-family house occupants were interviewed. But these few studies focused on examining the evacuation of occupants who had successfully evacuated, and not on determining the activities of individuals who perished.

Since the majority of studies on human factors in fire historically focused on occupants who were successful in escaping from fires, not ones who were unsuccessful and perished, this created the misleading impression that designers can solely consider behaviors that are goal-oriented and ignore behaviors that are counterproductive or otherwise detract from expeditious exiting. These priorities should be reversed—to improve fire safety, it is much more important to study the failures than the successes. This, of course, is more difficult since decedents cannot be interviewed nor can they fill out questionnaires. But, in most cases, facts can be gleaned by interviewing fire fighters, neighbors, and family members.

The RSET/ASET concept is highly simplistic and offers no incentive for improvements in fire safety so that more potential victims could be saved. It is a simplistically deterministic scheme improperly imposed upon a stochastic reality. The time period required for individuals to escape from fire cannot sensibly be expressed by a single number. Instead, there is a distribution. A fraction of persons encountering fire will indeed respond as well as a robot and athletically and single-mindedly propel themselves outdoors. At the other extreme are persons who would take forever, e.g., a bed-ridden invalid with no available rescuers. But in between these two extremes is a very wide range of behaviors and required egress times. Any rigidly set criterion number, unless so large as to capture everything but the extreme tail of the distribution, will unnecessarily sacrifice individuals who could otherwise be saved.

A stochastic distribution cannot be properly represented by a single value picked from the population. In the RSET/ASET scheme, the situation is actually even worse, since the final results are presented as categorical (i.e. yes/no) rather than quantitative. If RSET is assumed to be 100 s and there are two alternative design choices, one giving ASET $=105$ s and the second ASET $=$ $1000\,0s$, under the RSET/ASET scheme these two designs are deemed identical, since in both cases 'ASET $>$ RSET' is Yes. Thus, two designs that are obviously exceedingly different in practice get treated incorrectly as identical. It is not difficult to report the actual test result numbers and to allow a comparison to be made of alternative technologies.

It is especially misleading when RSET/ASET analyses are reported using low RSET values. Canadian researchers have shown that RSET $=11$ min (using the definition that RSET starts at the time of alarm) may sometimes need to be considered even if individuals are healthy and not handicapped. It also bears emphasizing that, in this research, they did not include counterproductive behaviors, which would greatly increase this time period.

The RSET/ASET concept ignores that the same building plus fire protection features may experience vastly different RSET and ASET values, simply because a different fire scenario is used, indicating that these variables have no true or unique value. A fire may occur when occupants are awake (typically a small RSET), or when they are asleep (potentially a large RSET). If the victim is intimate with a flaming fire, ASET might be zero, whereas with a smoldering fire, ASET may be 30 min or more. Even flaming fires vary greatly in their characteristics. In an ultra-fast fire, untenable conditions might be reached in 60–90 s whereas in a moderately fast growing fire, untenable conditions might not occur for 6–9 min.

The consequence of using the RSET/ASET concept for fire safety engineering or product design purposes is that fire deaths and injuries are permitted to occur that are preventable. The evaluation of all life safety warning systems, including smoke detectors, should be based on the earliest possible warning of the presence of a fire. The use of RSET/ASET analysis will not achieve

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this objective; therefore, such analysis should not be used as a design methodology by design professionals, or by detector manufacturers.

It is recommended that the RSET/ASET concept be abandoned and that egress analyses be properly reported on a comparative 'Margin of safety' basis. This applies not just to design work, but also to experimental research projects. The research required to obtain the data is invariably extensive and costly; hence, it is inappropriate to take shortcuts and oversimplify the findings so that the benefits are lost and fire safety is needlessly sacrificed. A 'Margin of safety' analysis constitutes a safety-conscious methodology that aims to deliver the maximum escape time that can be physically and economically provided.

Standards and guidance documents that are based on the RSET/ASET concept should be revised to provide adequate life safety for individuals who do not respond to fire circumstances in a robotic fashion. This process has already started to happen. Utilizing the 'Margin of Safety' concept and realistic assumptions regarding occupant behavior, and fire scenarios several governmental bodies [34–36] and fire safety organizations [37, 38] are starting to espouse the use of photoelectric technology, as opposed to ionization. It is hoped that the present paper stimulates this effort.

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