Wayfinding in Heavy Smoke:
Decisive Factors and Safety Products

Findings Related to Full Scale Tests

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Abstract

This paper presents a summary of a series of four reports on safe evacuation from smoke. The first report is a literature study on the subject. The next reports on a full scale test series and the third makes a discussion of the decisive factors involved in safe escape from smoke. The fourth report presents a way of calculating visibility in smoke. The focus is on the safety of individuals wearing no eye or breathing protection, on wayguidance marking, on human behavior and on visibility in smoke. Also, relations to the time humans may endure in severe smoke and to the travel distances involved, are considered.

The results are generic to public buildings or industries where there may be a possibility of several safety measures failing, including power failure and smoke blocking normal lighting, thus exposing individuals to extreme difficulties in navigating to a safe haven - be it a protected room or the outside of a structure. Being able to navigate and cope with short periods of exposure to severe smoke may be crucial in saving ones life, or even in performing vital operations such as shutdown procedures in order to save others.

The paper attempts to submit an overview of available safety products for way guidance in smoke of which 7 system categories were tested in full scale involving 84 human subjects. Test smoke conditions varied within optical smoke densities of OD 1.0/m and 1.5/m. 6 blind persons took part in the tests and made it possible to test the performance of tactile marking systems in 'total darkness' as well. One outstanding conclusion is that the visibility distance, not the luminance, is the most important factor of visibility in extreme smoke. This makes low luminance afterglowing line marking outperform electrically powered point sources of light.

Introduction

Emergency lighting and signage do not perform as expected at fire disasters. Very often systems are found to be nonoperative, not providing useful wayguidance or both. There are two common denominators: the systems are traditionally not required to be designed for *smoky* conditions and they are prone to failure by lack of maintenance or complexity.

By study of fire disasters /3/ it is clear that to increase fire safety substantially one may design wayguidance for smoke.

Seven different concepts of *Emergency Egress Information Systems* also referred to as *wayfinding* or *guidance* systems, were tested with human subjects. Concepts included visual and tactile, powered and nonpowered, systems /4/.

It was decided to review statistics of fire disasters and research experience in order to assess how far and for how long evacuees are capable of moving in fire until they are put out of action by the smoke /5/.

A method of calculating the visibility in a smoke was developed /6/. Optimal locations of wayguidance marking were determined /5/. Evacuation aided by audible information - informative voice messages - and smoke hoods, were also briefly dealt with /4/, but is not included in this paper.

Vital implications of safe evacuation in smoke

Limits of human endurance in exposure to smoke

Many researchers have suggested endurance limits in smoke /4/. A set of simple critical limits for human exposure to effects of fire were deduced: Temperature limit: 150 ^{o}C. Limit of visibility without wayfinding system ('turn back' limit): 5 m. Accumulated/dose CO: 30 000 ppm min. Synergy effects of one or more factors override these limits in a given fire. Reduction of visibility and the presence of CO are the prime risk factors when evacuating in smoke /3,4/.

The smoke severity to which wayfinding systems must perform

Instead of awaiting a full understanding of the synergetic effects of smoke on humans by smell, visibility, stress, toxicity etc some researchers have linked both *incapacitation, survivability, tenability and 'turn back'* limits to specific *smoke density levels*. This optical density concept were adapted for the wayfinding classification presented in this paper.

It appears from reports on catastrophes that a lot of people survive smoke that obviously exceed both the short term incapacitation and the survivability limits. While people will turn back at OD 0.25/m (no wayguidance) some people have apparently survived moving through smoke densities between OD 2/m and OD 10/m.

Statistically, those who survived smoke in fire catastrophes moved on average only 9.1 m in smoke. Only 10% moved through smoke more than 16 m. This equals time exposures substantially *shorter* than 1 min, while survivability thresholds typically are defined by 1 minute exposure. This may explain why people survive smoke densities exceeding 'survivability limits' like that of OD 1.64/m proposed by Gross /4/.

Importance of wayfinding

Very small margins have meant the difference between life and death in actual disaster situations. A few more meters, a few seconds less, choosing the right direction at just one junction, just a little less smoke or slightly better visibility, and lives could have been saved. This became clear from the literature study of fire disasters.

Some issues discussed in /5/ were:

- how far and for long can a person move in the smoke we may encounter in potential fire disasters?
- what dosages of toxins (dosages are a function of time and concentration) affect persons during evacuations?

    · how much smaller will these dosages be if evacuation times are reduced?

    · how long do escape hoods need to function in critically dense smoke in order to provide sufficient protection?

Even though research is scarce, it is quite clear that small improvements in visibility or reduction in smoke irritation may save many lives at multiple life fire risks. It is a fact that in fires, people remain too long in the smoke and consume excessive dosages of CO because they cannot find their way out. The most important factors that make people turn back or give up trying to escape are poor visibility and irritation of the eyes by smoke. The next most important is that smoke also irritate the respiratory system.

Serious smoke intoxication or the effects of heat are thus not the prime factors that stop the progress of evacuees. The fact that post-mortem reports describe respiratory damage and toxic compounds in the blood is of course a consequence of the environment at the time just before death rather than at the time the deceased stopped progressing or turned back. The reason evacuees stop or turn back may be poor visibility, irritation of the eyes, heat or a combination of factors. We find it reasonable to suppose that some time pass before the deceased meets high concentrations of CO and remains in them so long that he or she is incapacitated. After fainting or anesthesia, some time also pass before death occurs.

On board the Scandinavian Star the catastrophic fire developed in the evacuation route and the volume in which smoke could disperse was limited. For this reason the smoke was more dense than in any of the other disasters we considered. At the World Trade Center incident no one died despite several hours exposure to smoke as the toxic fumes became diluted throughout a large volume.

Travel distance in severe smoke

Toxins in the Scandinavian Star put people out of action after only 30 seconds (researchers guesstimate), corresponding to a walking distance of about 15 meters. During real-life evacuations, statistical data show that 90 per cent of survivors moved less than 16 meters in smoke. The smoke varied from light to extremely dense (optical density (OD) from 0.1/m up to 1.0/m). This suggest time available is about 50 seconds in severe smoke given a mean travel speed of 0.35 m/s.

Thus, given a good wayfinding system or a familiar route, the life saving potential is very substantial indeed. Class I wayfinding systems (definitions below) are called for, and/or escape hoods etc to protect eyes and respiratory system.

A wayfinding system is to no avail if people die on their way out, nor do escape hoods if they do not find the exit. A combination of these two measures is even better since they complement each other.

Walking speed

Careful studying has indicated a level of smoke severity and time of exposure (irritant smoke at density 1.53 to 2.26/m, exposure time 3 to 4 min, escape path 25 to 30 m) as the limit to what normal people will endure without protection - no matter what emergency egress information system is being used.

Speeds were within 0.2 to 0.5 m/s which appears to be the "ultimate speed in heavy smoke conditions", independent of the type of wayfinding system applied.

Importance of visibility in emergency operations

At industry plants, underground installations and complex high risk structures such as nuclear power plants or offshore drilling platforms visibility may become crucial in *severe* smoke. In order to perform shutdowns, extinguish fires, closing valves, rescue work or other intervening operations at imminent disaster, or indeed when all things have failed, personnel may encounter very dense smoke, if ever so briefly.

Normal and emergency lighting systems are easily blocked by smoke and may create total darkness or very dense foglike atmosphere reducing visibility to less than 2 m. Lighting systems often fail when subjected to structural damage, power shutdowns etc, in fire or other incidents. Most important are *reliability* as well as *visibility at close range*.

Visibility in smoke

The results of the tests showed that wayfinding systems performed very differently, and in many respects not according to expectations. Our mathematical calculations of visibility in smoke have been compared and verified by the tests. The method of calculation can be used to estimate if a given wayfinding system is suitable for a given smoke density, and we consider this the first available method to offer this degree of accuracy /6/.

We have made visibility diagrams for luminances from 0.0025 to 320 cd/m^2, as a function of percentage light-loss per meter and distance. The luminance of adaptation varied from 0.001 to 1 cd/m^2 /6/.

Viewing distance, not power or luminance, is the crucial factor at high smoke density. This relies not on obscuration by distance alone, but on the simple reason that visibility of any luminance must converge to zero at 100% obscuration.

Normal lighting, or indeed emergency lighting and any lighting that does not contribute to guide evacuees, will only distract and reduce visibility and readability of signs and information relevant to successful escape in smoke.

The photoluminescent strip built into the directional rail in test was 25 mm wide only, and tilted to an angle of only 30^{o} to the view direction. Amazingly, this design performed well even at smoke densities between OD 1.4/m and 1.5/m, but is explained by the short eye-to-object distance according to the above /4/.

The distinct green system offered the best visualized *readable information* of the systems tested, with black letters and arrows on direction and distance. But as with any system of point sources of light it becomes impractical to space the points close enough for smoke more dense than approximately 1.5 /m optical density /4/.

Test method for way guidance system visibility performance in smoke

Based on the experience /4/ a test method for determining visibility performance of visual way guidance systems in smoke has been proposed to working group 3B of technical committee 169 on European standard CEN /10/. Way guidance systems may be tested up to OD 2/m. The method does not apply to tactile systems but to any visual system - photoluminescent or powered. Preliminary tests are yet to be done.

Calculated and observed visibility performance

We recognized the need for tools that would enable us to select the most suitable wayfinding system for any given case. Such a tool is the set of nomograms of the relationships between smoke density, visibility, distance to visual markings, lighting parameters and the physical requirements of the eye, which we have developed and presented in /6/.

Previously published calculations made by Jin and Yamada /1,2/ were based on the visibility of conventional wayfinding systems when normal lighting was *on*. The method of calculation was internationally criticized because it failed to take into account the sensitivity of the eye to different angles of vision, and because it did not employ luminance values that are relevant to improved wayfinding systems.

Our calculations take the sensitivity of the eye into account. All available research results on evacuation in smoke show that when normal lighting is switched on, visibility is very much reduced. Our numerical tools allow calculations to be made *without* normal lighting, and employing relevant luminances. As well as being a practical tool, the systematic calculations offer a better physical and physiological understanding of visibility conditions in smoke. These calculations can thus help to further develop existing wayfinding systems or to develop new systems.

Wayfinding information

Researchers have insisted that wayfinding systems should include information on *direction* and *distance* to nearest exit. The test supported this view. Such information proved effective and two participating manufacturers promptly changed their policy. Wayfinding information is discussed further in Norwegian reports not referenced in this paper.

Location of marking and walking behaviour in smoke

In large building complexes, where the risk of a fire catastrophe prevail, one should prepare for a fast escape in upright or forward bent walking mode, rather than undue crawling that may possibly cause congestions and chaos, or worse: excessive time exposure to lethal smoke.

Following the research we recommend *continuous* marking at *low* location, i.e. below approximately 1000 mm height, and clearly visual signs above the exit doors. An optimum system design would be continuous marking at waist height, at skirting board or at the floor center line.

The recommendations are based on all conditions of visibility: Normal, smoke, blackout, normal and smoke as well as blackout and smoke.

Reliability

Powered (back-lit) lighting offer better readability of signs. But the higher luminance of powered systems compared to photoluminescent is marginal in dense smoke and do not justify implications of cost, reliability and aesthetics involved.

Photoluminescent or/and tactile systems were found to have superior reliability due to the inherent simplicity, and also most reliable in terms of visual information, provided they are designed to be continuous.

Way guidance system categories

A simple classification - *Classification of Emergency Egress Information Systems Designed to Perform in Smoke* - is introduced, dividing guiding systems in two classes by limits of optical density. Class I means smoke density exceeding OD 1.5/m, while class II is only up to OD 1.5/m.

To clarify: optical smoke density OD of 1.5/m is approximately equal to a visibility distance of 0.6 meter to forward illuminated objects, such as a hand outstretched, and of 1.5 meter to rearward illuminated (back-lit) sources of light.

Conventional emergency lighting signs do not qualify in either class because the spacing of light sources exceed the required viewing distance. All seven concepts tested and designed to perform *in smoke* will do as Class II systems, but some only if modified.

The superior overall system tested is a patented safety rail system: the only system tested to Class I. This nonpowered system combining visual and tactile information is a hand rail featuring directional notches and (optional) photoluminescent marking. As explained, however, even pure photoluminescent systems may be designed to Class I.

Wayfinding system Class	**Smoke density OD (m^{-1})**	**Visibility distance (m)**		**Wayfinding system design alternatives**	**Type of building structure**
		Rearward illuminated	**Forward illuminated**	(those designed for Class I also comply to Class II or No smoke)	
I	$\geq$ 1.5 1.5	< 1.5	< 0.6	Tactile, directional handrail. Visual handrails.	Large, complex public structures Complex industry structures. Underground structures. Other high risk areas/structures.
II	0.1-1.5	1.5-25	0.6-10	Continuous low location	Public buildings,

				marking	offices, hotels
No smoke	< 0.1	> 25	> 10	Point sources of light - 'conventional escape route marking'	Small, low risk public structures. Residences, workplaces, schools etc where one is familiar.

Performance of way guidance systems

Based on results of the full scale test and literature study the following comments were made on the potential suitability of different way guidance systems:

Spaced point sources of light (conventional emergency lighting)

These systems are generally not intended for smoky conditions. At typical spacing worldwide allowing viewing distances up to 30 m they may only be useful in smoke densities less than OD 0.1/m. Spacing less than 7 m (3.5 m viewing distance) should not be practical, as continuous visual systems then will be preferred. A 7 m spacing could do up to a smoke density of approximately OD 0.8-1/m. Systems based on space point sources do not conform to any class within the classification system proposed for wayfinding systems in smoke.

Photoluminescent (floor proximity systems or floor center line systems)

Improvement potential is considered significant if the material *on skirting boards or wall* (proximity systems) become more perpendicular angled towards upright walking persons, and located higher from the floor. Black should be preferred to green letters.

Floor center line systems: As the viewing distance is fixed improvements must rely either on higher luminance or larger arrows designed in photoluminescent material or both. The system may be complemented by some signage high above the floor, at strategic points such as rails and handles.

Photoluminescent continuous marking offered the best potential of the concepts in the test in terms of visibility, reliability and costeffectiveness.

Design improvements can be achieved by locating the strip closer to the eye of evacuees, and to a lesser extent also by increasing the excitation, the luminance and/or width of the strips. The systems have a large unexploited potential if the research results are implemented. The functional reliability is a definite asset as well as the very long operational times (exceeded 8 hours at time of test, new systems improved), the no glare effect, the unanimous delineated marking and the low cost and maintenance involved.

Floor proximity powered (back-lit) strip

A proximity back-lit strip was not tested as intended /4/. We can only assume that such a system would perform as well as the two continuous photoluminescent systems, and possibly even close to the performance of the distinct green semicontinuous system. A *directiona*l information element of the system would be required in any case.

Floor proximity semicontinuous distinct green

A system of semicontinuous (closely spaced point) sources of cold cathode tube light fixtures were tested. This patented system provide a distinct green light of high performance in smoke. Applied at the skirting-boards and spaced by 4 m, however, it only scarcely suffice to Class II requirement. Substantial improvement could be done if the system was *continuous*. As a further improvement the light tubes may be lifted to waist height to decrease viewing distance.

Directional rail

The Safety Rail System is a patented hand rail of directional notches so that anyone, in total darkness or blind, and independent of electric power, may sense by hand the escape route and direction. The embedded photoluminescent strip as in one tested version should be tilted, and/or the luminance and/or width of the strip should be slightly increased. It is vital that the tactile rail also incorporate a continuous visual line signage to prevent undue clinging to the rail.

Limitations

It should be observed that the full scale tests were performed with the general lighting turned off, and that the subjects entered the dark (except for visual marking) and smokefilled route with eye adaptation to approximately 150 lux. The route did not provide open spaces in excess of 15-20 m^2 or any straight lengths in excess of 8 m. The subjects wore closed circuit breathing apparatus for use in an emergency (mask used only in the real smoke tests) that prevented them from bending or crawling - this made test parameters uniform but disfavoured the low luminance low location systems.

The tested photoluminescent systems were all based on zinc sulfide. Current systems are being manufactured with new earth-borne pigments that provide a level of luminance several times higher.

Conclusions

A decisive factor to evacuees is the time they become exposed to heavy smoke. This time is governed by the perceived wayguidance of the evacuees - less by the length of the smoke filled escape route, which is within 16 m only in 90% of fire disasters by statistics - therefore wayfinding systems for smoky conditions play an important role.

One need to design for wayfinding in smoke exceeding OD 1.5/m in some industry as well as some public structures, contrary to current proposed general limits of OD 0.4/m within some international standardization bodies.

Very high performance of guiding people in smoke may be provided by simple *non*powered wayfinding systems: a tactile safety hand rail system or photoluminescent marking or both. Decisive factors in designing optimum wayfinding systems for smoky conditions are continuous marking less than 1meter above floor level, simplicity, independence of electric power, long operational times, simple maintenance and low cost.

Viewing distance, not power or luminance, is the crucial factor at high smoke density. This relies not on obscuration by distance alone, but on the simple reason that visibility of any luminance must converge to zero at 100% obscuration.

A photoluminescent strip at 0.5 m distance to the eye is more visible than the most powerful luminaries at just 1.5 m.

Without respiratory protection the time available in severe smoke is approximately 50 seconds at a mean travel speed of 0.35 m/s. This is relevant to the 16 m length of escape in smoke which accounts for 90% of incidents. Thus, given a good wayfinding system or a familiar route the life saving potential is very substantial. This calls for Class I wayfinding systems, and/or escape hoods etc to prevent irritation of eyes and respiratory system. A wayfinding system is to no avail if people die on their way out, nor do escape hoods if they we do not find the exit. A combination of these two measures is even better since they complement each other.

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