

Visibility of Exit Signs in Clear and Smoky Conditions

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Introduction

In the present study, the visibility of several types of internally lit exit signs was assessed under both clear and smoky conditions. In the evaluation both photometric and psychophysical measures were taken.

As background, a number of researchers have evaluated the appearance and visibility of exit signs in clear and smoky conditions. Rea, Clark, and Ouellette¹⁸, Clark, Rea, and Ouellette⁴, and Rea¹⁷ reported data from 16 volunteers who made threshold observations of the visibility of the exit signs in smoke. The effects of exit sign type, threshold visibility criterion and ambient smoke chamber illumination were evaluated for two visibility criteria, detectability and readability. The smoke density at which a sign was just below threshold was taken as the critical smoke density. Signs were chemiluminescent (tritium powered) self-illuminated signs or illuminated with either fluorescent or incandescent bulbs.

Analysis of the data indicated that sign type, sign luminance, evaluation criterion, and ambient illumination produced significant effects. Rea, et al, found that greater smoke density generally was required to mask the visibility of signs with higher luminances. Greater smoke density was also required to mask detectability than readability. Although both detectability and readability generally increased with overall luminance, there was considerable variability: Three red-and-white signs with luminances of 170, 391, and 1272 cd/m² were the best performers (Clark, et al). The chemiluminescent (tritium induced) signs, which had the lowest luminances (around 0.18 - 0.61 cd/m²), proved to be the most difficult to read. In addition, abnormal color vision proved to be an important factor, with four protan observers performing significantly more poorly particularly with red signs, as might be expected from their loss of long wavelength sensitivity. Furthermore, when ambient illuminance (75 lx) was provided in the chamber, sign visibility was reduced with a greater reduction in visibility threshold, although the effect was greater for certain signs.

Rea, et al, commented that when the supplementary ambient illumination was removed, the scattered light was reduced enabling the signs to become more visi-

ble. The scattered light seemed to reduce the readability of low contrast signs more than high contrast signs, as well as reduce the readability of smaller text. Rea, et al, recommended increasing the brightness of the sign itself while reducing scattered light from other sources including downlights. They also suggested that cutout, stencil-faced, signs may be more visible than panel-faced signs. Noting that many factors affect sign brightness, they suggested that translucent green materials will be brighter to more people than translucent red materials for the same light source. Rea¹⁷ discussed the need for "smart" fixtures which increase sign brightness while decreasing ambient illumination in smoke conditions.

In a subsequent study, Ouellette^{14,15} evaluated the effect of luminance and opacity of the sign legend and background to determine if in fact signs with transilluminated letters and opaque backgrounds would perform better. In Ouellette's experiment, 12 color-normal subjects adjusted the brightness of an exit sign to a just readable threshold for different configurations, smoke densities, and ambient illuminations. Three red-and-white rectangular signs containing the word *EXIT* were studied with various combinations of transilluminated and opaque letters and backgrounds. Two levels of smoke density were used with and without ambient illumination (0.55 lx). Ouellette found that smoke density had the greatest effect on sign readability, while ambient illumination, even as low as 0.55 lx also reduced sign readability. The sign with both transilluminated letters and background required greater luminance to be readable than the sign with illuminated letters and an opaque background - a result consistent with the idea that signs with illuminated backgrounds and text produce a veil in smoke which reduces their readability. Paradoxically such signs were somewhat less affected by increases in smoke density.

In a study of sign visibility during movement, Jin and Yamada⁹ reported that the visibility of internally lit signs was slightly greater in black smoke than in white smoke. They also determined that signs of 2000 cd/m² were more visible than signs of 500 cd/m², and observed a linear relationship between the product of the visibility of the sign at the obscuration threshold and the smoke density. In a second experiment, they found that when observers walked through irritating

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white smoke, the visibility of the exit sign decreased more sharply than with a less irritating black smoke. An experiment on visual acuity in smoke also indicated a marked decrease with increasing extinction coefficient, with an accompanying increase in eye blink rate. Thus, when the smoke was relatively thick, its irritating effects reduced visibility beyond its ability to obscure the sign physically.

Two studies assessed the visibility of exit signs in aircraft cabins. Rasmussen, Garner, Blethros and Lowrey¹⁶ evaluated the visibility of eight exit signs in a simulated aircraft cabin in smoke. The signs were viewed at a distance of 1956 mm (77 inches). Four levels of background luminance were assessed: 31, 89, 140, and 158 cd/m² while eight levels of sign height and width were evaluated—3.2 to 211.5 mm (0.13–8.33 in) in height, and 0.38–25.4 mm (0.01 to 1 in) in stroke width. The authors found that relatively similar smoke densities obscured the signs at the three higher luminances, while slightly less smoke was required for obscuration at the lowest luminance. Similarly, larger signs consistently required greater smoke density for obscuration, although the results for the six larger signs [above 13.4 mm (0.53 in) in height] were quite similar. Rasmussen, et al¹⁶ suggested that smoke effectively reduced sign luminance and hence apparent brightness to between 0.03 and 0.11 percent of clear air conditions. They concluded that signs that meet the FAA recommendation of 89 cd/m² will be visible in smoke densities of 3 to 3.55 (total optical densities). Increasing sign size above a certain minimum did not appreciably increase readability.

In a series of tests, Demaree⁸ found that smoke can rapidly and significantly obscure aircraft cabin illumination and signs in as little as 45 s, as well as decrease overall illumination. Because the obscuration was clearly a function of the distance from the floor, Demaree recommended locating illumination sources below 61.5 inches (1.56 m). Although Demaree's results did not indicate any significant effect of increasing sign luminance on visibility, he only examined three luminance levels (85.6, 171.3, and 256.9 cd/m²). Nevertheless, the signs with the greater luminance remained visible about 10–15 s longer than the 85.6 cd/m² signs, although the density of smoke determined the absolute time course for visibility.

Still other researchers have been concerned with the notion that the type of illuminant used in the sign would affect its visibility. Three studies examined both tritium (self-powered) and conventional signs. In the first, Beyreis and Castino² evaluated the effectiveness of tritium, phosphorescent, and electric internally lit signs in clear and smoky conditions. For clear conditions, the luminance of the electric sign was adjusted to be equivalent in visibility to that of an unlit exit sign

with 5 fc (53.8 lx) of external illumination on the face. In smoke conditions, the luminance was adjusted to give a visibility equivalent to the self-luminous sign at full life. Results from the clear condition indicated that the electrically illuminated sign was visible and legible at 300 ft (91.4 m). The tritium signs were legible at 75 ft (22.9 m) for the half-life sign and 100 ft (30.5 m) for the full-life sign, but neither was visible at 300 ft (91.4 m). The effects of smoke were assessed at a fixed distance of 12 ft (3.6 m) in a smoke filled chamber with about 5 fc (53.8 lx) ambient illumination. The optical density at which the electric signs were legible was greater (0.152/ft) than for the tritium sign (0.095/ft). When the brightness of the electric sign was reduced to be nearly equivalent to the tritium sign, legibility and visibility occurred at the same smoke density for both. The authors reported little effect of the backscattering of incident light when it was directed into the smoky room over the heads of the observers. It should be pointed out that the number of observers and their visual capabilities were not specified, while signs were viewed at only 12 ft (3.6 m). Furthermore, the performance of the electric sign was comparable to that of the tritium sign only when it had been dimmed. The performance of the tritium sign in clear conditions was markedly poorer, with a legibility distance of less than one-third that of the electric sign.

Schooley and Reagan¹⁹ evaluated the visibility of exit signs using five observers. Three sign types were used; a radioactive isotope self-powered sign, an unlit electric sign, and a lit panel-face electric sign (with two 25-W incandescent bulbs). All three signs were detectable at about 300 ft (91.4 m), distinguishable at 225 ft (68.6 m), and legible at 150 ft (45.7 m) under clear normal lighting conditions. In this test, luminance for the internally lit sign was reduced to 5 fL (17.1 cd/m²) from its normal 48.5 fL (166.2 cd/m²). When the corridor was darkened, the self-luminous sign was legible at 125 ft (38.1 m), as compared with 75 ft (22.9 m) for the lit electric sign. (No luminance was given for the self-luminous sign, however.) When smoke was added to the normally lit corridor, the three signs became legible at only about 40–50 ft (12.2–15.2 m), with essentially similar performance. Increasing the luminance of the electric sign to 25 fL (85.7 cd/m²) increased its visibility to 125 ft (38.1 m) and its legibility to 50 ft (15.2 m) in smoke, however. Yet, the authors concluded that the performance of the self-luminous sign is acceptable compared with that of the internally illuminated electric exit sign. Schooley and Reagan¹⁹ claimed that "increasing brightness of the electric sign did not have a major influence on improving legibility and indeed could be detrimental when certain thresholds are exceeded. . . a blurring phenomenon occurred which reduced legibility when the brightness exceeded 10-20

fl (34.3–68.6 cd/m²).” It should be noted that their data were based on only five observers, one of whom was protanopic, and that the luminance of the internally lit sign was deliberately reduced.

In support of revisions to the Australian Standard for Emergency Lighting in Buildings,¹ Wilson²³ evaluated the effectiveness of five green-and-white exit signs. Sign types included both internally and externally lit signs, an edgelit sign, and a tritium self-illuminated sign. Sign luminance ranged from about 1–720 cd/m² for all but the tritium sign; its luminance was less than 0.9 cd/m². The visibilities of all signs except the tritium sign were evaluated in clear and smoky conditions as well as with and without external room illumination, which was provided by four single tube fluorescent lamps. Because the luminance of the tritium sign was so low, it was excluded from the visibility study. Observers first viewed the four signs simultaneously and rank-ordered them in terms of effectiveness, and then assessed each sign individually on a rating scale of perceived effectiveness. The results indicated clearly that the two internally lit signs performed significantly better than the externally lit or edgelit signs for all conditions. The internally lit sign with illuminated letters remained visible for a longer time when smoke density was increased than a similar sign with an illuminated background. The performance of the externally lit sign was poorest, in smoke and in clear conditions with ambient room lighting. Wilson²³ suggested restricting such signs to areas that can extinguish or exclude smoke automatically, specifying the maximum distance of the external source from the sign, and increasing the minimum illuminance.

Standards for Exit Signs

The Life Safety Code of the National Fire Protection Association (NFPA) provides specifications for exit signs and lighting for emergency egress in NFPA 101-26.¹² The code states that exits are to be marked with an approved sign that is placed so that no point in the access to the exit is more than 100 ft (30.5 m) from the nearest visible sign. Signs are to be “located and of such size, distinctive color, and design as to be readily visible and shall provide contrast with decorations, interior finish or other signs.” Signs are required to have plainly legible letters at least 6 inches (152 mm) high with a stroke width of not less than 0.75 inches (19.1 mm). Externally illuminated signs are to be lit by not less than 5 fc (53.8 lx) and have a contrast ratio of not less than 0.50. Internally illuminated signs shall have a visibility equivalent to such an externally illuminated sign. The only exception is approved self-luminous or electroluminescent signs with evenly illuminated letters which may have a minimum

luminance of 0.06 ft (0.21 cd/m²) and which are used for low level exit signs located 6–8 inches (152–203 mm) above the floor.

Similar provisions are given by the IESNA¹⁰ and CIE.⁶ The CIE also recommended use of pictographs and suggested that their size be at least 1/300 of the maximum distance from which the sign would be viewed. Recommended minimum luminance for the pictograph is at least 15 cd/m² with a maximum of 300 cd/m². The IESNA notes that visibility is critically affected by smoke or other light scattering particles (such as dust), as well as by contrast, color, adaptation, and lighted vs. opaque backgrounds, although it provides no specific recommendations for any of these parameters. Other factors to be considered include glare and veiling reflections from external emergency or ambient illumination. Signs should be uniformly lit, with a variation of not more than ± 5 over the face of the sign. Signs within an area should be similar in color and design to aid in identification.

The National Building Code of Canada¹³ specifies the use of (a) red letters (or background) with a contrasting background (or letters) with a minimum letter height of 114 mm (4.5 inches) with a 19 mm (0.75 inches) stroke width for internally lit signs; or (b) white letters (background) on a red background (letters) with a minimum letter height of 150 mm (5.9 inches) and a 19 mm (0.75 inches) stroke width for externally illuminated sign. No specifications (maximum, mean, minimum) are given for either external sign illuminance or internal sign luminance.

The Australian standard¹ specifies the general use of white lettering on green backgrounds with a minimum letter height of 100 mm (3.9 in) and width of 12 mm (0.47 in). Internally illuminated signs shall have a background luminance of not less than 8 cd/m², with a ratio of legend to background luminance of not less than four-to-one. If the legend and background are reversed in color, so that the legend is green and the background opaque (white), the sign luminance should be between 2 and 25 cd/m². Variation in the legend and background luminance should not be more than five-to-one. An illuminance of not less than 50 lx (4.65 fc) is required for externally illuminated signs. Any external luminaire should be positioned such as to cause no reduction in sign contrast and be screened from the direct view of people moving through the area.

In a comparison of US and UK recommendations, Webber²² pointed out that the UK recommendation for exit sign sizes (about 4 inches) results in signs that subtend a visual angle half or two-thirds the size recommended for the US. Yet, the UK recommendation for the luminance of internally lit signs is about three times that of the US. Both standards specify

a luminance for self-luminous signs that is one – two times lower than that for conventionally lit signs. When the visibility of exit signs in smoke is considered, analysis of data for US style signs suggests that the legibility distance (ability to read the sign) is reduced from the recommended 30.5 m (100 ft) to about 10 m (32.8 ft) when the optical density of the smoke is between 0.05 and 0.01 od/m.

Experimental Approach

The preceding review of the literature indicated general agreement on the size, configuration, and spacing of letters in exit signs, but considerable disagreement on requirements for color, configuration, and luminance, particularly for sign visibility in smoke.

The present study assessed some of the characteristics that influence visibility for internally illuminated conventional and electroluminescent (EL) exit signs. Electroluminescent signs were included because it was thought that their greater uniformity might enhance their visibility. Twelve exit signs were evaluated, two incandescent, two fluorescent, and eight electroluminescent (EL). Ten of the signs could be considered either stencil- or panel-faced, meaning that the letters were illuminated for the stencil-face, while the background was illuminated for the panel-face. All signs met the UL 924 (1989) specifications of 6-inches (152 mm) height with 0.375 inch (50.8 mm) spacing and stroke width of 0.75 in (19.1 mm). One incandescent and one fluorescent sign were red; the

other two were green. Three EL signs were red; three were green; one was blue-green, and one was red on green.

The effectiveness of the signs was assessed in two different ways. First, the luminance of each individual sign was measured in detail to compare the different signs photometrically. Second, the visibility of each sign was determined for observers at a fixed distance in both clear and smoky conditions to compare the signs psychophysically.

In the photometric evaluation, the luminance of the letters and background for each [energized] exit sign was measured according to the luminance measurement test suggested in UL 924²⁰ with a laboratory photometer in a dark room. The photometer was located about 5 ft (1.5 m) from the sign, which was mounted about 5 ft (1.5 m) from the ground. The spot size measure on the sign subtended no more than 0.38 inches (9.5 mm) as indicated by UL 924. Luminance was measured at 20 points on the letters – eight points on the *E*, five points on the *X*, three points on the *I* and four points on the *T*. The luminance of the background was measured at 23 points immediately adjacent to the letters. The chromaticity of the exit signs was also measured at three – five points per sign, with a spectroradiometer located about 5 ft (1.5m) from the sign. Table 1 presents the mean luminance and chromaticity data averaged for each letter and its background for the 12 signs. Contrast between the average luminance for each letter and background was also calculated according to the formula given

Table 1—Luminance and chromaticity of exit signs.

Sign type		Luminance-contrast			Chromaticity		Chromaticity	
No.	Design	Letter	Background	Contrast	Letter x	Letter y	Background x	Background y
1	Inc green	21.5	0.1	0.944	0.2365	0.6547	0.3439	0.3121
2	Inc red	80.6	342.6	0.765	0.6925	0.3004	0.5188	0.4178
3	Fl green	140.9	0.8	0.995				
3	Fl red	324.9	2.0	0.994	0.6745	0.3193		
4	Fl red	173.8	1358	0.872	0.6558	0.3229	0.4873	0.4207
5	El red	5.7	0.1	0.988	0.6618	0.3348	0.4332	0.3861
6	El green	4.9	0.1	0.990				
6E	El green	23.5	0.2	0.992	0.1803	0.4876	0.346	0.3335
7	El red on green	0.1	3.4	0.971				
7E	El red on green	0.3	11.6	0.973	0.6829	0.3169	0.2097	0.5087
8	El blue-green	22.6	0.1	0.994	0.1732	0.3667	0.5053	0.4385
9	El red on green	0.9	0.001	0.988	0.2185	0.5209		
10	El red	0.6	0.001	0.989				
10E	El red	3.5	0.001	0.990	0.6371	0.3153	0.5057	0.4475
11	El green	8.5	0.1	0.992	0.2378	0.5561	0.3953	0.3648
12	El green	0.2	3.6	0.938				
12E	El green	0.8	13.1	0.936	0.0991	0.6675	0.2106	0.4994

Key: El = Electroluminescence

Inc = Incandescent

Fl = Fluorescent

in IESNA.¹⁰

Inspection of **Table 1** reveals considerable variation in luminance between signs. The four conventional signs (signs 1 to 4) had the highest luminances. Sign 4, a panel-faced fluorescent sign, had substantially greater luminance than the other three. As might be expected, the luminance of the letters was greatest for stencil-faced signs, while the luminance of the background was greatest for panel-faced signs. Thus, signs 1 and 3, both stencil-faced, had mean letter luminances of 22.9, 324.9 (3R), and 140.9 cd/m^2 (3G) respectively, while signs 2 and 4, both panel-faced, had mean background luminances of 297.7 and 1186.4 cd/m^2 . Background luminance for the stencil-faced signs was most likely due to spill from the illuminated letters to the metallic surround. The overall contrast for the panel-faced signs was lower (between 0.77 and 0.87), while the variation in uniformity, indicated by a greater standard deviation, was higher. Sign 3 was evaluated in two configurations—3G, which used a green diffusing panel for the letters, and 3R, which used a red diffusing panel for the letters. Luminance for the letters in the red configuration for sign 3 (3R) was much higher (324.9 cd/m^2) than for the green (140.9 cd/m^2). As compared with the conventional signs, the luminance of the electroluminescent signs was uniformly lower, although there was considerable variability among these signs as well. The mean luminance of sign 9 was the lowest, only 0.924 cd/m^2 for the letters, while that for signs 6 and 8 was the greatest, about 23 cd/m^2 . Operating signs 6, 7, 10, and 12 in emergency mode (indicated by E in **Table 1**) increased their mean luminance substantially as compared with non-emergency mode to as much as 24 cd/m^2 for sign 6. As a result, their visibility was tested in emergency mode—the mode they would operate in during a fire or other building emergency. The four EL signs (5, 8, 9, and 11) which could be operated only in one mode had generally low mean luminances, below 8.5 cd/m^2 , except sign 8 which had a mean luminance of 22.1 cd/m^2 . Contrasts for the EL signs were generally high (above 0.9) while the standard deviations were typically low, reflecting the greater uniformity in luminance for these signs. The chromaticity coordinates in **Table 1** reveal that the red signs were quite similar in chromaticity, while the green signs varied substantially.

Visibility Assessment

An essential consideration for determining the effectiveness of exit signs is their visibility for human observers in both clear and smoky conditions. For the present paper, visibility is defined as the ability to both see and identify a sign. It is important to realize that signs that are readily detectable and identifiable

under clear conditions may not be so under smoky conditions. To assess visibility in the present study, the 12 signs measured photometrically in section 2 were installed in a facility 172.8 m^2 or 1860 ft^2 in which smoke could be readily created. The signs' visibility was assessed by 21 adult observers. Signs were placed in an array of three rows with four signs per row. The topmost row of signs was located 254 mm (10 inches) from the ceiling; the second row was located 610 mm (24 inches from the ceiling); while the third row was located 1010 mm (40 inches) from the ceiling. The signs were arranged by luminance, with those with the highest luminance located on the top, and those with the lowest located on the bottom. This arrangement was designed to compensate for the tendency of smoke to layer from the ceiling down, and meant that the highest luminance signs would also be in the greatest smoke density. Signs were also generally arranged to alternate in color from red to green. The array of signs was located approximately 18.9 m (62 ft) from the viewing point.

Smoke for the visibility tests was produced by a 100-kW diffusion flame propane gas burner. The burner was an open top cylinder 0.61 m (2 ft) in diameter by 0.11 m (0.4 ft) deep. The cylinder was filled with sand, covered by a fibrous refractory material and then topped with expanded metal. The burner was located 6 m (20 ft) in front of the wall with the exit signs and 0.9 m (3 ft) to the right of the test area centerline. Shielding was installed around the burner to minimize reflections from the flame on the face of the exit signs and shield the test subjects and instrumentation from the illumination of the fire.

Measurements of the optical density of the smoke were made with extinction beam photometers. Optical density is determined by monitoring the attenuation of a beam of white light passing through the smoke. A discussion of the principles of smoke measurement and the extinction beam photometer design can be found in Bukowski.³ To summarize this measurement technique, the basic components of the extinction beam photometer are a stable light source and a photocell receiver. A fixed path length exists between the source and the receiver. The output from the receiver is used to calculate the optical density of the smoke by the following equation:

$$od = 1/d [\ln(I_o/I_s)]$$

where: od = optical density (m⁻¹)

d = path length (m)

I_o = receiver output under clear conditions

I_s = receiver output under smoke conditions

The three extinction beam photometers were positioned in the same horizontal planes as the exit signs at 0.25 m (0.83 ft), 0.6 m (2 ft), and 1 m (3.3 ft) below the ceiling. The centerline of the meters was 5.5 m (18 ft) in front of the exit signs and 1.2 m (3.9 ft) to the left of the center of the test area.

The meters occupied the same vertical plane. The path length of the extinction beam photometers in the present experiment was 1.2 m (4 ft). The output from the meters was read and recorded every 10 s by the data acquisition system. The measurements were then entered into the above equation to determine the optical density (OD) between the smoke meters and the sign. Optical density between the sign and the observer was not measured, although luminance measures were periodically made of sign 4, the sign with the highest luminance.

During the experiment, no supplementary room illumination was provided in the smoke chamber. Under smoky conditions some illumination was provided inadvertently by the fire which produced the smoke. To the extent possible, the fire was baffled from the observer, although complete baffling would have seriously hampered smoke dispersion. The luminance of the signs as installed was monitored at periodic intervals during the experiment, so the contribution, if any, of the fire to sign luminance is contained in those measurements.

A total of 21 adult observers (National Institute of Standards and Technology employees and visitors) participated in the experiment. Fourteen were males and seven were females. Five observers were between 18 and 30 years old; six between 31 and 40; nine between 41 and 50; and one between 56 and 60. Fourteen observers wore some type of corrective lenses—either glasses or contacts, while two reported deutan-type color deficiencies. Each observer viewed the signs individually during the experiment.

There were three phases to the visibility experiment, clear, smoke, and smoke exhaust. The visibility of the signs was first assessed under clear conditions, then under conditions of increasing smoke and finally under conditions of decreasing smoke (exhaust). The entire experiment took about 45 min for each observer. Observers were advised that they could terminate the experiment at any time if they became fatigued or bothered by the smoke.

Observers were brought to the experimental facility. They read the instructions and research participant agreement. Once the observers indicated that they understood the procedure, they were brought into the viewing chamber and seated at a chair in front of the viewing port. The viewing port consisted of a rectangular opening (10.5 by 15.5 inches) covered with clear plexiglass in a door into the smoke chamber to

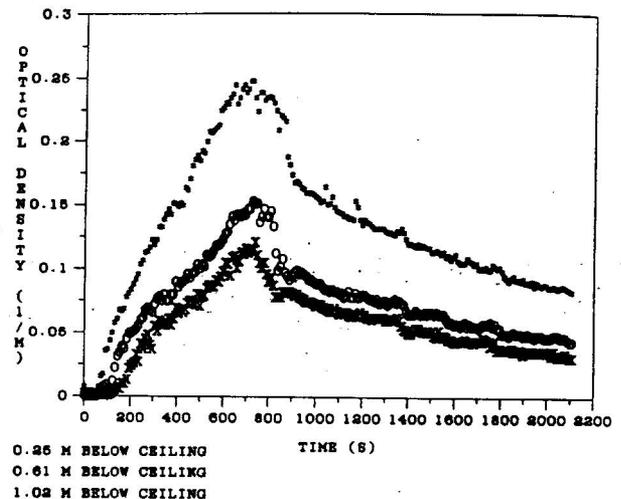


Figure 1—Optical density as a function of time showing the dispersal between the three sets of signs

shield observers from smoke. Illumination in the viewing chamber was maintained at about 5–10 lx (0.5–1 fc) to simulate emergency viewing conditions. (No reflections from the room lighting were visible on the plexiglass window.) Observers adapted to this ambient illumination for about 5 min. During the experiment, the observers' responses were recorded, along with sign luminance from the viewing port and optical density in the smoke chamber.

The experiment began with an assessment of the signs in clear conditions. Each observer rated each sign on a seven-point scale of visibility where visibility was defined as *the ability to see and recognize the sign*. On this scale a 1 meant *Not at all visible* and a 7 meant *Very visible*. Signs were energized individually for this assessment. Once all the signs had been rated, they were all energized and observers then indicated the three best signs (in terms of visibility) and the three worst and gave reasons for their selections. Although initial ratings were given for four electroluminescent signs in both emergency and non-emergency mode (signs 6, 7, 10, and 12), they were operated in emergency mode for this comparison and for subsequent assessments in smoke.

Once all assessments had been made under clear conditions, the second phase was initiated. In this phase a fire was ignited using a burner fueled with propane. This produced a black smoke that rapidly filled the room. As predicted, it did layer from the top down with the greatest obscuration for the top row, and lesser (but similar) amounts for the second and third rows. Figure 1 presents a calibration curve showing optical density as a function of total time following fire initiation. These curves depict the different smoke densities for

Table 2—Data from the visibility experiment

Table 2a—Observer Data (Means)

Clear		Smoke Conditions						Overall Mean
Sign #	Rating	Time to Disappear Sec	Ratings Order	First	Second	Third	Fourth	
1	4.7	220.7	2	2.5	2.8	3.5	4.2	3.25
2	5.2	433.0	10	5.2	5.5	5.9	6.1	5.68
3G	5.6	469.2	11	4.7	5.5	5.7	5.8	5.43
3R	6.2	497.8	12	6.1	6.5	6.8	6.9	6.59
4	5.6	571.8	13	6.1	6.4	6.6	6.8	6.49
5	6.2	262.5	4	2.0	3.1	4.5	5.4	3.74
6-E	6.0	281.6	6	2.2	3.4	4.3	5.3	3.80
7-E	5.7	250.1	3	2.0	2.5	3.3	4.7	3.12
8	6.0	277.8	5	2.2	3.1	4.1	5.2	3.67
9	2.9	206.2	1	1.0	1.0	1.1	1.3	1.11
10-E	6.0	298.5	8	1.9	2.7	4.1	5.0	3.43
11	5.9	300.3	9	2.2	3.1	4.3	5.3	3.73
12-E	5.3	297.5	7	2.8	3.5	4.5	5.3	4.02
6	4.9							
7	4.3		Avg Rating	3.3	4.0	4.7	5.3	4.29
10	4.2		Std Dev	1.7	1.6	1.5	1.3	1.49
12	4.9		Time (min)	18.4	20.8	22.8	26.1	22.04
			Sign 4 Luminance (cd/m ²)	9.2	19.0	48.5	96.3	43.24

Table 2b—Summary Physical Data for Smoke Experiment

Sign Number	Luminance of Sign Measured in Lab Clear Conditions		Mean	Disappearance In Smoke		Time
	Letter Mean	Bkground Mean		Mean Overall Contrast	Mean Optical Density	
1	21.5	0.14	10.82	0.994	0.0700	220.7
2	80.6	342.63	211.59	0.765	0.1181	433.0
3G	140.9	0.757	70.83	0.995	0.0952	469.2
3R	324.9	2.04	163.46	0.994	0.1652	497.8
4	173.8	1358.10	765.95	0.872	0.1552	571.8
5	5.6	0.07	2.86	0.988	0.0340	262.5
6-E	23.5	0.19	11.85	0.992	0.0412	281.6
7-E	0.3	11.56	5.94	0.973	0.0373	250.1
8	22.6	0.14	11.36	0.994	0.0384	277.8
9	0.9	0.01	0.47	0.988	0.0401	206.2
10-E	3.5	0.03	1.76	0.990	0.0481	298.5
11	8.5	0.07	4.28	0.992	0.0487	300.3
12-E	0.8	13.09	6.96	0.936	0.0481	297.5

the three rows of signs. Observers viewed the full array of illuminated signs, and indicated when each sign was no longer visible, using the criterion for visibility developed for clear conditions. Once all the signs had disappeared from view, the fire was extinguished. The time for the complete set of signs to disappear was typically 10–12 min.

In the final phase, smoke was removed from the room in four stages by an exhaust fan. Observers again rated the visibility of each sign using the seven-point scale. Ratings were made when the overall luminance of sign 4 reached 10 cd/m², 20 cd/m², 50 cd/m², and 100 cd/m². (These corresponded to mean optical den-

sities of 0.103, 0.097, 0.080, and 0.071 odm⁻¹ for row 1; 0.058, 0.55, 0.49, 0.38 odm⁻¹ for row 2; and 0.041, 0.27, 0.22, and 0.013 odm⁻¹ for row 3). Smoke exhaust was stopped during each rating period. Sign 4 was chosen as the control because it had the highest initial illuminance, and so could be measured more accurately in smoke conditions. At the greatest smoke density, none of the other signs were visible. The time to reach the final rating period was generally about 15 to 20 minutes after smoke exhaust was initiated. When observers gave their final ratings of sign visibility, they were again asked to select the best and worst signs and for any comments about the experiment.

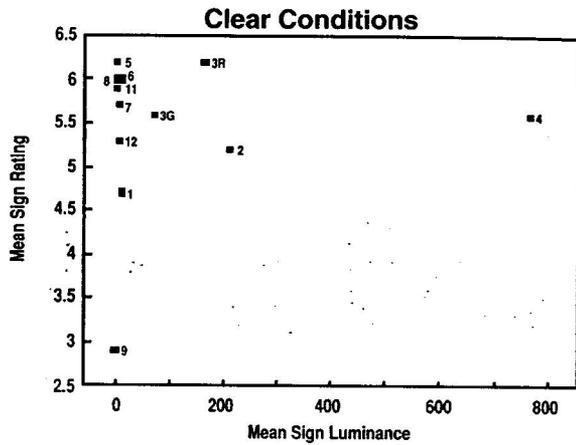


Figure 2—Comparison of mean sign luminance and visibility ratings for clear conditions.

Table 2a presents summary data for the psychophysical portion of the experiment. The first column presents the sign number; the second presents the average rating for each sign in clear conditions. Inspection of Table 2a indicates that the mean rating of visibility under clear conditions for each sign ranged from 2.9 for sign 9 to 6.2 for sign 4 and sign 3 in red (3 R). Only two signs received mean ratings below 5.0—sign 1 and sign 9. Figure 2 compares the mean ratings versus average sign luminance as measured in the lab. Luminance for the letters was averaged with the luminance of the background to obtain the average sign luminance in clear conditions in the darkened lab. Of course, luminance of individual areas was higher. Figure 2 indicates that although sign luminance was lowest for the lowest rated sign, 9, luminance and ratings of visibility in clear conditions did not appear to be directly related. Thus, the average luminance for sign 3R was substantially greater than that for sign 5, yet, both signs received comparable mean ratings. Figure 2 indicates that in fact, the majority of the signs received favorable ratings in clear conditions. Table 2a indicates that the four signs tested in non-emergency mode, with lower luminances, received mean ratings below 5, with the dimmest signs, 7 and 10, receiving the lowest ratings. These data suggest that once the luminance of the sign is above some lower limit, the sign tends to be perceived as reasonably visible. Other characteristics of the sign which may influence the visibility rating will be discussed later.

Next, the time for each sign to disappear in smoke was determined. Column three of Table 2a presents the average time in seconds for each sign to disappear. Inspection of this table reveals that sign 9 disappeared first, while sign 4 disappeared last. Figure 3 indicates clearly that signs with higher initial average luminances, namely 2, 3R, 3G, and 4, also took longer

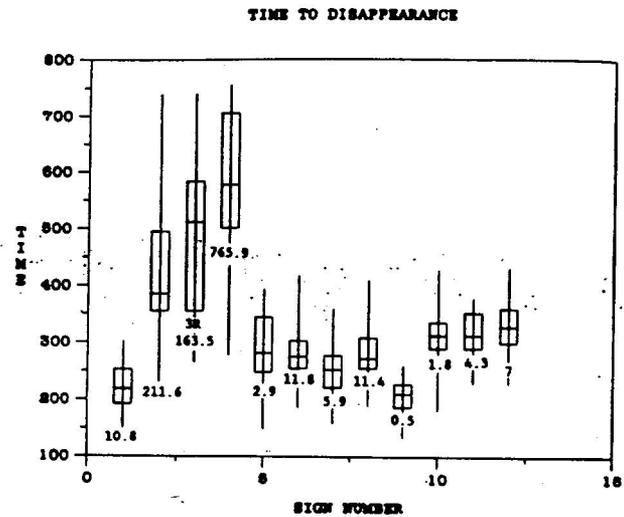


Figure 3—Boxplot comparing time to disappear in smoke with initial sign luminance. The boxplot graphs the entire data set, with the mid-range of the data represented by the box, the horizontal line representing the median, and the vertical lines representing the top and bottom points of the total range. The numbers below each box refer to the mean sign luminance as measured in the laboratory.

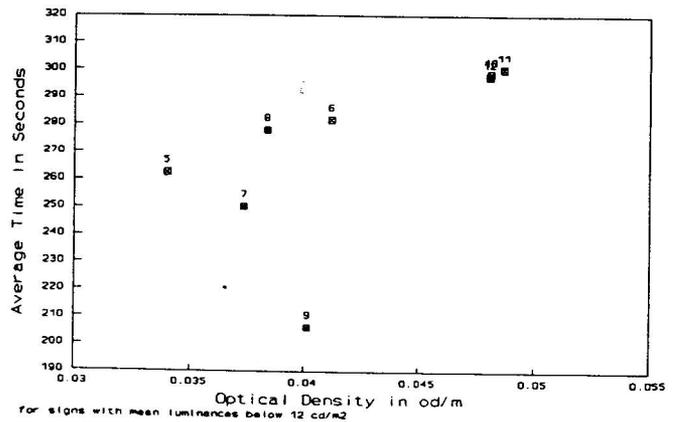
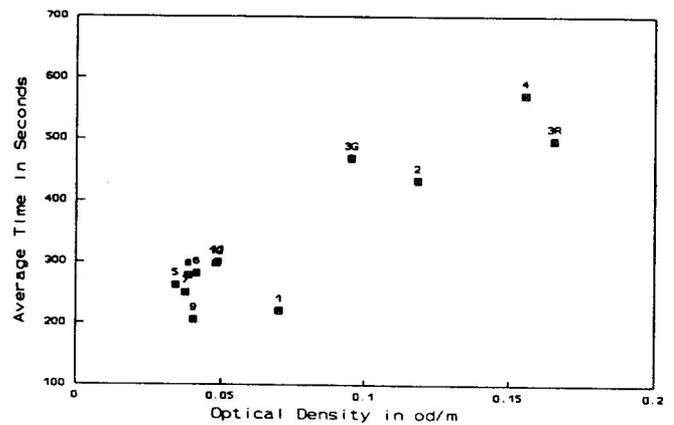


Figure 4—Time to disappearance as a function of optical density of smoke. The upper plot presents all the data, while the lower plot presents only the data for the signs which disappeared before 350 sec. These latter signs had mean luminances below 12 cd/m².

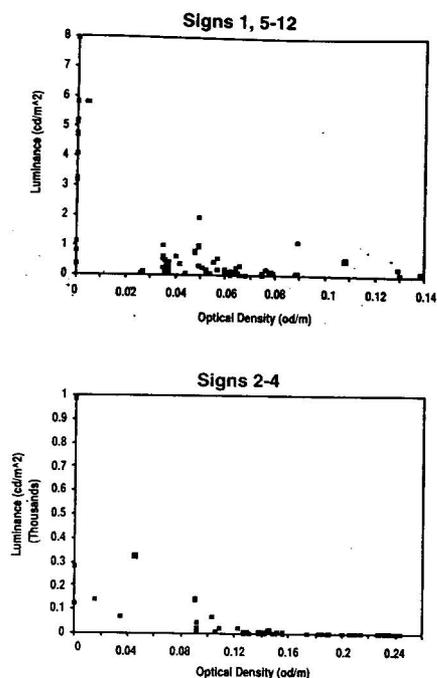


Figure 5—A comparison of optical density and luminance for all signs as measured during clear and smoke calibration.

to disappear. These signs all had average luminances above 70 cd/m^2 . As Figure 4 indicates, greater smoke density was required to obscure them.

Table 2b presents data for mean letter, background and sign luminance, mean calculated contrast, mean optical density of the smoke at disappearance, and mean time to disappearance. This table indicates that signs with mean luminances below 20 cd/m^2 were no longer visible after 300 s, and had mean optical smoke densities below 0.07 m^{-1} , while signs with luminances above 70 cd/m^2 were visible between 430 and 570 s, even with mean optical densities of 0.09 to 0.17 m^{-1} . Of course, time to disappearance would have been substantially longer for these signs had they been located in the lower rows of the sign layout which received lower smoke densities. Figure 5 compares sign luminance measured from the viewing port during the experiment with optical density for both clear and smoky conditions. The upper graph presents data for signs 2, 3R, and 4, while the lower graph presents data for signs 1 and 5 to 12 (which had substantially lower luminance.) On each plot, sign luminance as measured from the observer's viewing port under clear conditions is presented on the ordinate (od/m). Inspection of these graphs reveals that the luminance of all signs had dropped to near zero by the time an optical density of 0.14 od/m was reached and the sign had disappeared. The graphs also provide an indication of the sign luminances seen by the observers during clear and smoky conditions.

In the final portion of the experiment, the fire was extinguished and the smoke exhausted from the room. Observers rated the visibility of the signs using the seven-point scale discussed earlier at four times during smoke exhaust. These ratings were taken when the luminance of sign 4 reached four levels: 10 cd/m^2 , 20 cd/m^2 , 50 cd/m^2 , and 100 cd/m^2 . Ratings from the 21 observers were averaged for each sign. Ratings between 1 and 3 indicate that the signs were *not at all visible* or *not very visible*. Table 2a reveals that signs 1, 5, 6, 7, 8, 9, 10, 11, and 12 were not visible when the first set of ratings were made—about 18 min after fire initiation (and about 8 min after smoke exhaust began.) At this point, the optical densities for the smoke were greater than those measured when those signs disappeared, reinforcing the idea that they were not likely to be visible to the observers. The second series of ratings were taken about 2 min later, when the luminance of sign 4 reached 20 cd/m^2 . Again, only signs 2, 3 (R and G), and 4 received mean ratings above 5.5. Ratings for all other signs were lower than 3.6, although the mean rating for signs 5, 6, 8, and 11 had increased to between 3.1 and 3.5. By the third series of ratings, the mean ratings for signs 5, 6, 8, 10, and 12 had increased to between 4.1 and 4.5, while those for signs 2, 3, and 4 had increased to between 5.7 and 6.8 — or above their initial rating in clear conditions. By the fourth series of ratings, all signs received mean ratings above 5, except signs 1, 7, and 9. Signs 3R and 4, in fact, received mean ratings of 6.9 and 6.8, respectively, indicating almost perfect visibility.

Over the four ratings, the optical density of the smoke gradually declined. Table 2a indicates that the change in ratings from the first to last rating was greatest for the EL signs — particularly 5, 7, 10 and 11. In addition, sign 9 never received high ratings, and sign 4 always received high ratings.

It is also instructive to compare the mean ratings for clear conditions with those for the final smoke condition. Table 2a indicates that signs 2, 3R, 3G, and 4 received higher ratings for the final smoke condition, sign 12 received the same rating, while all other signs received lower ratings, some markedly lower. These data suggest that three of the conventional signs were viewed as more visible in smoke. Only sign 12 of the electroluminescent signs was rated as having the same visibility for the two comparisons. Sign 9, the EL sign with the lowest luminance, received the lowest ratings for smoke, being rated as *not at all visible* for all four sessions. In addition, it had the shortest time to disappearance in smoke and the lowest optical density. The performance of signs 7 (EL) and 1 (conventional) were also marginal with no initial mean ratings above 3.3, and rapid times to disappearance.

Sign luminance was not the only predictor of

visibility performance, however. The configuration of the sign—panel-face vs. stencil-face—also played an important role. This is demonstrated most clearly by a comparison of the performance of sign 3R with sign 4. Sign 3R was a stencil-faced sign with red letters on a non-luminous background, while sign 4 was a panel-faced sign with red letters on a white luminous background. The optical density required to obscure sign 3R was actually higher than that for sign 4 (0.1652 vs 0.1552 od/m). Yet the overall mean luminance of sign 4 was 765.9 cd/m² as compared with 163.5 cd/m² for sign 3R. (Sign 4 took longer to disappear, however). Sign 3R received the highest mean visibility ratings throughout the experiment, with only sign 5 receiving the same high mean rating in clear conditions. Observer comments revealed that they considered sign 3R to be sharper with less blur than sign 4. Several observers stated that sign 4 tended to blur and not be legible in clear conditions even though it was brighter. In smoke, it became a bright white spot rather than the word *EXIT*. Other stencil-faced signs performed better than panel-faced signs at comparable luminances, with greater smoke density required for obscuration and longer time for disappearance. This comparison can be made for sign 5 and sign 10, a stencil-faced sign that required greater smoke density (0.0481 vs. 0.0340 od m-1) and longer time to disappear (298.5 vs. 262.5 s) than sign 5 even though its luminance was slightly lower (1.76 vs 2.86 cd/m²); and sign 7 vs. sign 11 (with luminances of 5.94 vs. 4.28 cd/m², and optical densities of 0.0373 vs 0.0487 od m-1). Even for signs 1 and 3G and 4 and 3R, the stencil-faced sign took longer to disappear and required greater optical density. The data suggest that configurations which used illuminated letters and opaque backgrounds (stencil-faced) resulted in a more visible sign especially in smoke.

During the course of the visibility assessment, observers also selected the best sign, the best three signs, the worst sign, and the worst three signs under both clear and smoky conditions. Sign 9 was almost unanimously selected as the worst for both clear and smoky conditions, all but one person selecting it as worst. Choices for the best sign were less straightforward, although there was some consensus that signs 3 (both red and green), 4, and 10 were the best in clear conditions as selected by six, seven, and four people, respectively. Signs that were considered among the three best in clear conditions included signs 2, 3, 4, 5, 6, 8, and 10, a mix of EL and conventional signs. When smoke was a consideration, signs 8 and 10 were dropped from this category. This distribution changed significantly when the selections for smoke were considered, with signs 3 (3G and 3R) and 4 selected by all but one person. Conversely, signs 3 and 4 were in-

cluded in the selection of the three worst for clear conditions—probably because of their high luminance. Other candidates for the three worst included signs 1 and 7, as well as sign 9.

Reasons given for selecting the best signs for clear conditions included color, sharpness (distinctiveness), and contrast. The reason for selecting the sign 9 as the worst was unequivocal; it was too dim in both clear and smoky conditions. Signs that were considered to be among the worst included those that were missing portions or that were not very bright. The reasons given for selecting the best signs under smoky conditions appeared to be based largely on brightness and contrast. Thus signs 3 and 4 (with the highest luminances) were selected as best, while sign 9 (with the lowest) continued to be selected as worst. The reasons for selecting signs as best in either smoke or clear conditions included brightness. Clarity and contrast—or the ability to distinguish individual letters easily—were also important. Observer comments about stencil-faced signs suggested that they were sharper, with less tendency to blur. This suggests that the background luminance in panel-faced signs may have tended to mask the lettering by producing a veiling luminance.

Additional information about sign effectiveness was obtained in the form of spontaneous comments about the signs at the end of the experiment. Inspection of these reveals some belief among the observers that red is the appropriate color for exit signs. Of course, red is the color of choice at the NIST site where the experiment was performed. Several observers claimed that they had never seen a green exit sign. This feeling may be one reason why sign 3 was preferred only after it had been switched from green to red. The increase in its luminance from 70 to 160 cd/m² may have also accounted for the increased visibility and observer preference. While two observers who participated had deutan-type color defects, meaning that the green signs may have been less effective for them, they viewed sign 3 in the red configuration. Observers also commented on sign clarity and uniformity, noting that signs 1, 2, and 4 were not uniformly lit. Still others commented that sign 4 was too bright and tended to blur out in clear conditions, but be more visible in smoke. These comments indicate that some observers found the lack of uniformity for the conventional signs, particularly the panel-faced ones to be disturbing. By comparison the uniformity of the EL signs appealed to some observers, although others were troubled by their generally lower brightness, especially in smoke conditions.

Conclusions and recommendations

Results from the present experiment indicate the importance of sign luminance in determining the visibili-

ty of exit signs in smoke. Signs with mean luminances above 70 cd/m^2 required substantially greater optical density for obscuration and longer time to disappearance (by a factor of two). The optical density required to obscure these signs was between 0.07 and 0.16 od m^{-1} , in line with the densities observed by Rea, et al,¹⁸ Rea, et al,¹⁸ and Jin and Yamada⁹ also determined that signs with higher luminances were more visible through smoke.

Conversely the poor performance of the signs with low luminance, particularly sign 9, is of concern. This sign had the lowest mean luminance (0.47 cd/m^2) with an average letter luminance of 0.92 cd/m^2 and background luminance of 0.01 cd/m^2 . Smoke of mean optical density of 0.04 m^{-1} obscured this sign in a mean of only 206 s—almost a minute earlier than any other sign. This sign also received the lowest visibility ratings in both clear and smoke conditions. Comments by the observers revealed that they did not consider it to be at all effective. The data suggest that signs with low luminances, below 0.5 cd/m^2 , are likely to be less effective in smoke, particularly when located near the ceiling. In the present experiment, optical densities in excess of 0.04 od/m were reached in the first one to 3 min, meaning that this sign, if located above a door, would not have been visible. Other EL signs such as 5, 10, and 11, with higher mean luminances (1.7 to 4.3 cd/m^2) required greater optical densities and/or longer times to disappearance (260 to 300 s). Such signs may be more useful when located near the floor, as Keating suggested.¹¹

Sign luminance was not the only predictor of visibility performance, however. The configuration of the sign—panel-face vs. stencil-face—also played an important role. The data suggest that signs that are more visible in smoke tend to have higher luminances and be stencil-faced (have transilluminated letters). As noted earlier, the optical density of smoke required to obscure sign 3, particularly 3R, was actually greater than for sign 4, even though the overall mean luminance of sign 4 was higher. Observer comments revealed that they considered sign 3R to be sharper with less blur than sign 4 which tended to blur under both clear and smoky conditions. As discussed earlier, the stencil-faced signs often required greater smoke density and longer time to disappear than the panel-faced signs. These comparisons suggest that the use of illuminated letters with an opaque background resulted in a more visible sign. Observer comments about them indicated that they were sharper, with less tendency to blur. This suggests that the background luminance in panel-faced signs may tend to mask the lettering by producing a veiling luminance. Certainly, the stencil-faced signs tended to have higher contrasts, again suggesting that the perception of crispness was rooted in reality.

Ouellette^{14,15} and Wilson²³ also reported a tendency for signs with transilluminated (stencil-faced) letters to perform somewhat better in smoke.

When the performance of conventional and electroluminescent signs was compared, the conventional signs with higher sign luminance were superior in terms of the smoke density needed for sign obscuration and rated visibility particularly in smoke. When the performance of the two sign types for similar sign luminances was compared, as for signs 1, 8, 6 and 12, somewhat different findings emerged. The EL signs (8, 6, and 12) received higher initial and final mean ratings of visibility (5.3 to 6 vs. 4.7) and took longer to disappear (about 60 s) than sign 1, which used incandescent lamps. These data suggest that for signs of comparable luminance, EL signs may be superior in terms of time to disappear in smoke and visibility ratings. The worst performance, of course, was also by EL sign, 9, which had markedly lower sign luminance. The performance of EL signs may be improved under emergency conditions by increasing power to them and increasing their luminance.

The data obtained in the visibility portion of the present experiment are, of course, subjective. They are critically dependent on each person's criteria for visibility. While observers were instructed that visibility is the ability to both identify and recognize the sign as an exit sign, individual observers clearly interpreted these instructions differently. Thus, some defined it as the ability to read every letter easily; others defined it as the ability to read enough of the sign that they could reasonably interpret it to be an exit sign; and still others felt that any light located above a door would obviously indicate exit and so the ability to identify individual letters was less important. While there were undoubtedly variations in visibility criteria between observers, individual observers tended to be consistent in their own criteria throughout the experiment. Therefore, it is the relative ratings of the signs between the observers that is important. Thus, sign 9 was always worst, while signs 3R and 4 were generally best. Similarly, sign 9 disappeared first in smoke; signs 3R and 4 were last. These differences appear to relate meaningfully to sign luminance, configuration, uniformity, and contrast.

The results of the present experiment tend to confirm those of recent experiments at NRC Canada by Rea, et al,¹⁸ and Ouellette,^{14,15} in Japan by Jin and Yamada⁹, and in Australia by Wilson,²³. In contrast to Schooley and Reagan¹⁹ and Beyreis and Castino², these more recent studies indicate the importance of sign luminance in determining visibility in smoke. They also raise questions about the likelihood of reduced sign visibility due to ambient illumination. The present study also suggests that stencil-faced signs with transilluminated letters may be superior as Ouellette found.

Unlike Rea, et al, the present experiment did not support the idea that green signs are more visible, perhaps because the luminance of green signs tested was lower and because the observers were more familiar with red exit signs.

The research presented in the preceding pages raises almost as many questions as it answers. For example, the data suggest that the characteristics of an exit sign that determine its effectiveness in clear conditions may be somewhat different than in smoke conditions. In clear conditions, uniformity and contrast were considered important, while in smoke, luminance became more critical; although the combination of high luminance and good uniformity was considered to be the most visible. In fact, the best sign actually had lower average luminance but greater uniformity than the brightest sign. The study raises questions about sign configuration by hinting that stencil-faced signs are more visible than panel-faced, even though the latter frequently had slightly higher overall luminance. Questions also arose about minimum and maximum specifications for sign luminance. Certainly, the sign with the lowest luminance (0.9 cd/m^2) was ineffective in this experiment in both clear and smoky conditions. Yet, NFPA 101 currently provides an exclusion for self-luminous signs such as EL or tritium by allowing a minimum luminance of 0.06 fL (0.21 cd/m^2) for these signs. The data in the present experiment question the effectiveness of such low luminances for visibility especially in smoke conditions. On the other hand, while NFPA provides no maximum specification for sign luminance, the British standard does, again somewhat in contradiction to the current findings of greater visibility with higher sign luminances. Finally, the role of color remains uncertain. While Rea, et al,¹⁸ suggested that green might be a more effective color for exit markings, the present study indicated that red might be more effective, at least for the conditions studied. These findings suggest the need for a study in which the effects of exit sign luminance and color are studied parametrically, along with sign configuration and uniformity. The role of smoke type (white versus black), sign position, and ambient illuminance should also be examined critically in the same parametric experiment.

In conclusion, the present study indicates that some electroluminescent signs can be effective in clear conditions and in smoke, particularly if their average luminance is above about 10 cd/m^2 . The data clearly indicate, however, that overall sign luminance is a primary determinant of visibility with higher luminance being associated with greater visibility. The data also suggest that sign configuration is an important contributor with stencil-faced signs—signs with illuminated letters and opaque backgrounds—being

somewhat more visible than panel-faced signs.

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Discussions

The authors are to be congratulated on a thorough assessment of the visibility of a range of commercially available exit signs. The data reported in this paper more than justify the need for a parametric study of the effects of sign luminance, luminance uniformity, color, and configuration on visibility if more effective exit signs are to be produced. While I have no doubt about the general trends, there are two points concerning the smoke conditions that I would like the authors to address because they may affect the relative visibility of individual signs. The first concerns the horizontal uniformity of the smoke. The curves of optical density against time show marked differences in optical density over relatively short vertical distances. Given that the smoke generator was offset from the display of signs, how uniform were the horizontal layers of smoke? The second concerns the impact of having all the signs lit at the same time. Other researchers (Rea,

et al,¹⁸) have shown that ambient illumination in a smoke-filled chamber tends to reduce the visibility of exit signs. In the authors' experiment, I suspect that having all 12 signs lit at once will also produce a significant level of ambient illumination. If this occurred, then the visibility of all the signs would be reduced. Further, the visibility of low luminance signs would be reduced by scattered light from the high luminance signs, particularly if the signs were adjacent. The authors' observations on the extent to which these phenomena occurred would be appreciated.

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The paper "Visibility of Exit Signs in Clear and Smoky Conditions" identifies the sign characteristics that influence visibility of human observers in clear air and smoke. I will confine my comments principally to the generation of the smoky environment and how this may have influenced interpretation of the optical density. These suggestions for improving the control of the smoke would improve the accuracy of the optical density variable in your experiment. The paper stipulated that the signs were placed at different heights to compensate for the tendency of the smoke to layer from the ceiling down. While the smoke layers from the ceiling downward, it also spreads throughout an enclosure with uneven optical densities. The smoke will generally create a greater blocking effect in the area of the smoke's source and the blocking effect will wane as the smoke moves away from the source. Only one smoke generating source was used to create the smoky condition throughout the experiment. This source was located 6.1 m (20 ft) from the wall where the signs were displayed. The extinction beam photometers were placed with their centerline 5.5 m (18 ft) from the wall containing the signs. This array would tend to give an accurate measurement of the smoke's optical density in the vicinity of the smoke's source; however, the optical density along the path from the signs to the viewer would probably be inconsistent and different from the measured value. A more homogeneous optical density might have been achieved if circulating fans had been used to disperse the smoke through the test facility and if the smoke source had been located near the center of the test facility. If one incorporated circulating fans to homogenize the smoke, the three extinction beam photometers could be placed as follows: one 5-10 ft from the signs, one 5-10 ft from the viewer, and one near the center of the test facility. With this arrangement the 10-s meter output readings could have been averaged for a more accurate test facility optical density reading.

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The authors have tackled a very interesting problem and have done a very good job of consolidating the relevant literature on the subject. It was encouraging to see such good agreement between the reported results and earlier work, such as that from our laboratory. There is only one area of disagreement, and it is a relatively minor one involving different interpretations of the relative visibilities of red and green signs. Rea, Clark and I were careful to note that sign visibility cannot be evaluated simply by knowing color. Nevertheless, we noted that the colored diffusers of green signs tended to transmit more light than their red counterparts. Based on these early observations, we speculated that when all other parameters are equal, green signs might have a higher probability of being more visible than red ones. This should not be misinterpreted as an argument calling for green signs in favor of red. Indeed, we agree with the authors that more research is required before this question can be resolved. We have recently completed a study aimed at answering this very question, and hope to be able to present the results shortly.

On the subject of color, I have several questions. First would the authors elaborate on the nature of the colour deficiencies of the deutan color deficient subjects (i.e., deuteranomalous trichromats or deuteranopes)? Secondly, how did the data from these color deficient observers influence the general conclusions made about the relative visibilities of red and green signs? The third question relates to the authors' comment that the green signs varied substantially in chromaticity, while the red signs did not. Would it be reasonable to assume that the chromaticity coordinates in Table 1 are in terms of the CIE 1931 (x,y) chromaticity space which is compressed in the red and exaggerated in the green? Should we draw the same conclusion about the relative variabilities in the chromaticities of red and green signs when characterized in terms of a more uniform chromaticity space such as CIE 1976 (L*u*v*)?

On a different note, it was not clear to me whether the signs were illuminated and presented all together, or in sequence. If the subjects did view the full array of signs simultaneously, would there have been any effect of glare from a brighter sign influencing the visibility of a dimmer adjacent one? In smoke, would there have been an effect of scattered light from adjacent signs? In regards to the EL signs, the authors observed that they were generally not bright enough to give high visibility in smoke. We may find, however, that state sources will play a more significant and useful role in illuminating exit signs in the future. The science of solid state lighting is rapidly growing. Even now, commercial superluminescent diodes are available which give luminance significantly higher than what was available for EL signs at the time of this study. With

these points aside, I think this report represents a very significant piece of work. It certainly reinforces and extends the emerging data on the important parameters affecting sign visibility in clear and smoky conditions, most notably, that bright signs are needed for effective visibility in smoke.

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National Research Council
Canada

This is a fine study, adding to the limited knowledge on visibility of exit signs in smoke. Concerning the definition of optical density used in the study, would the authors clarify whether the logarithm is to base 10, as used in the Canadian studies or base e, used to calculate the extinction coefficient. My next point concerns the use of overall mean luminance of the sign as a predictor of performance in smoke. Because it is the portions of the sign with highest luminance which are the last to disappear in smoke, I have considered that for signs of high contrast, mean luminance of the letters or background, whichever is the greater, may be a more appropriate measure of visibility performance than overall mean luminance of the sign; i.e. letter plus background. For a sign where there are large differences in the mean luminance of the four letters or immediate background; for example, signs 1, 2, 3, 4, and 12, perhaps the lowest mean letter or immediate background luminance may be even more appropriate for all four letters to be visible in smoke. The variation of total optical density with logarithm of mean luminance (letter or background, whichever is the greater) is of interest. For the electroluminescent signs, there is little change in total optical density (0.95 to 1.1) when the mean luminance (letter or background) exceeds about 5 cd/m². This may be due to the Lambertian nature of electroluminescent signs and character of the luminance veil produced in smoke. With the incandescent and fluorescent signs, there is a more substantial increase in total optical density (1.3 to 3.1) with increase in luminance, similar to the Canadian studies. Another topic for study is the performance of pictogram signs for Exit and directional indicators in smoky conditions.

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Authors' response

To P. Boyce

In response to your first question, the difference in horizontal uniformity between the three layers of signs (0.25 m, 0.61 m and 1.02 m from the ceiling) was

markedly greater (almost double) for the first two layers. The difference between the second and third layers was much smaller as can be seen in **Table 2**. According to Alpert's Ceiling Jet Correlations our 100-kW fire had a maximum ceiling jet velocity of 11 ft/s and minimum velocities of 1.1 ft/s and 0.55 ft/s at the far side wall and the observation end wall respectively. These horizontal velocities are relatively fast compared to the layer descent velocity which is on the order of 0.01 ft/s. Hence it is reasonable that the smoke layer's stratification may be considered uniform and homogeneous. The authors agree that having all the signs lit at the same time is of some concern. The signs were switched individually for the visibility assessments under clear conditions but that was not possible for the smoke conditions. To compensate, the signs were arranged so that the signs with the highest luminance were at the top and received the greatest smoke density. The signs with the lowest luminance were located on the bottom row to minimize the impact of the higher luminance signs. In fact, the sign with the greatest luminance (sign 4) was as far as possible from the one with the lowest luminance (sign 9). As a result, we felt that we minimized light scatter. Furthermore, the relative performance of the twelve signs, and the clear differences between sign types (conventional versus EL) should not have been differentially affected by scatter. Ideally, of course, each sign would be studied individually, but this would result in a very long experiment. As you state, there truly is a need for a parametric experiment in which the effects on sign visibility of luminance, uniformity, color and configuration are studied for clear and smoky conditions.

Reference

- a. Alpert, R.L. 1972. Calculation of response time of ceiling mounted fire detectors. *Fire Technology*. 8:181-195.

To C. Chittum

The points that you raise are of interest and suggest a better way of measuring optical density. We feel that the smoke we produced was reasonably homogeneous and repeatable from session to session, however. In addition, we believe that the luminance measures taken on sign 4 throughout the experimental sessions provide some knowledge about the repeatability of the different smoke densities used. The authors agree with the comments that more instrumentation would have improved the study. We also agree that the smoke density dissipates as the layer entrains air as it moves along the ceiling. However, since we were operating in a confined space and our maximum horizontal smoke movement times were on the order of seconds whereas the observation times were on the order of minutes (with

minimum times to disappearances of 2.5-3 min), we believe at that time the layer should be distributed fairly uniformly across the ceiling. Thus, Cooper⁷ describes a two-zone model where the "... upper layer is described as having changing thickness, and changing, but spatially uniform temperature and concentration of combustion products. Actual full-scale testing of compartment fire environments has indicated that such a simple means of describing the distribution of products of combustion represents a reasonable compromise between accuracy in simulation and practicability in implementation."

To G. Webber

In response to your question about optical density of smoke, the logarithm used was to the base e, according to the equation given in the visibility section of the present paper. The authors debated using overall mean luminance or luminance of the brightest area of the sign and decided that overall mean luminance might be the better predictor. An equally good case could be made for the luminance of the brightest area as you indicate, however, particularly since some subjects in the experiment reported seeing blobs of light rather than clearly defined letters. The data suggest that great differences in letter luminance create veiling reflections and reduce visibility of the sign. I agree that the performance of pictograms for Exit and directional indicators under smoky conditions is of interest. Previous research at NIST⁵ identified a successful pictogram using simulated smoke but its performance should be verified for smoky conditions. In your private correspondence with us, you pointed out a discrepancy for sign 10, which was in fact an error. The data have been rechecked and corrected accordingly. We deeply appreciate your bringing this to our attention.

To M. Ouellette

We agree that there is a need for further research on color particularly since there is no agreement on the best color for an exit sign in North America. ISO and CIE do have agreement on green, but we are out of step. In the present experiment the luminance of the red sign was about twice that of the green sign which most likely accounted for its greater visibility, although the issues of familiarity and expectations cannot be totally discounted. The participants in the present experiment worked in a jurisdiction where exit signs are red, not green, and they expressed some dismay over the use of green signs. The two color deficiencies were identified by a color test that does not discriminate between the type of deficiency, although one individual appeared to have a greater loss than the other. Their results appeared to increase the variability in the data but not change the general trends. While

the x,y chromaticity data are in terms of the 1931 CIE system, the variability among the green signs was so large that it would have appeared even in the CIE L*u*v* system. Yes, the signs were viewed individually in clear conditions and together in smoky conditions. There may well have been some luminance spill, but we do not believe that it affected the relative performance of the various signs. Finally, it would be very interesting to assess some of the signs with the higher luminance that you describe, particularly because the uniformity and energy consumption characteristics of many EL signs makes them very attractive.