Fire
Science and
Technology Inc.

30 October 2019

PEER REVIEW OF FRNSW SMOKE ALARM STUDIES

Mr. Adrian Butler
World Fire Safety Foundation
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AUSTRALIA

Dear Adrian,

You asked me to perform a peer review on a smoke alarm study report by Fire & Rescue NSW, entitled "Smoke Alarms in Homes: Stage 2," dated 10 Dec. 2017. Herewith is my analysis and conclusions. This was performed as a professional service of behalf of fire safety of the public, without compensation.

This analysis is provided here in the main text. I also include five Appendices giving additional analyses and background information. I found it necessary to do this, since the Stage 2 report came about only as a consequence of some prior studies, and I considered it important to examine this context.

I gratefully acknowledge valuable comments offered on this subject by Mr David Isaac and by Boston Fire Department's Chief Jay Fleming.

Upon the completion of a draft of this report, the draft was submitted to FRNSW for their comments. Comments were received and taken on board, in regards to areas where it was considered that improvements or clarifications could fruitfully be made in this report. Thus, the document provided herewith is the final version, reflecting consideration of FRNSW comments.

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PEER REVIEW OF FRNSW SMOKE ALARM STUDIES

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Date: 30 October 2019

Task

This report constitutes a peer review of the study "Smoke Alarms in Homes: Stage 2," dated 10 Dec. 2017, issued by Fire & Rescue NSW (FRNSW). In addition, some related and prior work is also reviewed.

Background

Research on any scientific topic is rarely gotten right unless the underlying premises are first carefully analyzed and properly expressed. The scope of the analyzed study is the effectiveness of home smoke alarms. Thus, before one can analyze the effectiveness—and especially analyze any formulation of experimental plans—one must consider the purpose of a home smoke alarm. A residential smoke alarm does not extinguish fire, nor does it do anything else constructive to impede the progress of fire. Instead, it has one function, and one function only: To warn nearby householders of the presence of fire. It is important and certainly non-trivial to consider the role of this function. For the purposes of this analysis, what I will focus on is this: A warning of a hazard is useful only if the individual in question is not already aware of the hazard. In fact, it goes even further. A loud, noisy warning to an individual who is already aware of a hazard is an impediment, since the noise impinging on their consciousness may actively interfere with their focus needed for coping with the incident.

To explore this issue in more detail, in the absence of a smoke alarm warning signal, householders are unlikely to be woken by innate cues from a fire whilst they are sleeping. In some cases, noises or acrid smells from a fire may wake a sleeping person in a timely manner. But this does not occur sufficiently often to be a viable fire defense strategy. Thus, in these circumstances, a warning signal from a smoke alarm is likely to be an invaluable aid to the individual involved. By contrast, we can examine the opposite situation—fires which occur while householders are awake and aware. The presence of a smoke alarm warning signal in such circumstances is likely to be of much less benefit, if any. Most individuals are able to adequately both smell and see fire effluents, if they are awake. Thus, the need for a warning appliance under such circumstances is surely much less acute.

In view of the above, it is important to try to achieve an appreciation of what kinds of fires are more likely to benefit from a smoke alarm warning, versus the kinds less likely to benefit. Combustion science divides fires into two types—smoldering or flaming. But it must be realized that the combustion type can change during the course of a fire. Thus, the important variable to consider is the *type of fire that exists at the beginning stages of the fire*.

Consequently, in fire science it is recognized that different fire scenarios can be categorized as smoldering-start versus flaming-start fires. For example, fires resulting from tipping over a candle onto some furnishings, or overheating a pan of cooking oil, or stuffing a Christmas tree bodily into a fireplace will normally be flaming-start fires. Conversely, fires resulting from cigarettes dropped onto a couch, or faulty wire connections in a wall's void space, or improperly installed furnace flues will typically be smoldering-start fires, even though all of these, in their later stages, may transition into flaming combustion.

Now, we can examine what is a salient distinction between the former and latter categories of fire scenarios. It is rather plainly evident that the flaming-start fires are more likely to occur directly upon an unfortunate human action. In other words, they are less likely to happen unless an awake individual actively did something inappropriate. Meanwhile, for the latter category of scenarios (smoldering), the eruption of a fire is not expected to occur directly upon an individual performing an inappropriate action. Human action may, or may not be involved, but if it is, it is likely to be substantially separated in time. The classic example is the individual who falls asleep on a couch smoking a cigarette. Initial smoldering may start a few minutes after the cigarette contacts the sofa, but much longer will be required for a serious buildup of smoldering combustion toxic gases or the eruption of flaming.

These points could be quantified and reinforced by fire statistics, but unfortunately this is not easy. I have not studied Australian fire statistics, so I will reflect here on the basis of experience in my own country. In the US, fire departments do not report whether a fire incident started as flaming or smoldering. This is not due to an oversight, but due to issues of credible knowledge. Fire officers arriving at a fire scene cannot witness any earlier stages of the fire, prior to their arrival. In fact, a majority of fires attended by the fire services are likely to be in a flaming stage at the arrival of the first-in company. This is because a fire which gets noticed by householders whilst in the smoldering stage is likely to be extinguished by the householders, since it is likely to be at a still-manageable stage. I do not believe that there are useful current statistics on this point from other countries also, since the same considerations apply.

However, there is some older information from US fire services that indicates that smoldering-start fires constitute significantly more than half of the total. In 1963, the National Fire Protection Association (NFPA)[1] reported that 75% of dwelling fires originated as smoldering fires[2]. In the same vein, in 1980, the International Association of Fire Chiefs[3] reported that "*most home fires start from a smoldering source*."

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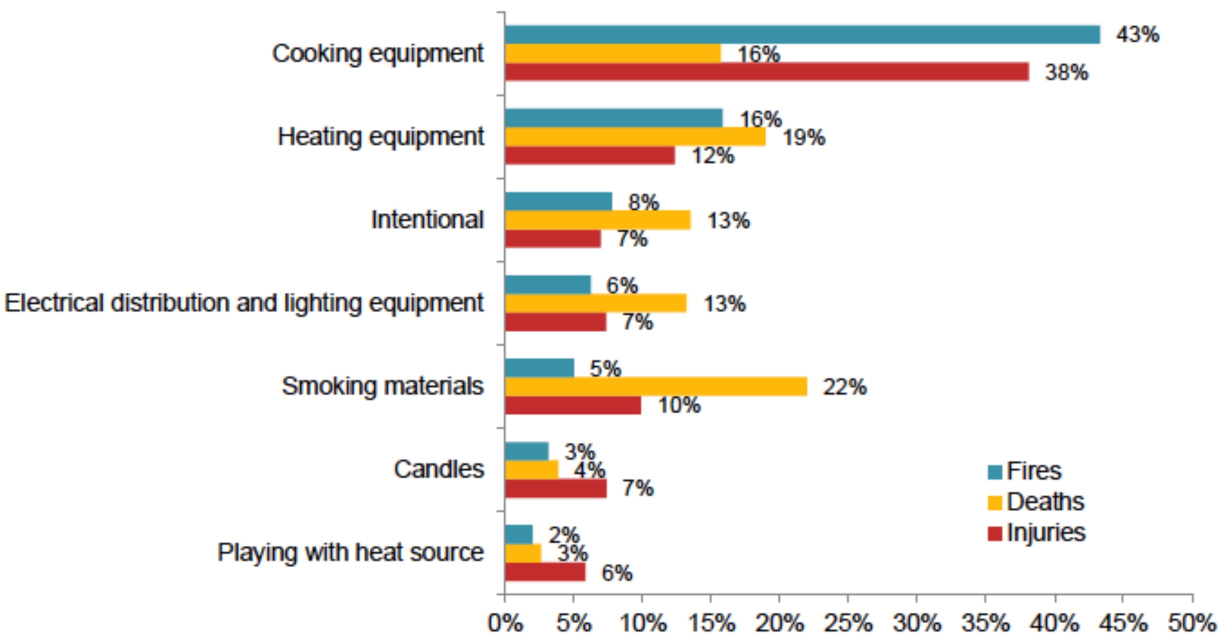
[1] Los Angeles Fire Department Tests—Fire Detection Systems in Dwellings, *NFPA Q.* **56**:3, 201-215 (Jan. 1963).
[2] A recent query was made to NFPA concerning the nature of the study that produced these conclusions, but the reply received was that the details no longer exist in their archives.
[3] Residential Smoke Alarm Report, *The International Fire Chief* **46**:9, 62-67 (Sep. 1980).

While direct statistics are not available, deductions may be made from the statistics analyzed in the US by the NFPA. Shown below is a recent graph of their findings, giving results for the top seven categories, which together account for 90% of the total fire deaths. Fires due to heating equipment, electrical distribution, and smoking materials will overwhelmingly be smoldering fires. This accounts for 54% of the fire fatalities[4]. Candles, playing with heat source, and intentional fires will overwhelmingly be flaming fires, and this accounts for 20%. Note however that deaths due to intentional fires are highly unlikely to be preventable by any smoke alarm strategy, and this alone comprises 13%[5]. This leaves only cooking equipment (16%). And with cooking equipment, about 50% are victims who were intimate with the fire[6], and these individuals cannot be protected by safety measures. Thus, there remains 8% as cooking equipment fires which can be presumed to be flaming and with the victim not being intimate. As a result, from the tabulated NFPA statistics, we may infer that 54% of fire fatalities are due to smoldering sources, while 15% (8 + 4 +3) are due to flaming sources; in this accounting, we omit incendiary fires and intimate-with-fire deaths, since we consider these to be non-addressable by means of smoke alarm strategies. Thus, even ignoring the issue of distinguishing fires where smoke alarms may help[7], from those where they are unlikely, the ratio is 3.6 : 1 for smoldering : flaming fires[8]. In other words, of fires where smoke alarms can be viewed as germane, smoldering fire deaths comprise 54/(54+15) = 78%. This is drastically different from assuming that deaths in smoldering and flaming fires are equally likely.

Figure 21. Major Causes of Home Structure Fire Deaths and Injuries 2007-2011



(Source: M. Ahrens, Characteristics of Home Fire Victims, National Fire Protection Association, 2014).

[4] This overestimates the total slightly, since some heating equipment and electrical distribution fires will start in the flaming mode. However, fire investigation experience indicates that these are minor and there is no valid way of quantifying them.
[5] Intentional fires are often set precisely to trap and kill victims. They are also often set in derelict premises, where no protective devices can be expected to exist.
[6] Ahrens, M., Home Cooking Fires, NFPA (2018).
[7] Apart from incendiary fires, where we categorically assumed lives will not be saved by smoke alarms.
[8] It may be noted that the NFPA statistics only add up to 90% of fire deaths. The remaining 10% are miscellaneous categories that NFPA has not included, thus no inference is drawn on the nature of the initial fire source.

Other NFPA statistics[9] have shown that, for US residential fires, only 20% of the fires occur during sleeping hours (11 pm to 7 am), yet 52% of the fire deaths are found during these hours. This indicates the importance of focusing on the sleeping individual, and what happens during sleeping hours, rather than on the individual who is awake and alert. This is reinforced by a NFPA study[10] which found out that smoke alarms gave the first notice in 61% of fires when everyone was asleep, but in only 34% of fires when at least one person was awake.

The above observations have profound implications on strategies for obtaining beneficial results from smoke alarms. Two pivotal conclusions may be drawn:

(1) Smoldering—rather than flaming—fires are responsible for about three-quarters of home fire fatalities.
(2) Smoldering fires are more likely to erupt when the householders are asleep (when an alarm is needed), while flaming fires are more likely to erupt when the householders are awake (when an alarm is less likely to be of value and may even be counterproductive). I know of no useful technique to quantify this disparity, but nonetheless it is clear that given the occurrence of a fire, there is likely to be greater need of a smoke alarm for a smoldering fire, than for a flaming fire.

The above can be condensed into a single, overarching conclusion. It is entirely inappropriate to propose a smoke alarm strategy where warnings for smoldering and for flaming fires are valued equally. Instead, it is crucial to focus on obtaining an optimal warning for smoldering fires. Furthermore, I note that, for the Australian context, Mr Greg Mullins, as Commissioner of FRNSW, provided the following testimony[11]: "*People have said that one is good for flaming fires (ionization) and one is good for smoldering (photoelectric). In my experience as a firefighter just about every fire I have ever been to started as a smoldering fire and went through a stage until it became a flaming fire. To say that they are equal and good for different circumstances is to me a fallacy. An absolute myth.*" Thus, I consider that the situation in Australia is found to be identical to that in the United States.

Sidebar: What about fast flaming fires?
In their comments to this author, FRNSW stated that they were concerned that flaming fires are now showing much faster growth rates than in previous years, on the basis of research reported by UL[12]. There are several observations that need to made concerning this study:

- The researchers in that study ignited a very large, sectional-type 'modern' sofa directly with an open flame source. The sofa was set up in a 'living room' which was much smaller than a typical living room and, as a result, the room was crammed full of fuel load. While such room conditions and such ignition scenarios are certainly possible, they do represent the worst possible conditions for tenability, short of making a large flammable liquid accelerant spill.

  Research shows that fire conditions are significantly worsened by piling a large fuel load into a small room[13]. While rare and unusual cases may always exist, most householders

[9] Ahrens, M., Home Structure Fires, NFPA (2017).
[10] Hall, J. R. jr., A Decade of Detectors: Measuring the Effect, *Fire J.* **79**:5, 37-43, 78 (Sep./Oct. 1985).
[11] Australian Senate Smoke Alarm Inquiry (Hansard transcript), Second Hearing, Parliament House, Canberra, A.C.T., (4 Dec. 2015); p. 3 par. 12.
[12] Kerber, S., Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes, UL report, UL, Northbrook IL (2012).
[13] Walton, W. D., and Thomas, P. H. Estimating Temperatures in Compartment Fires, pp. 3-134 to 3-147 in **SFPE Handbook of Fire Protection Engineering,** 2nd ed., NFPA, Quincy MA (1995).

would not consider the UL arrangement of furniture crammed into the mockup living room to be a habitable environment.

- The concept that polyurethane foam-containing is a ‘modern’ novelty is a serious misapprehension. By the late 1960s, and most certainly by the early 1970s, the dominant form of living room furniture being sold was already based on polyurethane foams. The sofa made and sold in 1969 is not different from the sofa made and sold in 2019, in any significant way that would affect fire. Thus, ‘modern’ is in no way modern, but is rather 50 years old. In fact, the furniture of today has somewhat reduced flammability compared to 1969 furniture, since during the late 1980s, manufacturers started inserting layers of polyester fiber batting beneath the surface upholstery fabric, effectively replacing a portion of the more flammable polyurethane.
- The time for a fire to develop is significantly affected by the location of the ignition source, even for scenarios where the fuel load is identical[14]. Most residential fires do not develop from worst-case ignition scenarios.

[14] Mitler, H. E., and Tu, K.-M., Effect of Ignition Location on Heat Release Rate of Burning Upholstered Furniture, Annual Conf. on Fire Research, Book of Abstracts. October 17-20, 1994 (NISTIR 5499), Nat. Inst. Stand. & Technol., Gaithersburg MD (1994).

Analysis of the FRNSW Stage 2 report

My analysis of the FRNSW Stage 2 report now proceeds in view of the background established.

Problems with sensitivity testing. The sensitivities of the smoke alarms utilized was only characterized in two appendices which were not in circulation in conjunction with the Stage 2 report. These two appendices were later supplied to me for my review. If they are now incorporated into the circulated report, then this formal deficiency is remedied. However, the technical quality of the appendices is comprehensively inadequate. The primary question that the reader will wish to know, "Were the sensitivities of the various alarms used matched sufficiently closely so that differences in sensitivity would not skew the results?" The CSIRO report was skeletal and basically useless since it did not answer this essential question. The authors, instead, provided smoke obscuration "Response threshold Value (dB/m)" readings, but only for the photoelectric and dual alarms. For the ionization models, they did not provide this data. Instead, they provided "MIC y " values. It is important to note that the dB/m and the MIC y values are, in general, not correlated to each other. Further information on this point is provided in another section of this report.

In my assessment, the lack of usable information from the CSIRO test report stemmed from the fact that they chose to execute a partial panel of tests in accordance with AS 3786-2014[15], which does not give information on actual smoke levels at which both types of smoke alarms activate for smoldering fires. They should have instead, examined the submitted smoke alarms in accordance with the smoke sensitivity test standard AS 2362.17-1993, as amended, which was a required test in the earlier smoke alarm standard AS 3786-1993. If they would have done this, they would have complied with Par. 7, which states that "*The following shall be reported: ... smoke density at which actuating device entered the alarm state*." I emphasize that this requirement is placed upon the testing laboratory for all technologies of smoke alarms, not being limited to photoelectric.

The serious problems with the CSIRO sensitivity testing can be contrasted directly to a study conducted earlier (2014) by BRANZ[39] in New Zealand. Since that study did provide useful sensitivity results, I discuss it in detail in a later section of this report. Both FRNSW and CSIRO might well have considered this to be an example on how to get the testing strategy right. I especially emphasize that proper variables were reported by BRANZ and that suitable test fuels were used in their study.

Finally, it is my understanding that the FRNSW testing work has been done in support of the AS 3786-2014 standard. Upon reviewing that standard, I make the recommendation that FRNSW would be well advised to suggest to Standards Australia that, in order to achieve adequate fire safety, this standard needs to be fundamentally revisited and revised. Specifically, the protocols therein offer no assurance that ionization smoke alarms will adequately respond to fires that produce large-size smoke particles, which is characteristic of, but not exclusive to, smoldering synthetic fires. I explain the technical aspects of this issue later in this document.

Problems with "Methods and materials." When research is done in science, engineering, or technology areas, if physical testing is involved, a crucial section which every report must have

[15] This is also referred to as AS 3786-2015, due to certain issues with the dating of the release.

is a description of the "Methods and materials." The physical materials or products involved in the testing must be fully described. Likewise, all the important details concerning the experimental apparatus or chemical analysis technique used must be specified. For research to be credible and reliable, it is essential that experimental work be able to be reproduced. By this, it is meant that researchers at another institution need to be given sufficient information so that they could re-create the tests and examine whether or not there is agreement with the results of the original researchers. This becomes precluded if the report sections on "Methods and materials" are vague or incomplete. Yet, vague and incomplete is the only possible assessment of the documentation of methods and materials in the Stage 2 report.

The basic test room layout, Fig. 1, should have had at least the major dimensions indicated on it. The report refers the reader to the Stage 1 report for some of the details, but this report has thus far not been publicly circulated. In any case, a report should not rely on some non-included material for laying out such basic facts.

More problematically, there is no useful description of the actual fuel load. Apart from the flooring and the kitchen walls—where material descriptions were given, the report only states "Modern furniture and furnishings were purchased to furnish the rooms." This problem is especially notable in the case of the soft-goods (beds or upholstered furniture) tests, where it is clear that multiple materials were involved, but there is no description of any of these materials.

I understand that the authors did not have the facilities for recording weight during the experiments. Nonetheless, expected care in experiments was not exercised by recording pre- and post-test weights of all the articles. Such weighing can be done with any scale of suitable resolution and does not require specialist equipment to be procured. Yet, because this was not done, the fire scenarios do not have quantitative meaningfulness.

I understand the FRNSW endeavored to complete this project "on the cheap," but nonetheless it must be noted that, in the 21st century, when actual fire hazard is being experimentally studied, heat release rates should be measured[16]. It is understood that this cannot be done inexpensively, since an expensive test rig is needed, nonetheless it is important to appreciate that fire hazard today is expressed first and foremost in terms of heat release rate (HRR)[17,18]. There are several facilities within Australia which possess such capability, with additional ones being available in New Zealand. A cooperative program should have been investigated involving one of these institutions. This may require that single-room testing be done, instead of a segment of an apartment. Nonetheless, if HRR is measured, the work product becomes greatly more useful.

I also note that one exceedingly important piece of kit was missing in the test instrumentation: smoke density meters to record the smoke density values at the various locations where smoke alarms were mounted. Standard laboratory practice should have been followed which entails

[16] Babrauskas, V., and Peacock, R. D., Heat Release Rate: The Single Most Important Variable in Fire Hazard, *Fire Safety J.* **18**, 255-272 (1992).
[17] Babrauskas, V., Fire Safety Improvements in the Combustion Toxicity Area: Is There a Role for LC_{50} Tests? *Fire and Materials* **24**, 113-119 (2000).
[18] Babrauskas, V., Quantifying the Combustion Product Hazard on the Basis of Test Results, pp. 339-353 in **Hazards of Combustion Products: Toxicity, Opacity, Corrosivity and Heat Release**, V. Babrauskas, R. G. Gann, and S. J. Grayson, eds., Interscience Communications Ltd., London (2008).

installing a smoke density meter at each location where smoke alarms are mounted[19]. Smoke density values should have been recorded and reported for each smoke alarm for the time at which the smoke alarm condition occurred.

Surrogates for cigarettes. There is no known surrogate for smoldering cigarettes that is a valid simulation of the cigarette smoldering process. A soldering iron, such as used in the FRNSW experiments, may be a repeatable experimental heat source, but it is not equivalent to the cigarette smoldering process. It should be pointed out, for example, that the recent California regulation[20] for the testing of upholstered furniture for smolder-ignition resistance is based on use of real cigarettes, not an electrical heat source, even though the latter would be much simpler to use. The issue is not the heat output of the source, but rather the fact that a smoldering cigarette is a travelling heat source—the hot zone progressively moves from the far end to the butt end of the cigarette. Any electrical heater, by contrast, is a fixed-position source of heat. The exposed substrates do not behave in an identical manner to fixed versus traveling heat sources. The report of Novozhilov et al. (Appendix B) specifically noted that cartridge heaters are not a true surrogate for smoldering cigarettes, however, in my experience, this is a minor limitation of the test program. Experience indicates that ignition by cartridge heater, instead of actual cigarette, is likely to shorten the transition time to flaming (if this, in fact, does happen); as a result, the available smoldering time may be shortened for the test. It is not clear, however, why the FRNSW did not revise their ignition source strategy more fundamentally for Stage 2 after having received this comment. Only 2 tests involved starting smoldering fires with cigarettes, while 9 tests utilized soldering irons or some other electrical device. In addition, there were 12 tests conducted with flaming ignitions.

Dead zones. The report implicitly accepts the Australian Building Codes Board's (ABCB) requirements for avoidance of "dead zones." These requirements consequently contain provisions that are highly inimical towards the rapid response of smoke alarms. The concept of "dead zones" for smoke alarm activation had been a long-term unsupported theory. The first study to directly examine the concept was conducted at the National Research Council (NRC) Canada by Su et al.[21] in 2003. Their experimental findings did not lend any support to the notion that smoke alarm activations will be slower or nonexistent for locations in a "dead zone," but at an otherwise reasonable height, i.e., not too far below the ceiling. The authors conservatively stated that more research would be desirable; nonetheless, their presented research is sufficient to conclude that, while anomalous airflow patterns may occur in rare circumstances, there is no merit in regulations that specify prohibited "dead zones."

More pointedly, the FRNSW Stage 1 report (Appendix A) constituted the second known effort to explore any justification for the "dead zone" proscription. And their findings were a resounding rejection of the concept: The best performance of smoke alarms was found to be when they were sited within the ostensible "dead zones." It is unfortunate that the Stage 2 work ignored this finding, instead of building upon it, which would have been the prudent strategy.

[19] O'Neill, J. G., and Hayes, W. D. jr., Full-Scale Fire Tests with Automatic Sprinklers in a Patient Room (NBSIR 79-1749), [U.S.] Natl. Bur. Stand., Gaithersburg MD (1979).
[20] Requirements, Test Procedure and Apparatus for Testing the Smolder Resistance of Materials Used in Upholstered Furniture (TB 117-2013), Bureau of Electronic & Appliance Repair, Home Furnishings & Thermal Insulation, Sacramento CA (2013).
[21] Su, J. Z., Crampton, G. P., Carpenter, D. W., McCartney, C., and Leroux, P., Kemano Fire Studies—Part 1: Response of Residential Smoke Alarms (Research Report 108), National Research Council Canada, Ottawa (2003).

The ABCB requirement that sidewall mounting be between 300 mm and 500 mm below the ceiling is notably poorly considered. By contrast, in the US, the corresponding recommendation[22] is between 100 mm and 300 mm, in view of the unsupported "dead zone" theory. There is no doubt that—in the vast majority of cases—a smoke alarm is likely to be more effective if placed somewhere around 200 mm below the ceiling (US practice) as opposed to somewhere around 400 mm (Australian practice). While it was not the scope of the Stage 2 report to offer smoke alarm installation recommendations to the ABCB, it is important to take this opportunity to emphasize that, if smoke alarms are to achieve their life safety potential, mounting-height requirements must be amended. To be very explicit, neither of the two known studies on the subject found any merit to the "dead zone" concept, with the Stage 1 report comprehensively demolishing it. An analysis should have been made of dead-zone alarm responses, versus those compliant to ABCB.

<u>Reporting of results</u>. The tables of results should not have been in mixed units. Some are given as min:sec, while others are given as decimals of a minute.

<u>Tenability analysis</u>. The tenability analysis was based on tenability criteria that have no research justification as being valid values for "escape impairment" or "incapacitation" as claimed. I will illustrate this with one example: the overwhelmingly most important combustion product from a toxicological point of view is carbon monoxide, CO. For CO, the report specifies "escape impairment" at 420 ppm and "incapacitation" at 600 ppm. This is intrinsically erroneous, since no statement or considerations of exposure times are given, yet incapacitation by the so-called narcotic toxic gases (of which CO is one example) is highly dependent on the exposure time. In other words, there cannot be *any* incapacitation value set, unless a corresponding time duration is specified.

The scope of the report is limited to house fires, as contrasted to, say disasters in mines, where rescues may take hours or days. The sole purpose of a residential smoke alarm is to assist in the self-rescue of the occupants of a house in the event of a fire. The profession has not established a specific time for a successful self-rescue from a residential house to be accomplished, but the National Institute of Standards and Technology (NIST)[23] suggests that 5 minutes is suitable time. This appears to be a reasonable estimate. Unlike for some other toxic gases, analysis of CO toxicity in fires is complicated, since the toxicity of CO is governed by the COHb (carboxyhemoglobin) content of the blood, rather than directly by the concentration of CO in the air. Babrauskas[24] recommended that the "incipient incapacitation" value for CO should be based on a criterion of COHb = 25%. According to the equations provided by Babrauskas, for a constant CO concentration, COHb = 25% occurs for a 5-minute exposure of CO at 5932 ppm. This is reasonable estimate, since experimental results from baboons (another primate species) are 6850 ppm[25]. Specifically, these experimental results are for "loss of escape capability after an exposure of 5 minutes." Thus, in the terminology of FRNSW, the "Effective concentration for incapacitation" by CO is 5932 – 6850 ppm, a far cry from their claimed 600 ppm.

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[22] National Fire Alarm and Signaling Code (NFPA 72), NFPA (2016).

[23] Gann, R. G, et al., International Study of the Sublethal Effects of Fire Smoke on Survivability and Health (SEFS): Phase I Final Report (NIST Tech. Note 1439), NIST, Gaithersburg MD (2001).

[24] Babrauskas, V., Combustion of Mattresses Exposed to Flaming Ignition Sources, Part I. Full-Scale Tests and Hazard Analysis (NBSIR 77-1290), [U. S.] Natl. Bur. Stand., Gaithersburg MD (1977).

[25] Kaplan, H. L., Grand, A. F., Switzer, W. G., Mitchell, D. S., Rogers, W. R., and Hartzell, G. E., Effects of Combustion Gases on Escape Performance of the Baboon and the Rat, *J. Fire Sciences* **3**, 228-244 (1985).

It might be added that the error in the FRNSW report is their use of AEGL values for toxicity criteria, as compiled by the US EPA. The latter is based on a study commissioned from the National Research Council of the US[26]. The AEGL-2 values were chosen as corresponding to a concentration of COHb = 4%. This represents an enormous, unrealistic, conservatism[27], since COHb = 4% is generally identified as a typical COHb value for a cigarette smoker undergoing no other exposure. However, more usefully, within the same NRC study, one also finds some information on actual human exposures to CO. Notably, at 5000 ppm for 11.5 minutes, "no symptoms." Meanwhile, at 3900 ppm, no symptoms for a duration of 15 minutes, while at 29 minutes, mild symptoms. These are intervals much longer than the 5 minutes taken as appropriate for the residential escape context. Thus, the range of 5932 – 6850 ppm for "Effective concentration for incapacitation" is supported by these findings. Furthermore, if 5000 ppm represents "no symptoms" for 11.5 minutes, clearly it also represents "no symptoms" for 5 minutes. It may further be noted that the Environmental Protection Agency (EPA) only provides acute exposure guideline levels for airborne chemicals (AEGL) values for 10 min, 30 min, 1 h, 4 h, and 8 h time periods. The 420 ppm value used by the FRNSW authors is published by EPA for a 10 min, not 5 min interval, and no 5-min interval recommendations are provided. It was an error on the part of the authors to not recognize that concentrations will necessarily change when the time duration is halved (in fact, allowable concentrations roughly double when the time duration is halved). The origin of the 600 ppm value adopted by the FRNSW authors could not be determined. It is claimed to come from the EPA AEGL document, but it does not.

What the FRNSW authors should have done is to consult an analytical report published by NIST[28] where an analysis of AEGL values for CO was performed for the specific context of tenability in fires (rather than various unrelated scenarios). Unlike the unrealistically overconservative values published by EPA, a more realistic spread of values was provided. For AEGL-2, the NIST compilation found the range "1590 to 3800" ppm for a 10-minute exposure. The 5-minute values will be roughly twice the 10-minute values, making the range 3180 to 7600 ppm for a 5-minute interval. This range is similar to the range of 5932 to 6850 ppm, as estimated above.

Lack of adequate burning. The smoldering fire tests were improperly set up and conducted since only trivial amounts of fuel were smoldered in these tests. While gross errors in assigning of incapacitation values can create an impression that untenable conditions were being analyzed, this is clearly evident to be untrue when the photographs of the post-test outcomes are examined. **Persons do not die from combustion toxicity when a small segment of a bed or of an upholstered chair is consumed**. These are nuisance fires at worst, not incidents that result in reported casualties. In fact, it should require no more than an examination of the post-test photographs to understand that the experiment design for this research study was crucially flawed.

[26] Acute Exposure Guidelines for Selected Airborne Chemicals, Volume 8, National Research Council, National Academies Press, Washington (2016).

[27] The NRC authors evidently adopted enormously conservative values to account for the segments of population that are already suffering from some impairments, such as heart disease. This is not a viable strategy, since there will always be a segment of the population that is "one step away from death." In other words, there will always be highly afflicted individuals who can tolerate no additional physiological burden without dying. A fire protection strategy may need to make special provisions for afflicted populations, but the baseline protection strategy has to be formulated on the assumption of normality.

[28] Kuligowski, E. D., Compilation of Data on the Sublethal Effects of Fire Effluent (Tech. Note 1644), NIST (2009).

The experiments for smoldering ignitions of ironing boards were equally improper. The tests generated only a scorch mark on the ironing board. But the researchers formulating the experimental program should have understood that, even if it had completely smoldered away, the fuel content in the coverings of an ironing board is simply insufficient to lead to fire casualties. Burning flimsy, lightweight chairs with trivial fuel content is similarly an unacceptable experiment design for examining the performance of smoke alarms.

Poor choices in selecting the test scenarios. The basic objective of the research was to compare smoke alarm technology types with regards to providing time for escape. As I have noted in the Background section, this needed to be done carefully, so that test scenarios would be identified which (a) correspond primarily to scenarios which have a high likelihood of casualty in real-life fires; and (b) correspond to real-life scenarios where a smoke alarm activation would likely do some good, as opposed to scenarios where this is less likely. The objective should NOT have been to compare the activation of smoke alarms across a broad expanse of "comprehensively selected" scenarios, since this would effectively end up averaging the outcomes of scenarios with widely disparate potentials for life saving. This would diminish from a focus on scenarios where smoke alarms are most likely to be of casualty-preventing benefit. By adopting—with only small modifications—the matrix suggested by Novozhilov et al., the authors ended up with a list of scenarios that do not emphasize the scenarios that have life-saving potential.

Burning of cotton versus PUR foam. Cotton, wood, and PUR foam can all smolder. But it is incorrect to conclude because of this, use of any of these three materials is good enough, in order to represent conditions for lethal smoldering fires. The smoke aerosols generated from these fuels are not the same and are not interchangeable. Schuchard[29] demonstrated that photoelectric smoke alarms respond much more rapidly to smoldering PUR than to smoldering wood, while ionization alarms respond much more rapidly to smoldering wood than to smoldering PUR; see table below developed from his data.

Results of Schuchard on room fire tests, giving alarm times, beam transmission %age values, and smoke obscuration in %/ft units

Type	Smoke box %/ft	White pine			Douglas fir			Polyester pillow			PUR mattress		
		Minutes	Beam %	%/Ft	Minutes	Beam %	%/Ft	Minutes	Beam %	%/Ft	Minutes	Beam %	%/Ft
Ph	1.68	28.1	94.1	1.2	29.4	95.8	0.85	9.1	95.1	1.0	5.9	97.5	0.5
Ph	1.5	29.4	93.7	1.3	34.5	92.3	1.6	11.1	86.8	2.8	15.7	83.3	3.6
Ph	1.23	32.7	93.2	1.4	41.8	89.5	2.2	13.3	70.3	6.8	27	71.5	6.5
Ion	lack	45.2	78.2	4.8	58.2	68.8	7.2	15.5	52.5	12.1	72	35.3	18.8
Ion	0.85	47.2	72.6	6.2	59.3	67	7.7	fail	fail	fail	73.3	32.8	20
Ion	1.1	48.4	68.1	7.4	lack	lack	lack	lack	21	26.8	81	29.6	21.6
Ion	1.3	49.5	62.7	8.9	62.2	55.2	11.2	17.5	29.2	21.8	74.5	32.8	20
Ion	3.7	50.1	60.4	9.6	67.9	37.1	18	lack	18.8	28.4	fail	fail	fail
Ion	1.78	50.1	57.7	10.4	66.3	42.8	15.6	lack	21	26.8	fail	fail	fail
Ion	lack	50.2	57.1	10.6	61.7	56.8	10.7	lack	13.5	33	fail	fail	fail
Ion	lack	50.5	55.8	11.0	68.1	35.1	18.9	fail	fail	fail	fail	fail	fail

lack – data not available
fail – no alarm

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[29] Schuchard, W. F., Smoldering Smoke, *Fire J.* **73**:1, 27-29,73 (Jan. 1979).

The materials examined in the present work were primarily cotton and PUR, not wood and PUR. Thus, we have to consider the response characteristics of cotton versus wood. Weinert et al.[30] determined the mass-median (so-called D_{43}) values for a number of fuels, see table below. This study tells us that using cotton as a surrogate for PUR is an even worse approach than is using wood. As a result, there is every reason to believe that had Schuchard done his tests with cotton and PUR foam, the inadequacies of cotton as being a surrogate for PUR would have been even more obvious.

Smoke aerosol mean diameters for smoldering or overheating materials measured by Weinert et al.

Material	D_{43} (μm)
cotton wick	0.31
toast	0.43
beech wood	1.5
cooking oil	1.6
PUR foam	2.0

The above information can be considered in view of the "m/y" ratio (smoke obscuration, divided by MIC value) for different fuels. The higher the m/y ratio, the more difficult it is to pass for the ionization alarm, and vice versa. Thus, one has to look where on this scale is PUR foam located, due to its unique importance in fire deaths due to smoldering. This question has been answered by Chagger[31], excerpts from whose study are given below. Test 13 for PUR foam gave m/y = 1.88, which is higher than smoldering wood (TF2) or cotton (TF3) by quite a large margin. Chagger's findings confirm that focus on smoldering PUR foam is essential for any realistic study of smoke alarm performance in real fires.

The m/y ratio for a number of test fires, conducted in the EN54 test room by Chagger

Test No.	Specimen	F/S	m/y
6	TF1 – wood	F	0.0794
12	PUR, FR	F	0.0938
9	MDF	F	0.148
2	TF4 – PUR	F	0.1962
3	TF5 – heptane	F	0.2164
5	TF3 – cotton	S	0.3429
10	TF2 – wood	S	0.8226
1	TF2 – wood	S	0.9384
13	PUR, FR	S	1.88
29	ABS	S	3.04

The above analysis leads to the conclusion that the ostensibly acceptable results for ionization alarms in the smoldering tests of the Stage 2 FRNSW work can be attributed to:

- Burning primarily cotton materials and not PUR foam. It should have been clear to the authors that, for smoldering fires which lead to casualties, PUR and not cotton is likely to make the dominant contribution to the smoke production. This is because, unlike for the 1960s or early 1970s, there is little furniture left in homes which uses cotton-batting padding; most furniture made since the late 1970s has used PUR foam as its resilient

[30] Weinert, D. W., Cleary, T. G., and Mulholland, G. W., Size Distribution and Light Scattering Properties of Test Smokes, pp. 58 –70 in *Proc. AUBE '01—Proc. 12th Intl. Conf. on Automatic Fire Detection*, Nat. Inst. Stand. and Technol., Gaithersburg MD (2001).

[31] Chagger, R., Characterizing the Smoke Produced from Modern Materials and Evaluating Smoke Detectors, BRE Trust, Watford, England (2014).

padding material, augmented by polyester fiber (which does not smolder and thus is not germane to the smoldering process). Furthermore, while cotton fabric was commonly used as an upholstery fabric material in the 1970s, ever since the 1990s, it is no longer a reasonable choice for a "typical" upholstery fabric material. Current-day fabrics are predominantly thermoplastic-fiber materials.

- Grossly inadequate burning time, related to grossly inadequate amount of fuel consumed.
- Selection of seriously incorrect incapacitation values for toxic gases.

Comparison to other studies. I have provided above the detailed results from the Schuchard study, which shows how—under more realistic test conditions—photoelectric smoke alarms show a massive safety margin in comparison to ionization alarms. But other studies also show a similar trend.

For example, in a program conducted by Factory Mutual (FM)[32], the average response time for smoldering fires of photoelectric alarms placed in the room of fire origin was 18.7 min while being 34.5 min for ionization alarms. NFPA[33] reported results from a program where most of the tests were of flaming fires, but for the one smoldering fire run, the results were 36.2 and 104.7 min, for photoelectric and ionization devices respectively. Even some earlier researchers from Victoria University[34] reported data on smoldering fires where the results were 29.0 and 52.2 min, respectively. Meanwhile, in the Stage 1 study of FRNSW (Table 27 therein), the activation times for the smoke alarms within the room of fire origin clearly showed the very substantive advantage of the photoelectric alarms. I believe the reason for the more credible results from Stage 1 testing is that, for the tests that used PUR foam, tests were run in such a way as to allow a more extensive involvement of the foam.

For the very elaborate NIST study[35], the average response time for smoldering fires of photoelectric alarms placed in the room of fire origin was 41.5 min, while being 63.2 min for ionization alarms. But the differences were even more striking when comparison of the Available Safe Egress Time (ASET[36]) was made. Below are the results published by NIST in a supplementary analysis[37] (here, converted from seconds to minutes for consistency).

Fires	**ASET (minutes)**	
	Photoelectric	**Ionization**
smoldering	35.6±16.9	4.6±5.5
flaming (ultra fast flaming)	2.2±1.2	3.0±1.2
cooking (normal fast flaming)	12.3±2.5	13.3±4.0

[32] Bill, R. G. jr., Kung, H.-C., Brown, W. R., and Hill, E. E., jr., An Evaluation of Extended Coverage Sidewall Sprinklers and Smoke Detectors in a Hotel Occupancy, FMRC J.I. 0M3N5.RA(4), Factory Mutual Research Corp., Norwood MA (1988).

[33] Drouin, J. A., and Cote, A. E., Smoke and Heat Detector Performance: Field Demonstration Test Results, *Fire J.* **78**:1, 34-38,69 (Jan.1984).

[34] Moore, I., and Beck, V., Smouldering and Flaming Fires—An Experimental Program (Tech. Report FCRC-TR-96-01), Fire Code Reform Centre, Sydney, Australia (1996).

[35] Bukowski, R. W., Peacock, R. D., Averill, J. D., Cleary, T. G., Bryner, N. P., Walton, W. D., Reneke, P. A., and Kuligowski, E. D., Performance of Home Smoke Alarms—Analysis of the Response of Several Available Technologies in Residential Fire Settings (NIST Tech. Note 1455-1 (2008).

[36] Note that this is a variable where higher numbers indicate a greater safety level.

[37] Questions and Answers Clarifying Findings of NIST Home Smoke Alarm Study, NIST (25 Feb. 2008).

The latest study on this topic was by Cleary and Peacock[38]. Its importance is that naked PUR foam was used, apart from a small circle of cotton fabric to allow a smoldering cigarette to ignite the specimen. The results, below, show a 3 : 1 advantage for photoelectric alarms over the ionization units.

Alarm	**Obscuration at alarm (%/ft)**	
	Flaming PUR	**Smoldering PUR**
ionization	2.07±1.34	9.71±1.15
photoelectric	6.75±1.33	3.19±1.72

Perhaps of most interest is a recent series of tests conducted in New Zealand by BRANZ[39]. This study comprised 78 test runs using some 20 different commercially available domestic smoke alarms representing four types of technologies: ionization, photoelectric, dual (ion + photo), and multi (photo + thermal). The testing was done by burning materials in a 2.4×3.6×2.4 m high test room, and measuring the response of smoke alarms at several locations along in a chamber at the outflow from the room. Two types of tests were conducted: (1) flaming tests, burning small arrays of timber sticks; and (2) smoldering tests, using a soldering iron placed onto PUR foam material. Their results are summarized in the table below.

Type	**Detected smoldering fires**	**Percent smoldering fires detected**	**Detected flaming fires**	**Percent flaming fires detected**	**Avg. obs. at smolder detection (%/ft)**	**Avg. obs. at flaming detection (%/ft)**
Ion	4/27	14.8	27/27	100.0	8.42	1.70
Photo	32/32	100.0	32/32	100.0	1.35	2.85
Dual	12/15	80.0	15/15	100.0	1.11	1.73
Multi	3/3	100.0	3/3	100.0	1.53	2.71

Some important conclusions can be drawn from these findings: (a) Ionization detectors were essentially incompetent at detecting smoldering fires, successfully alarming in only 15% of the tests. (b) Photoelectric and multi-criteria detectors, by contrast, alarmed in 100% of the tests. (c) All detectors were 100% successful in alarming during flaming-fire tests. (d) There was essentially no difference in obscuration needed for alarming in smoldering tests among the photoelectric, dual, and multi technologies. (e) For those few (15%) ionization alarms which were even capable of detecting smoldering fires at all, the average obscuration needed was 8.4%/ft; this contrasts to around 1.3%/ft needed for the three other technologies. By any conceivable measure, a ratio of 8.4 : 1.3 is an enormous difference. (f) The multi-criteria alarm tested in this study (there was only one model used) showed performance indistinguishable from the photoelectric models. (g) On the average, the dual-sensor devices performed less well than one would expect from a combination of a photoelectric and ionization sensors, since only 80% of smoldering fires were detected, while photoelectric alarms detected 100%.

The Stage 2 flaming fire tests. My analysis has focused on smoldering fires, since this **is** where the protection needs lie, and where tangible gains may be achieved. But it germane to point out that the flaming-fire experiments of Stage 2 report were also comprehensively flawed. Basically,

[38] Cleary, T., and Peacock, R., A Statistical Model for Smoke Alarm Activation in Upholstered Furniture Fires, SUPDET 17/AUBE 2017, NFPA, Quincy MA (2017).
[39] Collier, P. C. R., The Response of Smoke Alarms to Two Smoke Sources 2014 (FM5402), BRANZ, Wellington, New Zealand (2014).

these experiments suffered from the same problems as the smoldering fires: Not enough fuel was burned to threaten occupants who are not intimate with the fire. (Note that it is an axiom of the fire safety profession that no safety measures can protect the individual who is intimate with the fire. If, for example, the victim gets their nightgown caught on fire, neither smoke alarms nor fire sprinklers will save them from grievous injury).

How the experiment design could have been improved. It should not have been a difficult exercise to determine experimental conditions that are likely to lead to usable data. For order-of-magnitude estimates, according to ISO 13571[40], one can assume that lethal conditions for fire smoke correspond to a concentration×duration product of about 900 g m^{-3} min in the room or volume of interest. ISO further recommends that the tenability limit can be estimated as being ½ of the above value. Thus, for a 5-min exposure, the tenability limit can be estimated as being (½)×900/5 = 90 g m^{-3} for the volume in question. This would have required some pre-tests to be done, where the amount of fuel burned would have been determined; it can be a very simple exercise. Such a reality check should have been done before launching into a full-fledged testing program. Had this been done, an indication would clearly have been obtained that the fuel loadings are insufficient to attain untenable conditions in the experimental compartments, and therefore that the formulated experiments cannot produce results of utility.

The Milarcik study. The authors also evidently were unable to understand the shortcomings of the Milarcik et al.[41] study and proceeded, instead, to rely upon it. This study is a deeply-flawed work that appears to be an effort to find some metric whereby the life safety advantages of photoelectric smoke alarms over ionization alarms might somehow be minimized or obscured. Details are provided in Appendix D.

Conclusions

The Stage 2 FRNSW study did not produce useful data for comparing the performance of different smoke alarm technologies. This was primarily due to serious problems in experiment design: A series of tests was set up for various scenarios, but no consideration was given towards establish fire conditions sufficient to lead to incapacitation of the hypothetical occupants of these spaces. As a result, valid conclusions could not be drawn concerning the ability of various smoke alarm technologies to give adequate warning of untenable conditions. Simply put, trivially-small fires were lit which would threaten nobody apart from an individual intimate with the fire (yet such individuals cannot be protected by any known safety strategies). The error was largely due to the authors adopting exceptionally unrealistic values for incapacitation of fire-exposed victims from combustion gases.

The Stage 2 report authors adopted for use toxic incapacitation values published by the EPA from a report not focused on fire scenarios or fire escape activities. Fire safety-specific literature sources should have been used instead. Had the authors done that, unrealistically overconservative toxicity values would not have been utilized, since these choices precluded the study from being of practical validity.

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[40] Life-Threatening Components of Fire—Guidelines for the Estimation of Time to Compromised Tenability in Fire (ISO 13571), ISO, Geneva (2012).

[41] Milarcik, E. , Olenick, S. M., and Roby R. J., A Relative Time Analysis of the Performance of Residential Smoke Detection Technologies, *Fire Technology* **44**, 337-349 (2008).

In addition to trivially small fires, the lack of realism was compounded by an inappropriate arrangement of the materials, notably the use of cotton batting for the ignition source. The net result is that, for tests where there was smoldering, it appears that the overwhelming contribution was from smoldering cotton materials, and with only a small contribution from smoldering polyurethane (PUR) foam. Smoke alarm responses are not identical—nor even similar—for smoldering PUR foams versus smoldering cotton materials. Smoldering PUR foams is what represents the greatest life hazard in real fires and should have been carefully emphasized. The authors were evidently not aware that the response to smoldering cotton materials shows less advantage for the photoelectric alarms than does smoldering of PUR foam.

In addition, the authors failed to consider the relative importance of smoldering versus flaming fires in creating the potential for fire casualties.

The documentation of the "Methods and materials" used in the study does not meet minimum standards for reports involving experimental testing work.

FRNSW should suggest to Standards Australia to fundamentally revise AS 3786-2014 in order to develop test procedures which assure that smoke alarms which receive approval under the Australian Standard are indeed competent to detect smokes from fires generating large-size particles (most notably PUR foams) and to achieve this detection in an acceptable duration of time. Adequate provisions also need to be incorporated into the Australian Standard to ensure proper resistance of approved smoke alarms to nuisance smokes from cooking activities. The research of BRANZ might well be used to give some indications on how competent testing might be done.

I have provided a review of the Stage 1 report in Appendix A. Here, the conclusion has to be made that the Stage 1 report was useful and sound, despite some minor deficiencies. Yet, the same cannot be said about the Stage 2 report. The critique of Novozhilov et al. of the Stage 1 work was highly counterproductive and, it can be presumed, largely led to the inadequate experiment design of the Stage 2 program.

Finally, an additional observation with regards to consumers using smoke alarms is the following: Currently available, commercial photoelectric alarms can be expected to provide an overall satisfactory protection level. Currently available, commercial ionization alarms are not likely to provide an adequate protection level and should be replaced by photoelectric units. There has not been sufficient published testing on dual-sensor devices to make general conclusions about their level of performance. Advanced detector technologies, commonly known as "multi-criteria" devices, are in the initial stages of commercialization. Here, again, there has not been sufficient published research to be able to judge the level of performance of these devices.

APPENDIX A – Review of the Stage 1 report

The Stage 1 report is titled "Fire Research Report – Smoke Alarms in Homes: An Analysis." It was authored by M. Engelsman and carries an initial date of 10/04/2015 and a revised date of 11/12/17. I was provided with a copy of the 2017 version for my review.

The experimental work comprised 10 fire tests, with 8 being smoldering ignition and 2 flaming. In view of my discussion in the main report, I consider this to be a proper ratio. As I discussed above, according to US statistics, the prevalence of fire deaths is about 75% smoldering and 25% flaming-start fires. But furthermore, even though it cannot be quantified, experience indicates that a smoke alarm signal is likely to be more beneficial in smoldering fires (which are less likely to be detected without such aid) than flaming fires (which are more likely to be actively detected by awake individuals). Thus, an 80 : 20 weighting in the tests of Stage 1 was entirely appropriate.

The experimental program included sprinkler installation in half of the fire tests. While promotion and optimization of sprinkler usage is a pivotal component of good-quality fire safety practice, nonetheless this conflated variables in the experimental plan and was not helpful towards the primary focus of the study. (In fact, it is reasonable to conclude that in the presence of a competently installed automatic fire sprinkler protection system, the overwhelming life safety advantage is due to the presence of sprinklers and not due to smoke alarms.)

The authors make the conclusion that: "*Some studies suggested that the type of alarm is less important than the placement, as incorrect placement can result in failure across all alarms*." This is only part-true. Certainly, locations significantly below the ceiling are highly ill-advised and detection failure should be anticipated. But even with optimally sited alarms, the existing literature quite clearly indicates that photoelectric devices are more likely, overall, to provide timely warning of fire.

The author spends some time discussing the point that hallway-only smoke alarms may not be effective. This is belaboring the obvious. In many countries, including the US, it has been learned some time ago that siting smoke alarms in each and every bedroom is crucial and also that no form of fire detection is likely to be effective across a closed door. If this is not currently mandated in Australia, it should be a crucial priority to get it accomplished. Unlike some industrial fire detection systems, domestic smoke alarms are point devices and are not likely to provide adequate coverage of compartments from which they are absent. In the US, photoelectric smoke alarms can be purchased at retail outlets for less than $20. Given this, usage should be maximized by whatever means possible. It is pointless to delve into the details of cost/benefit studies when the costs are so trivially low.

The author notes that the NFPA 72 code, used in the U.S., requires significantly more smoke alarms in residences than do Australian regulations. An effort should be made to upgrade Australian regulations to more resemble the American ones in this regards.

I strongly applaud the author's conclusion that: "*the best performing alarms were located in 'dead space' positions, positions not recommended as per NSW legislation, Australian Standards, and the Building Code of Australia.*" I already discussed above the fact that the conventional mandate to avoid purported "dead spaces" is a self-referential strategy, based on no credible science, and contradicted by focused research on the topic. I believe that FRNSW should have carried through this recommendation into the Stage 2 report to hammer home the point of its importance.

The author concluded that: "*Across the test fires photoelectric and dual alarms were found to produce statistically superior results, with ionisation alarms clearly inferior in performance*." For this, she was roundly criticized in the Novozhilov report. Far from being unwarranted or dubious, this conclusion is sound and is entirely consistent with the analysis of the prior literature (see main text and also Appendix E). The criticism of the Novozhilov report was unsound and inappropriate, and this conclusion by the author should have been permitted to be disseminated.

The author somewhat weakened her primary conclusion by following it with the reservation that: "*Further testing and analysis is required to more thoroughly research each of the varying conditions assessed in this research project, therefore ensuring more definitive conclusions*." While nobody should ever discourage additional research on societally important problems, the situation is clear that diverse authors from diverse countries and with greatly differing test rigs produced data which very clearly support the author's conclusion. Thus, it is not appropriate to consider this conclusion as provisional. Instead, it should be considered as valid since it is entirely consistent with the bulk of published experimental research, in other words, on the basis of a meta-analysis of published studies.

The Stage 1 report contains a very large introductory section where fire characteristics, smoke alarm characteristics, and other basic technical issues important to understanding smoke alarm functionality are discussed. This is generally thoughtful, helpful, and well-done. I will not make detailed critiques of this overview, other than to note that it is questionable to infer that increased use of smoke alarms should show up as a statistic of fewer fires. Unlike fire sprinklers, smoke alarms do not do anything to the fire itself, therefore no effect in this regards should be expected, at least to the first order. A secondary factor could come into play, however, in that wider usage of smoke alarms might result in some fires which would have been reported now becoming unreported since the householders were alerted at an early stage and extinguished the fire themselves.

The author pertinently notes that "*the majority of fatal fires occur between the hours of 12:00am to 6:00am*." This recognition is important since it indicates that FRNSW appreciates the fact that the waking of sleeping individuals is the dominant function of a smoke alarm.

All of the smoldering fires in Stage 1 tests were ignited with an electric cartridge heater. This is a significant drawback, but, nonetheless, useful findings were obtained from the study.

The Stage 1 report is extensive, but the main test findings are not easy to use. There should have been:

- A 3-d drawing showing the smoke alarm placement locations and their pertinent codes
- A single table where there is given for all 10 tests the alarm activation times, the sprinkler discharge start times, and the time to transition from smoldering to flaming (for tests where this happened).

The experience in the fire safety testing field is that, for smoldering fires, activation of ionization alarms is likely to happen at, or close to the point when the fire transitions to flaming, whereas for photoelectric alarms, this usually occurs quite a while earlier. The Stage 1 study could fruitfully have reflected on this issue.

Emphasis should be placed primarily on the performance of smoke alarms sited within the room of fire origin. It is appropriate to document that hallway smoke alarms are likely to be of minimal value, but this should be undertaken as a separate issue. The main data should only concern the in-room alarms.

Overall, I consider the Stage 1 report to be thoughtful, competent, and recommend that it should be published. I emphatically reject the view of Novozhilov et al. that the report should be rejected because of an insufficient number of tests. Having a plethora of experiments is valuable for addressing any technical problem, but this does not need to be achieved in the course of a single test program. A large number of experiments for analysis may be achieved by performing a meta analysis, which should be possible for any professional well-versed in a specific field to do. Furthermore, this should not be viewed as an exercise in convoluted maths. Rather, in many cases robust conclusions may be reached by performing a very simple examination of collected data, without any major computational exercises. Even if it were feasible for one author or one institution to conduct a very large number of tests in a single rig, this would not necessarily give the most useful information. Fire fatalities occur under diverse circumstances and in geometries which are significantly varied. Having recourse to data from various investigators who had different ideas on how to best construct fire scenarios (provided they are properly focused) is an advantage, not a drawback.

APPENDIX B – Analysis of Novozhilov report

The Stage 2 report, analyzed above, was the second of two smoke alarm studies undertaken by FRNSW. The original report on the subject ("Stage 1") was issued in 2015 as "Smoke Alarms in Homes: An Analysis." It is my understanding that the Stage 2 effort was undertaken due a review by six authors associated with Victoria University (VU), and sometimes known as the "Novozhilov report," in reference to its first author, Vasily Novozhilov. The report is based on these authors' view "*that both scenarios are equally important taking into account fire frequencies, as well as death and injuries rates*" (p. 48). As I have discussed at length above, this is not a viewpoint which is consistent with successful optimization of smoke alarm strategies for the purpose of saving lives in residences. Even worse, the authors focus on statistics showing that "cooking equipment represented the leading causes of total fires (43%)" (p. 54). It is of course very well known that cooking equipment represents the leading cause of reported fires, and an even greater fraction of fires which are not reported to fire brigades (78%, in one study[42]). But, as explained above, it is a serious error to weight equally various scenarios, instead of giving preference to scenarios where smoke alarms may reasonably be expected to warn occupants who would otherwise fail to observe the fire. U.S. statistics[6] indicate that about half of cooking fire deaths occur due to the individual being intimate with the fire. Smoke alarms will not reduce these casualties and, even more broadly stated, the fire safety profession does not offer useful strategies for assisting such individuals. In blunt and simple terms, a smoke alarm will not be of value to the individual who just got their nightgown ignited on the gas hob in the kitchen.

Because of their inability to distinguish important scenarios (where smoke alarms might be usefully expected to provide an early warning of fire conditions), from less important scenarios (where smoke alarms are unlikely to improved chances of survival), Novozhilov et al. recommended a sequence of tests where identical numbers of smoldering and flaming ignitions would be implemented. As noted above, FRNSW followed this suggestion, but with a counterproductive outcome.

Novozhilov et al. then offered their basic technical conclusion: "*Across the set of experiments, photoelectric detectors responded to smouldering fires approximately 39% faster (in terms of average activation times), and ionisation detectors responded to flaming fires approximately 35% faster. The two figures are statistically indistinguishable.*" (p. 60). If interpretation is made with a sound understanding of fire death scenarios, this statistic will not lead to the conclusion that the two technologies are equally meritorious. On the contrary, the authors should have properly interpreted this statistic in terms of two factors: (1) Photoelectric alarms have an advantage over ionization alarms in smoldering fires which is often found to be on the order of ½ to 1 hour faster, while ionization alarms are likely to have a time advantage over photoelectric units in flaming fires which is measured in seconds. And (2) The individual who encounters a smoldering-fire scenario is much more likely to be able to benefit from a smoke alarm signal than is the individual in a flaming-fire scenario.

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[42] 1984 National Sample Survey of Unreported, Residential Fires (Contract No. C-83-1239), prepared for CPSC, Audits & Surveys, Princeton NJ (1985).

The authors spend considerable amount of effort on urging the use of various advanced statistical data treatments. This is inappropriate when the physical differences are categorically patent. In fact, mounting elaborate statistical analysis programs is likely to be counterproductive, since the results are likely to lose meaningfulness to individuals who are not statisticians.

Novozhilov et al. did not seem to appreciate that the emphasis in experiment design and in data analysis has to be on performance of smoke alarms in the room of fire origin, not in the hallway, behind a closed door, etc. The issue of mandating sufficient smoke alarms is an entirely different issue from mandating the most fruitful technology. The need for analyzing remote activations can be simply and effectively eliminated by mandating installation of smoke alarms in all bedrooms and, potentially, in certain other additional rooms (but not kitchens!).

The authors did not do a thorough enough job of their literature examination in order to retrieve studies which clearly and unambiguously show the exceptionally large advantage of photoelectric alarms in smoldering fires. I examined a number of such studies with useful data in my main analysis; these are all published documents which the VU authors should have analyzed.

In view of the importance of smoldering fires for assessing the performance of smoke alarms, FRNSW were entirely justified in weighting their Stage 1 tests 8 : 2 in favor of smoldering scenarios. The raw data obtained for photoelectric versus ionization alarms were categorically different and did not need assistance from advanced statistical techniques to be able to draw useful conclusions.

APPENDIX C – Review of the Joseph report

I was also supplied a copy of a report prepared by Dr. Paul Joseph, of Victoria University, reviewing the Stage 2 report. This report is titled: "Fire and Rescue NSW (FRNSW): Fire research report - Smoke Alarms in Homes: Stage2."

The author of this report took a narrow view of the task, focusing solely on experimental and analytical details, without questioning the experimental design from a basic fire safety science perspective. I largely agree with his comments on such details. But that is, effectively, using a microscope to examine a galaxy—a technique which will not reveal strengths or weaknesses of the fundamental conception of the research program. Dr. Joseph does provide similar reservations to mine on the use of soldering irons as a surrogate for smoldering cigarettes, and I agree with those.

Dr. Joseph brings out a good point, but rather inadvertently, by stating that "*Given the wide variability, scarcity of a stipulated and harmonious standard test protocol relevant to the study, and other associated complicated features (such as nature and layout of the test rig, materials used for its construction and the associated contents, ventilation factors, temperature profiles, nature and composition of the combustible volatiles, the prevailing ambient atmospheric condition, and the nature, intensity, and duration of the pilot, etc.) for enclosure fires…"* However, he seems to view the absence of a standardized test rig as a drawback. I take the contrary view: that it is essential not to solely test smoke alarms in a standardized rig, if results of wide applicability are to be gleaned. Accidental fires are wide-ranging, not standardized. Thus, if one focuses on a single test rig, one is likely to create a data set of only narrow applicability. In my view, it is fortunate indeed that experimentalists have used a wide array of un-harmonized test rigs, materials, and protocols. If one has the results from an array of such tests, then one can perform a meta-analysis and determine conclusions which do have a broad range of applicability. But yet again, I need to reiterate my most pivotal conclusion: Emphasis has to be placed on scenarios where the signal from a smoke alarm has a high probability of preventing a casualty, and deemphasize scenarios where the contrary is true. The authors of the Stage 2 report unfortunately did not appreciate this pivotal issue.

Finally, Dr. Joseph takes the Milarcik study (Appendix D) at its face value and does not seem to appreciate how the normalization technique adopted by its authors is grossly biased in favor of concluding that there is no difference between the effectiveness of photoelectric versus ionization smoke alarms. It serves as another example of the fact that fruitful smoke alarm test programs cannot be designed by simply adopting competent engineering experiment design strategies. They have to emanate from a thorough understanding of the fire safety science issues involved.

APPENDIX D – Analysis of the Milarcik paper

The Stage 2 report made considerable use of the following paper: Milarcik, E. , Olenick, S. M., and Roby R. J., A Relative Time Analysis of the Performance of Residential Smoke Detection Technologies, *Fire Technology* **44**, 337-349 (2008). Thus, an analysis of this work is appropriate here.

Reading the paper, one can only conclude that it is a highly biased presentation, apparently intended to demonstrate that ionization alarms are not deficient, by any means necessary to achieve this objective.

The authors of this study undertook to reanalyze three existing studies on smoke alarm performance; no new experiments were reported. Performance in the original 1975 Dunes tests, the "Dunes 2000" tests, and the Kemano (NRC Canada) tests were represented by normalizing alarm times to the time of the first-alarming device. This can only be interpreted as being intended to obscure the fact that, in true time units, when it comes to smoldering fires, ionization alarms exhibit responses that are often around ½ and hour to 1 hour longer than photoelectric alarms. For flaming fires, photoelectric alarms are slower, but both types typically respond within seconds to a flaming fire. However, human beings need real time, not normalized time, in order to escape. The authors' presentation obscures the fact that, if one technology is better than another for smoldering fires by time intervals of around an hour, while another technology is better for flaming fires, but by a margin measured in fractions of a minute, the former is much better at saving lives, despite the fact that "each wins 1 of 2." The authors also failed to recognize that, to achieve maximum fire safety, the evaluation should be weighted in favor of smoldering performance, rather than weighting technologies equally.

Furthermore, ionization alarms often do not detect smoldering fires until after incapacitation would have been reached, a fact which the authors obscure in their analysis.

Additionally, use of the 1975 Dunes test data clearly misrepresents the performance of smoke alarms from the 1990s, or later. The photoelectric alarms of the 1970s had major 'entrance' problems (which were subsequently remedied), and thus do not represent more recent models of these devices. Meanwhile U.S. ionization alarms from the 1970s were better at detecting all fires, including smoldering fires, than they are now. This is due to a subsequent change in the UL standards which required that their sensitivity be reduced due to unacceptable levels of false alarms.

Furthermore, the authors incorrectly made use of the Kemano tests (as 1/3 of their total papers studied!). In the Kemano test series, there was only one smoldering test, while the remaining 12 tests started as smoldering and transitioned to flaming. Thus, the Kemano data on these 12 tests cannot legitimately be used to reflect either on flaming or on smoldering fires.

Also, the authors pointedly avoided including data sets (e.g., Moore and Beck, or Schuchard) which most clearly demonstrate the advantage of photoelectric alarms.

My conclusion is that the meta-analysis of Milarcik et al. is so deeply flawed that no useful conclusions can emerge from it. As such, use should not be made of these authors' techniques nor of their findings.

APPENDIX E – Editorial with meta-analysis of important smoke alarm test programs

Citation: Babrauskas, V., Smoke Detectors: Technologies Are NOT of Equal Value or Interchangeable, *Fire Safety & Technology Bull.* **3**:12, 2-4 (Dec. 2008).

Introduction

We are fortunate this month that our guest editorial, by Vyto Babrauskas, addresses a key issue in fire protection: advances in smoke alarm technology.

This should also serve as a reminder to all of our readers that the editorial page always remains open for volunteers who would like to contribute ideas intended to help develop fire technology or improve fire safety.

This issue marks the end of the third year of the Fire Safety & Technology Bulletin. I do not want to miss this opportunity to wish all of our readers a Great and Happy New Year and a Wonderful 2009.

Marcelo M. Hirschler

Editorial

Smoke Detectors: Technologies Are NOT of Equal Value nor Interchangeable

By Vyto Babrauskas, Ph.D.

"Smoke alarms of either the ionization or the photoelectric type consistently provide time for occupants to escape from most residential fires." (NIST report Tech. Note 1455-1, February 2008). This message has been delivered to the American public by many institutions over the years, especially NIST. Unfortunately, the message is incorrect, misleading, and has been an active obstacle towards providing better life safety in American residences.

In slightly more detail, the traditional message has been saying that ionization detectors respond more quickly to flaming fires, photoelectric detectors respond more quickly to smoldering, but you don't know which type of fire you will have, so your odds are just as good with either technology. This statement is incorrect for two reasons:

(1) people do not have an equal need for being warned of smoldering, versus flaming fires; and

(2) there are huge differences between the warning time advantages in the two cases. So we need to consider these issues in more detail.

Smoke detectors (smoke alarms) by themselves do not put out fires, their only function is to sound an alarm. A person will most notably need warning if he is asleep. If the person is awake, he is both more likely to observe the fire without the benefit of a smoke detector, and he will also be in a much better position to safely make his exit.

Surprisingly, the US fire statistics reporting system (NFIRS) does not ask the question if the fire originated in a flaming or in a smoldering mode. But the experience of fire officials and fire researchers is that if a fire occurs when the occupants are asleep, it is much more likely to start out as smoldering rather than flaming.

Smoldering fires originate from cigarette ignitions, many electric wiring problems, and numerous types of furnace, fireplace, fluepipe, and chimney malfunctions. Conversely, flaming fires are most typically associated with activities of an awake, alert individual. These include cooking (by far the most common cause of all house fires, although a very high percentage of these fires are never reported), improperly fueling a fireplace, and actively using open flames in the household.

It is not uncommon for fire investigators doing a reconstruction test of a smoldering fire to find that an ionization detector will never sound, although the smoke has gotten so bad that a person cannot see their hand in front of their face. But when ionization detectors actually do work in a smoldering fire, the response is generally extremely slow. In the NIST study mentioned above, photoelectric detectors used with smoldering fires gave 31 minutes more warning, on the average, than did ionization detectors. By contrast, in the same study, for flaming fires, ionization detectors gave only 48 seconds more warning.

This is a huge disparity, and it does not justify the claim that neither type has an overall advantage. It is also not a new finding. In 1978, researchers at the Fire Research Station in England (Kennedy et al.) ran smoldering-fire tests and found that photoelectric detectors gave warning on the average 113 minutes before ionization detectors did. Another study (Schuchard, 1979) found that for smoldering mattress fires, photoelectric detectors sounded an alarm on the average 59 minutes quicker than did ionization detectors. A study organized by NFPA (Drouin and Cote, 1984) found a 68 minute faster photoelectric detector response in the case of a smoldering fire, but only a 12 second faster ionization detector response for flaming.

The latest results are from experiments by the National Research Council Canada (Su et al., 2008) involving 11 flaming house fires. These showed an average 16 s alarm time advantage for ionization detectors, compared to photoelectric. Thus, it is clear that photoelectric detectors will provide a huge advantage in smolder fires (30 minutes to 1 hour, or more), while ionization detectors provide a trivial advantage (a few seconds) in flaming fires.

By the way, proponents of ionization detectors sometimes argue that, even though the time advantage of ionization detectors for flaming fires may be very small, it is still an important advantage since flaming fires reach untenable conditions much more quickly. This is a specious argument, since it fails to take into account human behavior. In a real fire emergency, individuals do not behave in a robotic fashion, moving quickly and directly to the correct exit. Instead, they are most likely to engage in numerous activities before proceeding to the exit and may, even then, choose a poor exit. Minutes, not seconds, are generally likely to be needed before all the occupants of a house have successfully exited. In the context of that reality, a time difference of 12-48 seconds is very unlikely to make the difference between life and death.

The NIST policy of claiming that detector technologies are interchangeable, as far as occupant protection goes, is actually very old. Their original "Indiana Dunes" studies of 1975-77 contained the same conclusions. At the time, this was a reasonable conclusion, since (a) most houses did not have any detection and it was considered that any type of detector has to be better than nothing; and (b) during that era, battery-powered photoelectric detectors were not yet available, while battery-powered ionization detectors were. Since the initial push had to focus on retrofits, rather than new housing, it was essential to not discourage householders from installing ionization detectors. But battery-powered photoelectric detectors have now been available for more than two decades; consequently these original reasons have lost all of their validity.

An additional reason why photoelectric detectors should be preferred has to do with false alarms. A large fraction of fires that become serious involve homes where a smoke detector once existed, but was then disabled. This is most commonly due to excessive false alarms. A study in Alaska (Fazzini et al., 2000) found that false alarms are 9 times more likely to be experienced for houses with ionization detectors, as compared to photoelectric ones.

For a number of years now, consumers had the ability to buy a combination sensor detector, where both ionization and photoelectric detector elements are incorporated into one device. Theoretically, such a detector would be the ideal detection device. In actuality, this turns out not to be the case. Evidently most of the manufacturers made the unfortunate decision in designing these units to focus on false alarms rather than on detection time. The consequence is that these dual-mode detectors do not offer the early-warning advantage that they would be capable of, if appropriately designed.

It is sometimes argued that photoelectric detectors should not be promoted because their retail price is roughly double of the ionization detectors. This is not a reasonable claim, since even with the price premium, a photoelectric detector can easily be purchased for $20.

But the price difference is solely a chicken-and-egg question. Photoelectric technology does not require costlier parts to make the unit, nor is it more complex. But single-station ionization detectors currently outsell photoelectric detectors by around 20:1. Consequently, manufacturers charge more for photoelectric units, simply because the market is much smaller. Interestingly, in commercial occupancies, central-panel type smoke detectors are predominantly photoelectric, rather than ionization. But this does not have a large effect on fire fatalities, since, if an individual dies in a fire, this is overwhelming likely to be at home and not in an office, workplace, school, or other non-residential occupancy.

Very recently the situation is beginning to improve, due especially to the efforts of Jay Fleming, Deputy Chief at the Boston Fire Department. Chief Fleming found that there were recurring fire fatalities in Boston which could have been prevented had the occupants used photoelectric, instead of ionization detectors. Thus, for a number of years he campaigned to introduce requirements mandating photoelectric detectors.

Fleming's efforts are now starting to bear fruit, primarily in the Northeast. A number of jurisdictions have recently issued regulations which will require photoelectric technology. Details of these, along with an engineering analysis of problem will be given in a paper (Babrauskas, Fleming, and Russell) at the Fire and Materials 2009 conference in January (*see Calendar)*.

The WFSF thanks Dr Babrauskas. This report and supporting documents are at: www.SmokeAlarmWarning.org/frnsw