

## Light plus Sound = Safescape

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2:00am, April 7, 1990.

A fire ignites, probably the result of arson in a pile of laundry in the aft section of the starboard corridor of the Scandinavian Star passenger ferry as it courses through Norwegian waters on an overnight voyage from Oslo in Norway to Fredrikshavn in Denmark. This tragedy kills 158 people, including 29 children from a total of 482 passengers and crew. Within 12 minutes, the fire has spread rapidly to staircases and upper levels. 50 people die of (asphyxiation?) in the corridors from the toxic smoke. Rescuers later find 99 casualties lying lifeless in their cabins, some in the bathroom or shower room with a towel covering their faces as an act of self preservation from the smoke.

Many factors precipitated the ease of flame/smoke spread, and number of fatalities. Evacuation routes were generally complex, involving several changes of direction through narrow, confined corridors (some leading to dead ends) onto discontinuous escape staircases.

The overwhelming rapidity of fire development and the speculation that all who lost their lives had probably died within 45 minutes of its inception resulted in the launch of the biggest marine investigation ever held in Scandinavia. Part of the investigation concentrated on why people died where they stood...why they never made it on deck even though they were so close to the emergency exits.

- During post-incident interviews, many survivors claimed that it was impossible to see Emergency Exit Signs thru the smoke, resulting in SINTEF NBL – the Norwegian Fire Research Laboratory performing a series of evacuation trials on a reconstructed section of the Scandinavian Star.
- Using existing emergency signage provision, it was found that *“40% [of test subjects] could not find the emergency exit. They either passed it or tried to get out through the wrong door, and some turned round on the way out...It was disturbing to realise that so many people managed to make a mess of the evacuation process in spite of the fact that they know that they were taking part in an experiment, and that the corridor we had built up was relatively simple in comparison with many hotel or ship corridors....we do know that emergency lighting and marking signs do not help to distribute people among the evacuation routes available. People try to get out the same way as they came in, and this can easily cause overcrowding. Our suspicion that signs do not live up to expectations has been reinforced by a major study that only 8% of the people noticed signs when they were fleeing from a fire.”*<sup>1</sup>

In their summary, The Norwegian Official Report (NOR 1991:1E) on the disaster stated:

- *“The committee recommends that a requirement be introduced that audible signals with a sound that clearly distinguishes them from the alarm bells be installed by the exit doors in escape routes on board passenger ships, as directions for escape in conditions of reduced visibility.”*

*Midnight, 23<sup>RD</sup> June 2000.*

In the early hours of the morning fire engulfed a backpackers Hostel in Childers, Queensland. 15 young people died and 5 were seriously injured. Jocky Visser from Holland was one of the lucky ones to get out. He recalled *“We opened the door and we could hear people screaming and yelling for help because all the hallways were full of smoke. Keith O’Brien recalls “I tried to get out through the corridors but the smoke was in front of your face. You couldn’t see.”* Many survivors repeated that the smoke was the real problem in evacuating. Childer was not a one-off event.

- The Victorian Metropolitan Fire Brigade reported 878 fire incidents in multi-storey Budget accommodation over 9 years ending in 2002 alone. It’s a great complement to their service that only 2 lives were lost and 55 injured.

Over the last 20 years fires in Commercial Premises have claimed close to 100 lives, injured hundreds more and caused thousands of forced evacuations in Australia. It’s not just Fire and Smoke that our Emergency Services have to deal with today. Hazmat or hazardous material incidents have greatly increased. The Federal Governments official EMA Disasters database lists many toxic chemical and gas incidents which over the 20 years have claimed 52 lives and injured 834.

Today we suffer Bomb scares and other terrorist acts reported daily. Getting people out of a building quickly and safely in life threatening conditions, in smoke, toxic fumes, dust, dark or daylight is crucial. Some people may have perfect 20/20 vision, others maybe less than perfect and sight impaired. Others may suffer physical impairment and we all get a little slower as the years role by!

*Smoke effects on Viewing Distance!*

During IES’s Lux Pacifica Conference in Cairns, the Japanese delegation from University of Kyoto and their highly respected General Building Research Corporation gave two papers on their studies on the “Visibility of Emergency Signs in Fire Smoke”. They commented “that smoke spreads much faster and wider in a building than fire growth”. Further they stated “that smoke adheres to sign surface reducing luminance and attenuates the light transmission”.

In 1997 Dr. Tadahisa Jin of Japan’s Fire Protection & Safety Centre was invited to give the Plenary Lecture at the International Symposium for Fire Safety Science. His paper was titled ‘Studies on Human Behaviour and Tenability in Fire Smoke’ and he commented in his Abstract that “many evacuees are trapped in the early stages of a fire by relatively thin smoke and loss of visibility is an indirect but fatal death cause”.

His extensive research over many years is frequently referenced and held in high regard. In particular the relationship between visibility and optical density of fire smokes for which he proposed some practical equations and most importantly, human behaviour in an emergency evacuation. He stated that “in an emergency it is very important to have leaders who are familiar with the inside of the building” and further “unless there are reliable leaders, other, substitution ways, are required”.

The UK Building Research Establishment has also conducted extensive research in emergency lighting and wayfinding systems through the 90’s publishing numerous papers available from HMSO. (*For those who want a single comprehensive document referencing a broad cross section of research papers I recommend HMSO ISBN 0-7176-1611-8 as an excellent doc*).

Summarising BRE’s and Jin’s work in the context of viewing distances in smoke. Both demonstrate similar smoke obscuration effects on signage. Jin recommended viewing distances for buildings we are familiar with as follows:

	VISIBILITY (m)	OPTICAL DENSITY (m-1)
Familiar Bldgs	3-5	0.4 to 0.7

**BRE tests closely correlated to Jin’s results, demonstrating that with an optical smoke density of 0.5 (m-1) viewing distance is reduced to 6 metres.**

This OD of smoke is generally regarded as bordering a moderate density but normally regarded as survivable smoke i.e. smoke that you should be able to transit thru an escape route, to the nearest fire exit, in a realistic timeline as provided by Fire Engineering design/guidelines.

However if you can’t see high mounted escape signs down the escape route at say every 24 metres in smoke or in a toxic hazmat event, you really do have a major problem when evacuating. Smokes do tend to have greater densities at ceiling level. This is also where we traditionally mount our escape signs!

#### *Smoke and Survivability.*

Whilst I’ve focussed on the issues of visibility and viewing distances of exit signs in smoke, planners and regulators should also take account of the irritating effects of smoke on your eyes which reduces your visual acuity (the ability to read shapes or lettering) and most importantly the smokes toxic effects on your breathing. Together these can very quickly cause evacuees to become emotionally unstable. The longer you are exposed to smoke the greater these effects can be.

**Yin’s work and broad recommendations took some account of these factors. Whilst he recommended a 5 metres viewing distance to an escape sign in thicker and more dangerous moderate 0.7 OD of smoke in familiar buildings, he recommended a greater 15 m viewing distance to an escape sign, in much thinner and less dangerous 0.1 OD smoke. Highly toxic Hazmat events would probably fall outside these broad guidelines.**

To round this off let me quote the smoke classifications used by Federal Aviation Authority in USA. Light (or thin) smoke is having an OD of less than 0.35; moderate smoke is between 0.35 and 1.17; dense smoke is between 1.17 and 3.5.

NOW I'VE FRIGHTENED YOU TO DEATH LET ME EXPLAIN MY SOLUTION.

**Finding a better cost effective method of aiding a 'faster and safer evacuation' was the impetus for my research into Audio Evacuation aids and its potential to substantially enhance existing Visual methods i.e. Emergency Evacuation Lighting Systems.**

- If sound is to be combined with visual signage the type of sound used is critically important.
- There is one particular part of our central nervous system that plays a vital role in the detecting of and, equally importantly responding to a sound source. This area is part of the mid-brain and is called the *Superior Colliculus (SC)*. Neurophysiologists studying the properties of neurones in the SC together with psychoacousticians studying human responses to sound have enabled us to understand how the brain processes information relating to a sound source and, importantly, what type of sound is needed for a degree of accuracy to be achieved.
- It has long been recognised that localizing a sound source requires a vast amount of neural processing. Only certain types of sounds are inherently localizable and what is crucial is that they contain a large spectrum of frequencies that is broadband noise.
- Pure tones, simple tone combinations or narrowband noise cannot be localized. To understand why this is the case, the cues given by sound, recognised by the brain, must be considered.
- **The task of locating the direction of a sound source is one of the most complicated tasks our brain performs without us being aware of it.**

Nevertheless, we have the potential to be very accurate at sound localization and are easily capable of determining the position of a sound source to an accuracy of 2 – 4 degrees. However, it is an extremely complex perceptual process that involves integrating information derived from multiple cues.

For truly accurate sound localization, our brains have to decode three types of sound cues which in isolation convey only limited amounts of spatially ambiguous information. The overall effectiveness of these cues is also dependent on the interaction of additional variables, such as the type of sound presented (tone or noise based for example), the medium in which the sound propagates (outdoors or within a narrow corridor), whether there is a visual target, and whether the listener turns their head or remains stationary for the task

### *Binaural and Monaural Auditory Localization*

Two primary cues which govern auditory localization are known as the binaural cues. These binaural cues make use of the fact that we have two ears separated by the width of our head. Binaural cues are fundamentally dependent on the arrival of the initial sound waves at the two ears. For example, if source A is straight in front of the listener, therefore a sound which emanates from this source reaches both ears at the same time with the same intensity as the path lengths are the same. However, if we consider a source B, 30° offset to the right of the listener, the path lengths are now unequal with sound at the left ear arriving not only later, but also more attenuated than the right. It is this difference in path lengths which forms the basis for this binaural phenomenon.

Unfortunately, the geometrical nature of sound propagation and auditory system processing complicates the way in which these auditory cues work. First of all, the auditory system is very sensitive to the phase of an incoming waveform at frequencies below 1.5 kHz, so interaural time differences (ITDs – the time difference between each ear) are only really applicable for frequencies below this threshold. In addition, loudness differences (IID – interaural intensity differences) do not work at these low frequencies as sound diffracts with ease around the head in this range, thus causing no real attenuation. For such interaural intensity differences to come into play, the source must emit a sound that has wavelength components smaller than the diameter of the head – approximately 3 kHz and above.

Unfortunately, there are further problems as the cue of timing and intensity is virtually identical for sounds emanating either directly in front of or behind the head. To resolve this ambiguity, the auditory system uses a third type of monaural cue, known as a spectral cue. These spectral cues are initiated due to the way the external ear, or pinna, modifies the spectrum of the sound source. More specifically, as sound passes over the bumps and convolutions of the pinna (and of the torso), it is modified in such a way that some frequencies are attenuated, some are amplified, and most are distorted in time.

Given the complex interaction of these three cues, the type of signal presented is of paramount importance in the formation of sound source location decisions. So, to provide complete localization knowledge, information from all three cues must be combined. In other words, the larger the frequency content of the sound used, the greater the accuracy will be in locating it. *For a sound to be localizable it must contain as much of the audible frequency range as possible (20-20000 Hz), i.e. broadband sound, and this is the primary reason why neither conventional alarms nor speech will work in this situation.* Existing alarms operate over only a tiny portion of our hearing range, approximately 800 Hz to 3 kHz, and the same can be said for speech. Indeed, the range in which they operate, although maximally sensitive to our ears with regards to loudness, is the worst band for localization!

### *Light plus Sound.*

There is a compelling rationale for combining visual and auditory sensory information in an evacuation aid.

- The area of the brain that responds to spatial sensory information (the superior colliculus) also initiates the response to the sensory stimulus, containing cells that are tuned to more than one sensory modality.
- These neurones respond to light by itself and also to sound alone.
- However, when light and sound are presented together the response of these cells is far greater than the summation of the response to either modality alone.
- **Some cells respond over 1,000% better when light and sound are used together (and spatially coherent) than the response to either modality alone.**

In other words, to activate an individual to 'flight', a stimulus containing both light and sound will be far more effective than light or sound alone. As I've stated previously if sound is to effectively combined with visual exit signage the sound must be inherently localizable by us.

**Pure tones, simple or narrow band sounds cannot be localised by us.**

**Sounds must contain a large spectrum of frequencies.**

**That is BROADBAND directional sound.**

*The remainder of this paper documents research undertaken on the efficacy of using broadband sound as a complementary evacuation aid. Although the data are presented from trials onboard ships similar research has been undertaken in buildings, aircraft and tunnels.*

**The United Kingdom's Maritime and Coastguard Agency (MCA) expressed interest in carrying out shipboard trials to assess the effectiveness of the broadband sound beacons for mustering people on passenger ships.**

As a result, real-life trials were conducted in 2001 onboard two roll-on-roll-off ferries to determine the effectiveness of the designed beacons in accommodation areas, along corridors, on stairways and in open public spaces. Conditions were varied such that comparisons could be made with existing evacuation provision, especially low-location lighting. The following report chronicles briefly these ferry trials.

## **PARTICIPANTS**

Participants were recruited from the local population of towns surrounding Greenock and Ardrossan on the Clyde coast. Ages ranged from 17 to 67, including both hearing and visually impaired participants. In total, 360 subjects were employed for the study and were paid £20.00 per head. *Unfortunately, this financial incentive meant that we attracted individuals under the influence of drink and drugs, but this was deemed representative of a general ships population.*

## **STIMULI / APPARATUS / METHODOLOGY**

From our research and testing we selected a suitable “speaker” to generate the required broadband noise without distortion. This is little bit of our “black-art” that we now passed on to Clevertronics for their product development.

For safety reasons, non-toxic, artificial (theatrical) smoke was used in the trials, reducing visibility to 3% of normal density (i.e. participants couldn’t even see their hands in front of their face). Participants were asked to imagine that they were in real fire / evacuation scenarios and to behave as such. Of course, there were obvious behavioural differences but nonetheless, it is common practice to use this type of non-emergency test for validation.

Evacuation times were recorded for all individuals in every trial, their behaviour captured using thermal-imaging cameras. For further analysis, all participants completed an in-depth questionnaire related to their trial.

## **EXPERIMENTS**

In total, the trials were split into 2 scenarios, each reflecting different aspects of evacuation from passenger ships

*Scenario 1:* These trials were conducted in the crew accommodation area of a small Ro-Ro ferry to represent a night scenario (figure 1). 20 participants took part in each trial, all naïve to the trial area. On the inside of each cabin door there was a standard plan illustrating all three emergency exits for that area. Trials were structured to combine low-location lighting (LLL), directional sound navigation beacons on / off and pre-briefing / no briefing (i.e. what the navigation beacon sound meant). Additionally, either all 3 exits, or only a single exit was available for evacuation. Briefly, the purpose of these trials was to determine:

- a. How directional sound compared to assistance / no assistance from low-location lighting?
- b. What happened when a pre-planned route was blocked?
- c. Whether multiple directional sound beacons caused confusion?
- d. Whether a briefing on the meaning of the sound was essential?

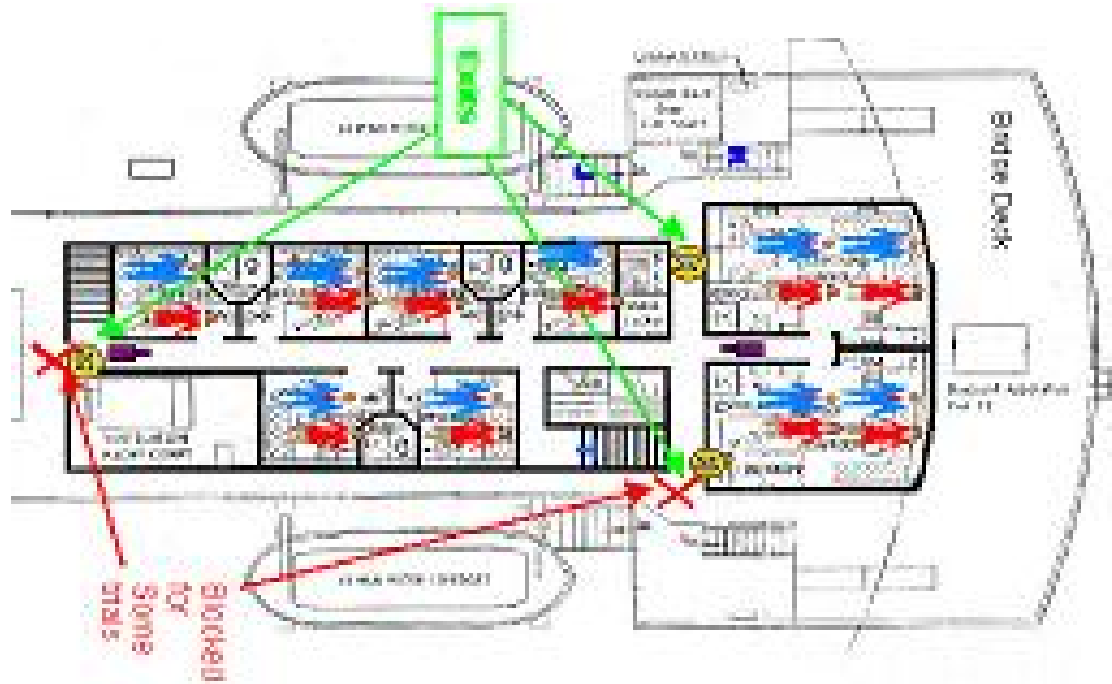


Figure 1. Ferry 1 crew accommodation.

*Scenario 2 (Figure 2):* These trials were conducted onboard a larger Ro-Ro ferry in the forward restaurant and lounge areas. These were large open public spaces, furnished with tables and chairs. 20 participants were released at 15 second intervals, having a choice of four exits. The two nearest exits accessed (via stairways) the deck above whilst the farthest were wide main exits to the central area of the ferry. These latter exits were fully visible in no-smoke conditions. Briefly, the purpose of these trials was to determine:

- a. Whether the directional sound navigation beacons reduced evacuation times in open spaces both with and without smoke?
- b. What was the impact of the directional sound navigation beacons when combined with low location lighting on edges of corridors and stairs?
- c. How passengers chose between alternative available exits?
- d. Whether confusion existed with multiple directional sound navigation beacons?
- e. Whether briefing on the meaning of the sound was essential?

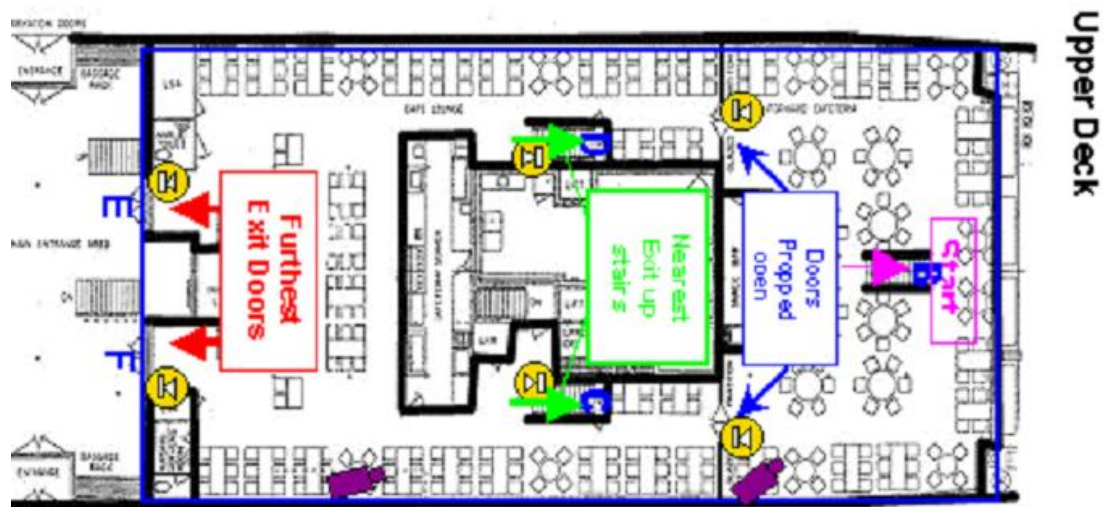


Figure 2. Ferry 2 lounge and restaurant.

All trials were filmed with thermal imaging cameras to allow group and individual behavioural responses to be assessed.

## RESULTS

### Scenario 1

The 10 trials of 20 participants each were divided into two main groups. Group 1 consisted of four trials with all three exits available, whilst group 2 consisted of six trials with only one exit available.

Briefly, where all three exits were available, exit times were short with the positive effect of the directional sound navigation beacons limited (a reduction in total exit time of 9 – 17%). However, where only one exit was available, the differences were substantial (table 1).

LLL	Sound	Briefed	Exit time of 18 <sup>th</sup> Person (secs)
			286
	X		109
X			205
X	X		100
	X	X	82

Table 1. Evacuation times based on exit of 18<sup>th</sup> person.

As can be seen, the presence of the directional sound beacons dramatically reduced evacuation times, irrespective of whether low-location lighting was present or not (by more than 50% in many cases).

**In addition, if the subject was briefed as to the nature of the sound, their exit time was considerably faster, at only 82 seconds!**

Examination of the thermal-imaging data gave a good insight into what was happening during the evacuation process. In trials without sound, when participants came across a locked exit door, they returned along the passageways searching for an alternative exit, entering open cabins. Given the constrained nature of the passageways, bottlenecks occurred rapidly and frequently with participants losing patience, starting to search for alternative, unavailable exits.

However, when the directional sound navigation beacons were present, participant behaviour differed considerably. Participants left their cabins, moving towards their pre-planned exit. After a short time, they realised this was not the way to proceed, turned and moved towards the origin of the sound. Contrary to the no-sound condition, participants queued patiently at exits marked by the navigation beacons.

*Scenario 2*

The 6 trials of 20 participants each were divided into three combinations, namely:

- With and without smoke
- With and without navigation beacons
- With and without prior briefing

Table 2 illustrates the exit choice and time taken for this series of trials. In brief, the presence of directional sound navigation beacons improved (for the most part) the rate at which participants evacuated via the nearest available exit. In the without smoke condition, correct exit choice improved substantially, but there was very little difference in overall evacuation time whether participants were briefed or not.

Smoke	Sound	Briefed	Exit time of 18 <sup>th</sup> Person (secs)	% Persons Evacuating via Nearest Exit
			54	55
	X		46	45
	X	X	45	90
X			206	30
X	X		141	100
X	X	X	170	95

*Table 2. Evacuation times and exit choice.*

Where smoke conditions existed, the effect of the directional sound navigation beacons was clearly marked. As well as having a substantial effect on overall evacuation time, correct exit choice improved dramatically.

Analysis of the thermal imaging data (combined with the questionnaires) showed that the presence of low-location lighting in open spaces had nominal effect. Without the directional sound navigation beacons and in smoke conditions, participants felt their way along walls, tables and chairs until an exit was located. Only then did the low location lighting confirm that their choice was an actual exit. In trials where the directional sound navigation beacons were activated, 95% of participants indicated that the sound guided them to an exit, with 85% considering it to be the most helpful of aids provided.

Similarly, in smoke-free conditions, 82% of participants indicated that the beacons led them to an available exit, but that the visual exit signs were the most obvious help with sound confirming them as a safe exit.

Regarding the presence of multiple beacons, 84% of participants answered that they were aware of more than one beacon with 88% choosing to move towards the loudest one.

Overall, where smoke existed, 85% of the participants indicated a preference to relying on the directional sound navigation beacons as opposed to the low location lighting. The remaining 15% said they would prefer to rely on both sound and low location lighting. In the smoke free cases, 73% said they would rather rely on sound, 22% on low location lighting and 5% would rather rely on both.

## DISCUSSION

The results from these ferry trials confirmed our prediction that the directional sound navigation beacons had a marked effect on not only evacuation time but also exit choice in simulated emergency conditions. Irrespective of whether participants could see their route or not, the beacons proved to be a very important navigation aid, whatever their age or disability. In addition, the presence of multiple beacons caused no indecision as far as exit choice was concerned.

## CONCLUSIONS

- This final exploration in the project has proven a resounding success for the use and implementation of directional sound navigation beacons for Building emergency egress.
- Although these trials were executed on passenger ships, their results are easily applicable to any Building type that requires either complex route navigation or simple perimeter marking.
- Undoubtedly, the directional sound beacons instilled more confidence in the evacuation process, the ear directed to the exits without frantic searching. This may be explained by the fact that the overall complexity of the environment is reduced substantially to a nominal number of cues relevant to the immediate problem of escape, namely following the sound.

It should be emphasised that we do not advocate escape through smoke as part of the primary safety plan of the environment, nevertheless, according to Professor J L Bryan of Maryland University USA, who studied survivors from 400 different fires, 53% of survivors from fires reported travelling through smoke.

Accepting that survival may require travel through smoke implies that providing directional sound navigation beacons will ensure maximal survivability in such emergency situations. Combining the broadband sound, used in the research studies, with visual signage provides people with the optimal sensory cues for evacuation and ensures faster evacuation times both in smoke conditions and no-smoke conditions.

### *Notes:*

*International standards and codes have now been accepted for the installation, testing and maintenance of Directional Sound Evacuation (DSE) systems both in the building and marine environments.*

*The USA government National Institute of Standards & Technology (NIST) has produced a report following collapse of the World Trade Centre on 9/11. Recommendations 18, 19 & 20 from this report highlight improvements required for the evacuations systems.*

*The addition of 'audible exit marking' (DSE) into the forthcoming release of the US National Fire Alarm Code (NFPA 72) is in specific response to these recommendations.*

*In the UK, British Standard BS8456 is a code of practice for the design and installation of DSE systems in the building environment*

*Additionally, the Maritime Safety Committee (MSC) of the International Maritime Organisation issued circulars 1167 & 1168 in 2005 detailing the testing, approval and maintenance of evacuation guidance systems as an alternative to the use of low location lighting systems.*

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THANK YOU TO THE IES FOR INVITING ME.  
Professor Deborah Withington