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Photoluminescent Stairway Installation for Evacuation in Office Buildings

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ABSTRACT: Two experiments were conducted to assess the effectiveness of photoluminescent material (PLM) in support of occupant evacuation in office buildings. The first study completed in 1999 was designed to assess the potential use of PLM as a safety communication system to support office occupant evacuation. The study, conducted with PLM made of zinc sulphide pigments, measured the occupants' premovement time, movement time and evacuation speed in four stairways with different lighting and PLM installations. The positive outcome of the first study regarding a comparable speed of movement in the different stairways used and the conclusive feedback from the evacuees regarding the PLM wayguidance system led to a second study. The second study, completed in 2008, compared 3 stairway installations of PLM markings and a stairway with emergency lighting, which acted as a reference stairway. This second study used the new generation of alkali earth aluminates PLM pigments providing a brighter output then the first study. Results show comparable speed of movement under severe crowd conditions for the 4 stairways studied. Overall, two-thirds of the respondents felt comfortable going down the stairways with PLM markings particularly in the 2 stairways where the marking was installed across each step. The stairway, which had only emergency lighting, and the stairway with L-shaped markers at the edge of each step were less appreciated by the occupants. Occupants commented that the landings and mid-landings were difficult to identify in all the stairways, which suggest that additional marking should be provided in these areas. The findings of these two studies led to the development of a best practice Guide for installation of PLM marking in exit stairways.

KEY WORDS: *photoluminescent, pathway marking, way guidance, evacuation movement, emergency lighting, stairway evacuation, office evacuation*

INTRODUCTION

Back in the early 1990s photoluminescent material (PLM) was relatively unknown in North America. The terrorist attack on the World Trade Center

(WTC) in New York City in February 1993 changed that situation [1]. At the WTC, the explosion caused by a vehicle filled with explosives parked in the underground garage resulted in an intense fire. The fire involved about 30 vehicles producing thick black smoke, which rapidly migrated through the elevator and stairway shafts to the different floors of the twin towers and the Vista Hotel. The explosion also destroyed the control center of the complex, as well as most of the active fire protection systems including the fire alarm communication system. To make matters worse all the stairways were in complete darkness due to the absence of both normal and emergency power. As the different floors started to fill with smoke, several thousand occupants, estimated at 50,000 to 100,000, were faced with evacuation in completely dark smoky stairways.

The stairways in the WTC twin towers had the particularity in having varying numbers of steps between landings and crossover corridors to go around mechanical elements. A person going down a stairway could descend 6, 9, 11 or 13 steps before getting to a landing and might have to go through a door, down a corridor, through another door to continue descending the same stairway shaft. In full lighting these design particularities were unimportant, however, in complete darkness they posed a serious challenge to the evacuees. During the 1993 blackout evacuation, occupants had to feel their way down one step at a time very slowly to make sure they were negotiating a step, a landing or a corridor. When going through a crossover corridor they had a hard time understanding where they were, wondering if they had left the stairway enclosure, where was the rest of the stairway, or if they should try to force open locked doors in the crossover corridor, which typically led to mechanical rooms. This evacuation in crowded smoky dark stairways took around 1 to 3 hours for most of the evacuees [2]. It was a traumatising experience.

Soon after this event, the Port Authority of New York and New Jersey, on the recommendation of evacuation experts, decided to install PLM markings in all the stairways of the WTC complex. The installation was made with a PLM paint product from Permalight. The paint installation was a labour intensive job. It required to mask with tape the outline to be painted, apply a base white coat, 3 coats of PLM paint, and a clear sealant on top. The PLM paint was made of zinc sulphide pigments. As can be seen in Figure 1, PLM paint was applied on the handrails, on the nose and side of each step and as a continuous strip on every landing and mid-landings. PLM signs were added on every door in the stairway enclosure identifying the floor level, stairway name and closest re-entry floors.

Figure 1. Pictures of a WTC stairway before and after PLM installation after the 1993 event

This PLM wayguidance system proved invaluable on September 11, 2001. The 9 - 11 terrorist attack on the WTC led to a very different evacuation compared to the 1993 event. Among the differences is the fact that most of the stairways were fully lit for a long time during the 9-11 evacuation. Evacuees surveyed by NIST were asked if they were helped by building features during their evacuation [3]. In WTC1 33% of the evacuees and 17% of those in WTC2 mentioned noticing and being helped by the PLM marking. The difference between the two towers might be due to the fact that lights were lost in WTC1 after WTC2 collapsed so descending occupants could benefit from the PLM marking, while several evacuees in WTC2 used an elevator to evacuate and thus were not exposed to the PLM. Even occupants descending in full lighting mentioned being reassured by the PLM marking, which was confirming to them that they were in an emergency exit stairway.

This feedback from the WTC evacuees is a clear confirmation that PLM marking helps occupants during building evacuation. Although the WTC evacuation was a unique situation, it is acknowledged that every emergency is characterised by the failure of systems. Having a passive system such as PLM marking to support the occupant’s evacuation provides an incomparable level of life safety.

The performance of the PLM marking at the WTC on 9-11 could have in itself led code officials to require such marking in building exit stairways. However, it is probably the blackout that struck Ontario and the North East of the USA in August 2003 that was the catalyst to promulgate New York City Reference Standard 6-1 on Photoluminescent exit path markings [4]. The blackout demonstrated that despite the obligation to provide emergency lighting in buildings when the regular power fails, some of these systems do not work as planned. In August 2003, several generators and backup battery power that were meant to feed emergency lighting simply did not work, sending thousands of occupants to evacuate in completely dark stairways. This was another traumatising experience.

New York City Reference Standard 6-1 was the first to require PLM marking in exit stairways of new and existing high-rise commercial buildings. Since the publication of this standard in 2005, several jurisdictions are discussing, proposing or soon requiring PLM marking in building stairways.

The plain lack of reliability of emergency lighting systems demonstrated during different emergency situations has led to consider alternative means to support occupant evacuation movement. The further evidence that smoke tends to rise and obscure light fixtures defeats the usefulness of ceiling or high-mounted lights during fire evacuation. The installation of a PLM system along the evacuation route appears to be an effective way to improve occupant evacuation during emergencies. From the start, PLM emerged as a promising addition to building safety features. Among its advantages are that PLM is a passive system that is fail-safe, provided it has been exposed to light, it requires essentially no maintenance and since it is installed as a continuous marking positioned low along the evacuation route, the system is more likely to be visible and will guide evacuees every step of the way to safety.

Through the years the PLM pigments used in the material suitable for egress marking have evolved tremendously. From the first generation of zinc sulphide pigments that required a relatively long charging time for limited luminescence output which decayed within a few hours, the new generation of alkali earth aluminates luminescent material products are much superior on all accounts. Nowadays, at a minimum, the material exposed to 10 lux of fluorescent illumination for 60 minutes will allow the material to glow at 30 mcd/m^2 after 10 minutes of light removal, 7.0 mcd/m^2 after 60 minutes and 5.0 mcd/m^2 after 90 minutes.

This paper will summarize the two studies that were conducted to evaluate PLM as a wayguidance system and the installation guide that was developed based on the findings of the two studies.

FIRST STUDY

The first study conducted by the National Research Council Canada (NRC) on PLM marking was elaborated in 1996-1999 [5]. The general objective was to assess the potential use of PLM as a safety communication system to support office occupant evacuation. The study was more specifically aimed at measuring the occupant time to start (premovement), move and evacuate an office building under emergency lighting and PLM marking. To achieve the study objectives it was decided to conduct an evacuation with the participation of naïve subjects.

Methodology

An unannounced evacuation drill was conducted. The building selected for the study was the Jean-Talon building, a 13-storey concrete structure built in 1979, glazed on all sides and almost square in shape. Each floor area of 3700 m^2 was an open-plan concept divided into 4 quadrants, identified as A, B, C and D; one exit stairway served each of the quadrants, see Figure 2. There were approximately 150 office workers on each floor doing research and clerical activities.

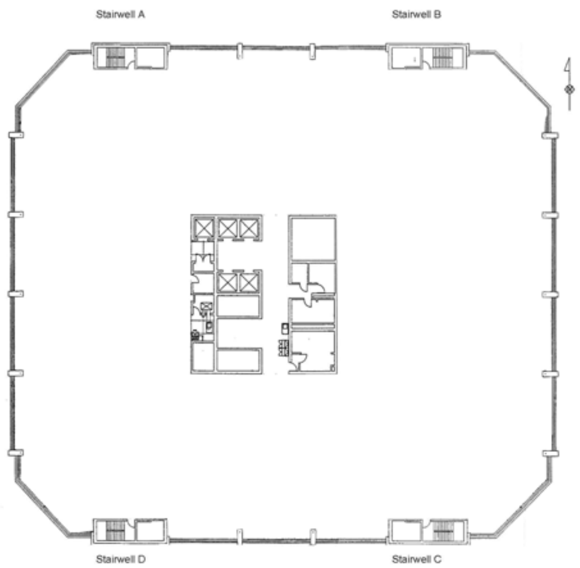

Figure 2. Building layout and stairway location, First Study, Jean Talon building

The building's four stairways were identical in dimension and design. The stairs were 1.1 m in width with step riser of 18 cm. For the study, the four stairways were set up with different conditions, as shown in Figure 3. It is important to mention that, in the stairways of that building, the emergency lighting was the full lighting, which provided a very well lit stairway with an average output of 245 lux. For this study, the lighting conditions in three of the four stairways were modified. Lighting in Stairways A and D was modified to obtain a reduced output of not less than 3.3 lux, which is a code requirement. To obtain this output, 2 out of 3 double-tube luminaires were switched off in Stairways A and D. With this design, Stairway A had an average lighting of 57 lux and Stairway D had a slightly higher average lighting of 74 lux. Stairway D also had PLM signs and a wayguidance system installed. Jalite PLC from the UK, provided and installed the PLM marking and signs for this study. A few minutes before the evacuation, all lights were switched off in Stairway C, which had PLM signs and a wayguidance system. Finally, Stairway B received no treatment; it acted as the control stairway.

B A

D C

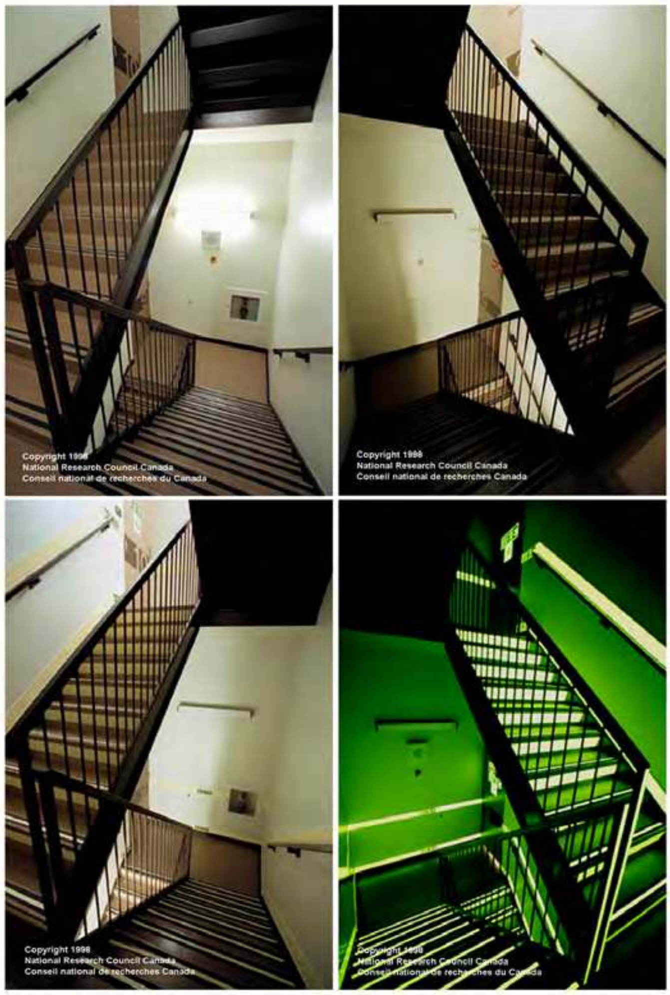

Figure 3. Pictures of the four studied stairways, First Study

The material used for this study was composed of zinc sulphide pigments, which was a first generation of PLM. The 2 stairways equipped with PLM followed the Photoluminescent Safety Products Association Standard 002 Part 1, which met the Luminous Class 1 specification (PSPA, 1997). As shown in Figure 3, Stairways C and D were equipped with two continuous lines of 10 cm in width; one line at the skirting board and the other 1 m from the floor. Directional signs of 30 cm x 10 cm, were enclosed within these continuous lines. A 2 cm strip was fixed on the tread of each step and a 10 cm piece was positioned on the full width of the riser of each step. A sign identifying the floor number was installed on each door, as well as a sign identifying the "Transfer Floors" on Floors 4, 9 and 13. Directional signs were positioned on each door and at mid-landing at 1.7 m from the floor. In accordance with Canadian practice, signs were positioned at the top of each exit door, identifying them as a final exit.

The typical illumination in the four stairways prior to the fire alarm activation was on average 245 lux. When the alarm was activated, lights were switched off in Stairway C as shown in Figure 4. The PLM output in Stairway C was 89.1 mcd/m^2 after 2 min of switch off, 7.0 mcd/m^2 after 30 min and 3.2 mcd/m^2 after 60 min. This luminance would not meet the brightness rating required today by NYC RS 6-1, although at the time it exceeded the PSPA standard of 4 mcd/m^2 after 30 min.

Figure 4: Stairway C with PLM marking, lights on and off, First Study

The phased-evacuation procedure planned for this building was unchanged for the study. The drill was unannounced. It took place on a Wednesday in November, at 13:45. This day and time was chosen to obtain a maximum number of occupants in the building. The temperature outside was -3°C with light snowflakes falling. The fire alarm was activated by a staff member on the 10th floor. The alarm bells started ringing immediately throughout the building. Occupants gathered by their designated evacuation exit awaiting instructions. The average premovement time of occupants was 1 min 12 s. The alarm bell rang for 2 min then a voice communication message was delivered to occupants stating that an evacuation was going to be conducted under emergency lighting conditions and then that an incident had occurred on the 10th floor, so occupants on Floors 9, 10 and 11 should evacuate. Occupants with disabilities were told to gather at Stairway D and stand by for instructions. With this procedure of waiting for the instructions given through the voice communication system, the evacuation down the stairs started around 5 min after the alarm activation. Video cameras were used to gather data during the evacuation drill. They were installed on the morning of the drill and started 30 minutes before the alarm was activated and ran non-stop until after the drill was completed. The cameras were located inside the stairways to capture the behaviour and speed of movement of evacuees, as well as the overall mood and parts of conversations. A questionnaire was handed out to evacuees as they exited the building. The evacuation drill unfolded as planned. Overall, the evacuation drill took less than 20 min.

Results and Discussion

A total of 392 evacuees who travelled from one of the evacuated floors to an outside exit were captured by the video cameras. Out of the questionnaires distributed, 216 were returned representing a 55% returned rate. Of the respondents, 68% were male and 32% female with a mean age in the low 40s.

Twelve people or 6% indicated having a limitation that could impede their evacuation although they took part in the drill and descended one of the stairways. One mentioned a visual limitation but stated no difficulty evacuating from stairway D. All respondents heard the fire alarm and 84% reported being at their desk at the time. The most prevalent responses to the alarm were to get dressed, listen for instruction from the voice communication system and gather at the meeting point by one of the exit stairways.

The questionnaire had several questions on the evacuee experience while descending the stairway (a copy of the questionnaire can be found in [5]). They were asked if they encountered any problems during their descent. The problem that was most frequently identified (32%) was that people entering from lower floors were blocking their descent and for 26% that people in front of them were too slow. Also 21% said that they had difficulty seeing due to poor lighting and 11%, all in stairway C (PLM) mentioned difficulty finding the handrail. Among the respondents who descended Stairway C (PLM), 96% felt the material was useful in finding their way down the stairway while 45% of the respondents who descended Stairway D (PLM+ 74 lux) felt the same. For respondents who descended Stairway C (PLM), 10 or 14% mentioned that the material became brighter as they descended, 3 or 3% said it became darker and 62 (84%) said the brightness did not change.

Respondents were asked to assess, from four choices, the quality of the lighting in the stairway they used. The results are presented in Table 1. It is important to note that the question was worded "How would you assess the quality of the emergency lighting in the stairwell you used?" Several respondents from Stairway C (PLM) added the comment on their questionnaire that there was no emergency lighting in the stairway they used, so they left the question blank or they assessed the lighting as dangerous because it was non-existent. The objective of the question was to obtain a subjective assessment of the conditions in the stairway so it seems that the question was badly worded as it has been interpreted differently by different respondents. Nevertheless all the respondents assessed the lighting as “very good” or “acceptable” in Stairway B (245 lux) and in Stairway D (PLM + 74 lux). In Stairway A (57 lux) among the 47 respondents, 3 or 7% judged as “poor” this level of reduced lighting, although 57 lux is well above the minimum average of 10 lux required by codes. For Stairway C (PLM), 50 respondents or 70%, judged the lighting as “very good” or “acceptable” and, 30% or 22 respondents, judged the lighting as “poor” or “dangerous”.

Table 1 Question to evacuees: "How would you assess the quality of the emergency lighting in the stairwell you used?"

Lighting Quality	Frequency (Valid Percent)			
Option	Stairway A 57 lux	Stairway B 245 lux	Stairway C PLM	Stairway D PLM + 74 lux
Very Good and Acceptable	93%	100%	70%	100%
Poor and Dangerous	7%	0%	30%	0%

The exact speed of movement for each evacuee was noted from the videotapes, then the average speed of movement in each stairway was calculated, which is presented in Table 2. The slowest mean speed of movement was in Stairway C (PLM), where the mean speed was 0.57 m/s. Stairway A (57 lux) had a mean speed of 0.70 m/s and Stairway B (245 lux) had a mean speed of 0.61 m/s. Finally, Stairway D (PLM + 74 lux) had a mean speed of 0.72 m/s.

Table 2 Speed of movement in the four stairways, First Study

Stairway	Experimental Design	Mean Speed m/s	Std Dev.	Number of Evacuees
A	Emergency Lighting at 57 lux	0.70	0.1556	82
B	Control: Full Lighting 245 lux	0.61	0.1016	101
C	PLM only	0.57	0.1202	144
D	PLM and Emergency Lighting at 74 lux	0.72	0.0854	65
Total		0.63	0.1347	392

An Analysis of Variance shows a significant difference in speed of movement between the four stairways as presented in the ANOVA table, Table 3. A multiple comparison procedure (Bonferroni test), shows that the mean speed of movement for evacuees in Stairway C (PLM) is significantly slower ($\overline{X} = 0.57$, $p < 0.05$) compared to Stairway B (245 lux) ($\overline{X} = 0.61$, $p < 0.05$), Stairway A (57 lux) ($\overline{X} = 0.70$, $p < 0.05$) and Stairway D (PLM + 74 lux) ($\overline{X} = 0.72$, $p < 0.05$). There is also a significant difference between Stairway B (245 lux) ($\overline{X} = 0.61$, $p < 0.05$) and the two stairways with emergency lighting reduced to 57 and 74 lux, Stairway A ($\overline{X} = 0.70$, $p < 0.05$) and Stairway D ($\overline{X} = 0.72$, $p < 0.05$).

Table 3 ANOVA table on the mean speed of movement in the four stairways, First Study

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2527012.6	57	44333.555	3.902	.000
Within Groups	3795052.2	334	11362.432		
Total	6322064.8	391			

Overall the results indicate that the speed of movement was faster in the two stairways with emergency lighting reduced to 57 and 74 lux, compared to the stairway that had the PLM only and the stairway with full lighting! The latter finding appears incongruous; how to explain that occupants move faster in stairways with reduced lighting compared to a fully-lit stairway? After examining the data closely, an explanation for these results appeared. Stairway C (PLM) had the slowest speed of movement (0.57 m/s), but it also had the largest crowd in the stairway with 144 people. In that stairway, there was also the unplanned upward movement of 3 firefighters, which forced evacuees, who were descending in a scattered fashion, to form a single line, which backed up evacuees and slowed down all the descending occupants. Stairway B (245 lux) was the second slowest (0.61 m/s), and was also the second most crowded of the stairways with 101 evacuees. Stairway A (57 lux), was the second fastest (0.70 m/s) and least crowded with 82 evacuees. Finally, Stairway D (74 lux + PLM) had the fastest overall speed (0.72 m/s) and also the least amount of people in the stairway with 65 evacuees. Therefore, the more plausible explanation for the decrease in speed in the different stairways is related to crowding and not to the lighting conditions in each stairway.

In a field study, since the research team wants the event to unfold as naturally as possible and given that the occupants are not informed prior to the drill, it can be expected that the occupants density will vary in each stairway. The density of evacuees was calculated in each stairway for the three busiest minutes of the evacuation. Stairway C (PLM) had the highest density with an average of 2.05 p/m^2, which is almost 3 people for every 5 steps. Stairways A (57 lux) and B (245 lux) were similar with, respectively, 1.25 p/m^2 and 1.30 p/m^2. Finally, Stairway D (74 lux+ PLM) had the lowest density with an average of 1.0 p/m^2. Pauls [6] developed, from 21 case studies of high-rise office building evacuations, a relationship between stairway density and the expected speed of movement of occupants going down stairways under normal conditions. The equation is,

$$s = 1.08 - 0.29d \qquad (1)$$

where s is the speed of movement in m/s and d is the density.

The speed of movement as calculated with Equation 1, is slightly higher than the observed speed of movement for Stairways A, B, and D. For Stairway C, the calculated speed is lower than the observed speed. Results of observed and calculated speed of movement are presented in Table 4.

Table 4 Density, observed and calculated speed of movement in the four stairways, First Study

Stairway	Number of evacuees	Density (p/m^2)	Observed mean speed (m/s)	Calculated speed (m/s)
A (57 lux)	82	1.25	0.70	0.72
B (245 lux)	101	1.30	0.61	0.70
C (PLM only)	144	2.05	0.57	0.49
D (PLM + 74 lux)	65	1.00	0.72	0.79

The counter-flow created by the upcoming firefighters in Stairway C had a major impact on the speed of movement of the descending evacuees. The impact of speed reduction due to counter-flows has been documented by different researchers [7, 8]. Occupants who were descending 2 x 2 or who were descending in a scattered pattern, had to form a single line to the left. This created a queue of 28 evacuees on the 9th floor who had to wait for 34 s to enter Stairway C.

First Study Conclusions

The majority of the occupants, who participated in the drill, were faced with a PLM wayguidance system for the first time. Despite their lack of training or past exposure to PLM they were prepared to travel in a stairway with PLM without any other illumination source.

The majority of the evacuees assessed the quality of the lighting in stairways with emergency lighting or full lighting as "very good" or "acceptable". There is little difference in their assessment of the stairway with full lighting or reduced emergency lighting. This means that stairway lighting, reduced to an average of 57 or 74 lux, appears acceptable to most of the evacuees.

The "lighting quality" in the stairway with PLM only was assessed as "poor" or "dangerous" by 30% of the evacuees who used that stairway. It was mentioned earlier that this question was badly worded, so respondents might have been inclined not to respond to this question or to give a negative answer. Nevertheless, the fact that close to one-third of the respondents assessed the "lighting quality" negatively is enough to raise a few concerns. To address this issue three areas for improvement have been identified; training, increasing PLM luminescence and increasing material quantity.

The occupants who participated in this first study were completely naïve and were experiencing a PLM wayguidance system in the dark for the first time. Education and training with such systems, would remove the initial hesitation of the person facing an unknown environment.

Further, the luminance of the PLM components should be increased. The luminance properties of the PLM material made of zinc sulphide was not the highest that can technically be achieved. PLM manufacturers are now selling PLM components, made of alkali earth aluminates for example, that present brightness levels up to 10 times greater than the tested material in the same activation illuminance conditions.

Finally, the quantity of material installed could be increased. In an attempt to maintain the amount of material to the minimum required under the Photoluminescent Safety Products Association Standard [9], it is possible that the quantity of material used was not enough for the location. Several respondents wrote on their questionnaire that they had difficulty finding the handrail; others complained that the last step to the landing was not identified. This should be considered in future installations.

One of the most important findings of this study is the speed of movement of a natural crowd descending four stairways under different lighting conditions. Findings show that, irrespective of the lighting conditions tested, speeds of movement are comparable to speeds obtained in previous studies in stairways with full lighting [7, 10]. The results indicate that the stairway with PLM signs and wayguidance system had the expected speed of movement for the observed density. In that stairway, there was also the unplanned upward movement of 3 firefighters, which slowed down all descending occupants. Close examination of the speed of movement results leads to the conclusion that the decrease in speed in the different stairways is more related to the occupant density in the stairway than to the lighting conditions.

Faster speed of movement in the two stairways with emergency lighting reduced to 57 and 74 lux compared to the fully lit stairway may seem, at first, incongruous. However, this result is explained by the fact that the reduced lighting had no impact on the occupants' speed: it is the density of occupants in the stairway that had an impact on the speed of movement. Reduction of lighting output in stairways could be considered a cost-effective decision without impact on occupant satisfaction and speed of movement in the stairway.

This study shows the interesting potential of PLM signs and wayguidance system to support occupant evacuation. Such provisions, properly installed, can address deficiencies in the traditional approach to emergency lighting associated with power failure or smoke logging of ceiling or high-mounted lights. To obtain the expected outcome, though, it is essential to install the material as a continuous strip with markings on steps and handrails, as well as identification and directional signs. The occupants' behaviour, their speed of movement and their subjective appraisal of the material are all in agreement to conclude that PLM signs and PLM safety wayguidance systems could be a worthwhile addition in improving occupant life safety in office buildings.

SECOND STUDY

Following the first study, a literature review of research studies that have been carried out on the use of PLM as a safety wayguidance system was conducted in 2006 [11]. The review revealed that lessons learned from past tragedies and factual benefits of PLM wayguidance systems have led to the development of requirements, product technical standards and installation guides [4, 12, 13]. The concerns, however, are that none of these installation standards have been tested with human subjects during an evacuation. Further, the installations proposed vary considerably regarding the quantity and location of the material as demonstrated in Figure 5. It is not known if these proposed installations are excessive, costing more than is required or are too minimal to properly support safe and effective occupants evacuation.

The review of the PLM technology and its applications has led to three recommendations: 1) PLM systems have a unique potential for buildings as an effective and sustainable wayguidance system to enhance the security of occupants during building evacuation; 2) further research and field tests are needed to assess the effectiveness of the PLM wayguidance system under evacuation conditions; and 3) to ensure that the technology is used properly, a methodology for the installation of PLM wayguidance systems should be developed in line with research findings. As a result of these recommendations, a second study was developed by NRC to address three objectives: 1) assess the effectiveness of 3 stairway installations of a PLM wayguidance system in an office building environment; 2) compare the effectiveness of PLM wayguidance systems to a stairway under emergency lighting condition; and 3) develop, based on the research results, an installation guide for PLM wayguidance system. To achieve these objectives a field study with the participation of naïve subjects was conducted.

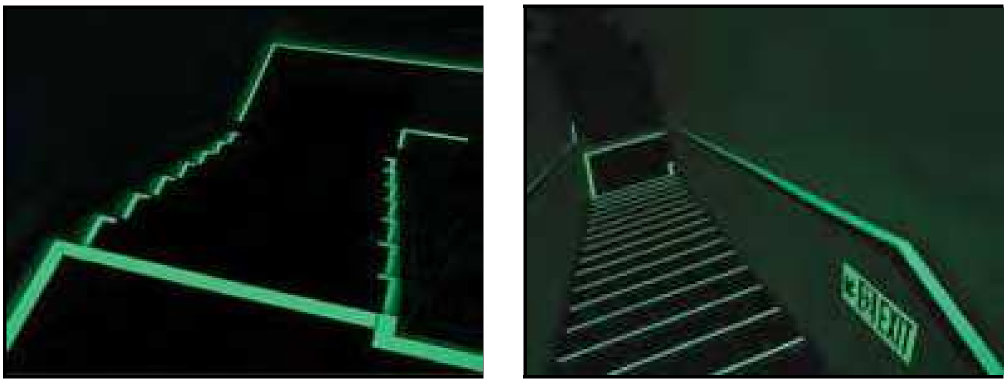

Figure 5. Examples of PLM safety marking in stairways [14]

Methodology

The building selected for the Second Study was built in 1977 and has 13 storeys [15]. Each office floor area is approximately 8000 m^2, housing around 350 workers on every floor. The building has 6 geometrically identical stairways among which 4 are windowless; see Figure 6. Each stairway width was 1.1 m with a handrail on both sides. All stairways discharge directly to the street. The building has a central fire alarm bell system and sprinklers. The evacuation procedure is a full evacuation upon alarm activation.

It is expected that as many as 4,000 employees could be in the building during normal working hours. This large number of occupants was of particular interest for this study to allow for measurement of the occupants' speed of movement under crowd conditions. Occupants of the building are typical office workers aged between 18 and 65 years with a mix of men and women. It was expected that some occupants could have limitations preventing them from participating in the evacuation drill. Floor Emergency Officers are trained to assist these occupants in accordance with the Fire Safety Plan.

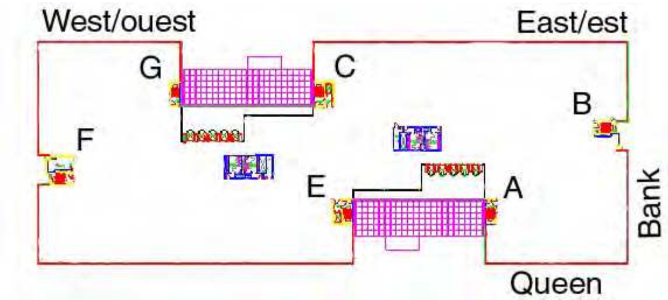

Figure 6. Stairways location, Second Study, C.D. Howe building

In accordance with a request from the NRC Research Ethics Board, an information sheet detailing the study and the fact that PLM had been installed in some of the building stairways was sent by e-mail to all building employees a week prior to the experiment. The day and time of the drill was, however, not mentioned. The drill or experiment was conducted on a Thursday in October 2006 starting at 10:35 a.m.; the outside temperature was 8°C. The emergency evacuation procedure for the building was followed: at the sound of the fire alarm all occupants, supported by the Floor Emergency Officers, started to move toward their designated stairway and descended to exit at street level. At alarm activation, the 3 PLM stairways (Stairways A, E and G) were simultaneously put in total darkness. Stairway C had its lighting reduced by removing 2 out of 3 double-tube fluorescents (the same procedure as in the first study) providing an average level of lighting of 37 lux. The current code accepts that the emergency lighting be reduced to an average as low as 10 lux. Video cameras, installed on the morning of the drill, were started 30 minutes before the alarm was activated and ran non-stop until after the drill was completed. The cameras were located inside the stairways to capture the behaviour and speed of movement of evacuees, as well as the overall mood and parts of conversations. Upon exiting the studied stairways, evacuees were handed a questionnaire to fill out (a copy of the questionnaire can be found in [15]). On location were members of the Building Fire Emergency Organization, the research team, observers, firefighters, paramedics and the police. The evacuation was completed in 12 minutes after which all occupants were allowed to return into the building.

The PLM material and installation was provided by three suppliers, Prolink North America, Jessup Manufacturing Company and Jalite USA. All materials used was made of alkali earth aluminates pigments and had received certification in accordance with New York City Standard 6-1 2005 [4]. Consequently, the material brightness rating in the laboratory had a minimum of 30-7-5 mcd/m^2 at 10, 60 and 90 minutes, respectively, after light extinction. The lighting in the stairways had an average output of 80 lux of light at all time: depending on the location of the measurement the illuminance varied from a minimum of 30 lux to 150 lux. Three of the stairways were equipped with PLM installations. Table 5 summarizes the elements that were installed in the tested stairways. The 4th stairway studied, Stairway C, had no PLM marking but had reduced lighting to an average of 37 lux to represent emergency lighting. Figure 7 shows the 4 studied stairways as experienced by the evacuees.

Table 5 Experimental installation of the stairways, Second Study

Marking	Stairway A	Stairway E	Stairway G	Stairway C
Steps	L marker 1”	Marking 1” across each step Anti-slip strip 1”	Marking 2” across each step plus L marker Anti-slip strip 1”	No marking
Handrail	Continuous 1”	Continuous 1”	Continuous 1”	No marking
Demarcation on landing	Continuous 1”	Continuous 1”	Continuous 2”	No marking
Directional sign “running-man”	On each landing	On each landing	On each landing	No marking
Obstruction	Zebra marking and tag	Zebra marking and tag	Zebra marking and tag	No marking
Final Door	Around door 1” and sign “Final”	Around door 1” and sign “Final”	Around door 2” and sign “Final”	No marking
Lighting	No	No	No	37 lux average

The experimental design offered the advantage of comparing the speed of movement and occupant evaluation of the 3 PLM stairway installations, which could be compared to a stairway with emergency lighting. Video cameras were positioned inside the stairway to gather data on movement time and behaviour of evacuees. The questionnaire contained questions on the participants' characteristics, specific questions on the comfort and safety felt and overall evaluation of the PLM system in the stairway used.

C A

E G

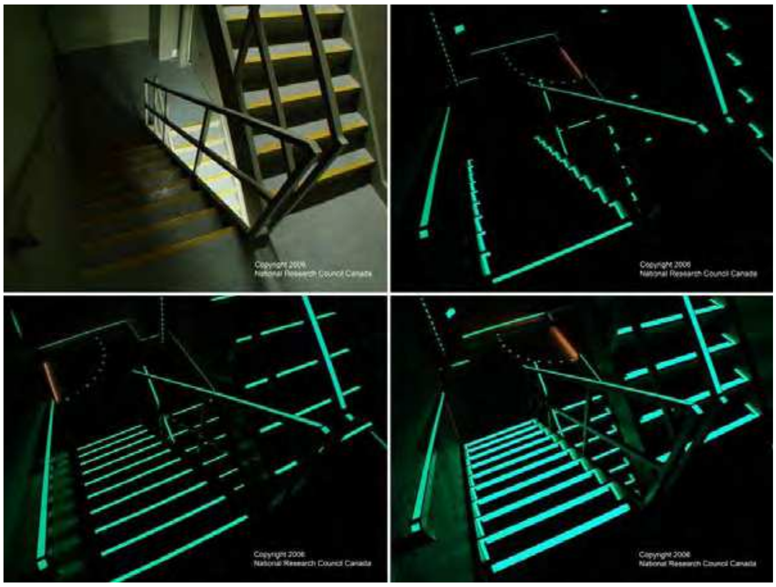

Figure 7. Pictures of the four studied stairways, Second Study, C.D. Howe Building

Results and Discussion

The evacuation drill unfolded as planned without any unexpected incident to report. The video recordings provided a complete account of the movement of occupants. The average time taken by the first occupants to arrive at each stairway was 1 min 7 s and they started down the stairway right away. Overall, the full evacuation lasted just under 12 min. It seems that the reduced lighting of Stairway C and the PLM marking without lighting in the other 3 studied stairways had no impact on the overall time to evacuate that building since the annual evacuation drill takes typically around 14 min.

In total, 489 questionnaires were returned from the 1191 evacuees observed on the video recordings, which is a return rate of 41%. Assuming that this sample represents a random selection of the building evacuees, it is calculated that the questionnaire results can be generalized to the entire building population. A statistical analysis on the number of returned questionnaires shows that there are no statistical differences between the 3 PLM stairways. Therefore, it is possible to compare the tested stairways with confidence.

Respondents were 65% female and 35% male with an age distribution demonstrating a rather mature crowd in their low 50s. An important occupant characteristic that can have an impact on an evacuation is the presence of people with limitations. Among the respondents, 41 individuals or 8% stated that they had a form of limitation that could impede their evacuation from the building, among them 3 stated visual limitations. Nevertheless, all these respondents evacuated the building using a stairway since they filled out a questionnaire. Among the respondents the most prevalent condition reported was asthma at 26%, followed by being overweight at 23% and arthritis at 17%. It is important mentioning that occupants with a severe mobility limitation who could not use the stairways to evacuate are not part of this sample. Respondents who reported a disability were well distributed in the 4 stairways: 8 used Stairway A and 11 used each of the other 3 stairways.

At the start of the evacuation 99% heard the fire alarm. At the time, 81% of the respondents were at their desks, and most took the time to “get dressed”, “gather valuables” and “secure files or information” before starting their evacuation.

Due to the building’s large surface area and the configuration of the offices and cubicles, it was not possible to record the exact starting time of each occupant upon hearing the fire alarm. It was, however, possible to observe the time of arrival of each person at the at the stairway exit door. The premovement time reported by 46% of the respondents was that they started to leave in less than 1 minute, which is in line with the observation made from the video recordings. Some 29% estimated they took between 1 to 2 minutes to start leaving, 14% took 2 to 3 minutes, and 4% took 3 to 4 minutes. Over 6% or 31 respondents said it took more than 4 minutes to start leaving. Figure 8 shows a distribution of the premovement time. Once occupants decided to evacuate their floor, they moved toward their assigned stairway.

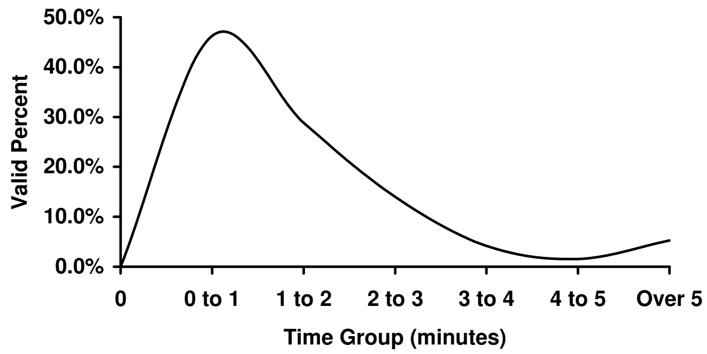

Figure 8. Distribution of premovement time, Second Study

The questionnaire had several questions for respondents to express their experience descending the studied stairways. The questionnaire asked the respondents if they encountered any problems as they entered and negotiated the stairways. The problem that was the most frequently identified was the difficulty seeing because of poor lighting. This problem was mentioned by about half the respondents in each of the studied stairways. The second problem most frequently mentioned was that the people in front were moving too slowly.

Evacuees were asked to judge the visibility in the stairway they used. Table 6 shows the results when combining the judgements “excellent” and “good” versus “not very good” and “poor”. Stairways E (1” across) and G (2” across) received more judgement that the visibility in these stairways was good or excellent while Stairways A (L marker) and C (37 lux) received less positive judgement, however, these different appreciations were not statistically different (x^2=16.804(9), ns).

Table 6 Question : "How would you judge the visibility in the stairwell you used?"

Visibility Quality	Percent			
Option	Stairway A L marker	Stairway E 1" across	Stairway G 2" across + L	Stairway C 37 lux
Excellent and Good	50%	67%	62%	56%
Not very good and Poor	50%	33%	38%	44%

The evacuees were asked to provide their degree of agreement with 8 specific statements regarding wayguidance elements experienced in the stairway. The respondents considered the handrail to be easy to find in the 4 studied stairways. When asked if the first step to each flight was easy to locate, respondents from the 4 stairways were positive toward this statement with Stairways E (1" across) and G (2" across) respondents providing a larger number of people who strongly agree. When asked if each step was easy to identify Stairway E and G with marking across each step obtained a much better rating then Stairway A ("L" marker) and Stairway C (37 lux). Respondents were asked about the easiness to locate the last step of each flight. Of all stairways, Stairway A (L marker) received the largest proportion of disagreement that the last step was easy to find. Stairway E (1" across) obtained the largest percentage of positive assessment. Overall, if we take the stairway attributes individually and look at the stairway that received the most favourable appreciations for each feature, Stairway E (1" across) is systematically in first place with Stairway G (2" across) second, Stairways A (L marker) and C (37 lux) are in turn at the third and last positions.

Evacuees were questioned on their sense of comfort while going down the stairs during the evacuation. Overall, 75% of the respondents felt comfortable going down any of the stairways. Respondents were asked to judge the density of the crowd in the stairway they used and Stairway E was judged the most crowded.

From the questionnaire it appears that respondents judged Stairways A (L marker) and C (37 lux) similar on several questions while these two stairways appear less positively evaluated than Stairway E and G (1" and 2" across). Stairway E (1" across) obtained the best positive evaluation despite the fact that this was also the stairway that was felt to be the most crowded and that problems such as occupants at the front moving too slowly were identified. Stairway G seems also to have been positively evaluated but somewhat less so than Stairway E on some of the attributes.

From the video recording the average time for the first person to reach the exit door on their floor after the alarm is 1 min 7 s and 5 min 29 s for the last person respectively. Among the last to enter the stairways were Floor Emergency Officers, who have as part of their duty to ensure that the area under their responsibility is empty when they leave. Several took the time to visit each office as well as coffee rooms and washrooms before leaving their floor.

The speed of movement of each evacuee in each stairway was calculated. The slowest mean speed of movement was in Stairway E (1” across), which had a mean speed of 0.40 m/s. Stairway G (2” across) had a mean speed of 0.57 m/s and Stairways A (L marker) and C (37 lux) shared the highest mean speed of 0.66 m/s, see Table 7.

Table 7 Speed of movement in the four stairways, Second Study

Stairway	Experimental Design	Mean Speed m/s	Std Dev.	Number of Evacuees
A	PLM L shaped marker at the edge	0.66	0.2462	345
E	PLM 1” across each step	0.40	0.1661	287
G	PLM 2” across each step	0.57	0.2133	281
C	Lighting reduced to 37 lux	0.66	0.3053	278
Total		0.57	0.2335	1191

An Analysis of Variance shows differences in mean speed of movement between stairways as presented in the ANOVA table, Table 8. A multiple comparison procedure, called Tukey’s HSD, was undertaken. This test was used to identify which pairs of groups have significantly different means. The results show that the mean speed of movement in Stairways A and C are essentially the same at 0.66 m/s. That speed is significantly higher than the speed of movement in Stairway G ($q=6.45$, $p<0.01$ and $q=6.01$, $p<0.01$, respectively) and Stairway E ($q=17.64$, $p<0.01$ and $q=16.76$, $p<0.01$, respectively). The speed of movement is significantly different in Stairways G and E as Stairway E is significantly slower at 0.40 m/s ($q=11.09$, $p<0.01$).

Table 8 ANOVA table on the mean speed of movement in the four stairways, Second Study

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	10.987	3	3.662	62.804	.000
Within Groups	65.194	1118	.058		
Total	76.181	1121			

The slowest mean speed of movement was in Stairway E (1” across), which had a speed significantly slower then the 3 other stairways. Stairway G (2” across) is also significantly slower than Stairways A (L markers) and C (37 lux) which shared the highest mean speed. As in the First Study it is important to consider these speeds of movement in relation to the density of the occupants descending each stairway. The density of evacuees was calculated during the five busiest minutes of the evacuation; see Table 9. The last column shows the calculated speed of movement, as defined by Pauls [6]. The calculated speeds and the observed speeds are similar in Stairways A, G and C. Stairway E, however, demonstrates a marked difference as its observed mean speed of 0.40 m/s is considerably lower than its calculated speed of 0.62 m/s. A closer look at Stairway E indicated that it was more crowded earlier in the evacuation than the other stairways. This could help explain in part the lower observed mean speed of evacuation. Having most of the evacuees entering the stairway at the same time would cause a lot of crowding because of merging from all floors, and therefore reduce the evacuation speed. When further studying Stairway E, it was also noticed that two individuals with limitations had a major impact on the speed of movement in that stairway. Entering from floor 7, a heavy person started going down Stairway E one step at a time, moving sideways to the stairs, taking the full stairway width. Almost at the same time another person holding a cane entered from floor 1 with two accompanying occupants who remained behind. Nobody over-took these two evacuees who were slower than the rest of the crowd. A gap soon formed in front of these two persons leaving a full flight of stairs empty. The entry of these 2 slower evacuees had a substantial impact on the descending crowd: at one point the crowd was completely stalled for 1 min 20 s.

Table 9 Density, observed and calculated speed of movement in the four stairways, Second Study

Stairway	Number of evacuees	Density (p/m^2)	Observed mean speed (m/s)	Calculated speed (m/s)
A (L markers)	345	1.56	0.66	0.63
E (1” across)	287	1.60	0.40	0.62
G (2” across)	281	1.58	0.57	0.62
C (37 lux)	278	1.60	0.66	0.62

Crowding and holding of the handrails, were obtained from the video recordings. There was significant crowding observed in all of the stairways. The bottom few floors had the largest amount of evacuees, but tended to move along well because there was little merging with lower floors. The middle floors got congested very quickly, and during the busiest few minutes of the evacuation, movement could stop completely for up to 15 s in Stairways A, C and G.

Holding of the handrail also contributed to crowding and slowing down movement in the stairways. Evacuees using the handrails were descending at the sides of the stairway, tending to favour the inside handrails. This caused them to descend in a single file, which in turn slowed their speed of descent to the speed of the slowest person ahead of them. Some evacuees not using the handrails were able to pass through the middle of the stairway. In some areas, 4-5 evacuees were observed in each stairway holding on to the handrails on both sides, making it difficult for faster occupants to get by. The frequency of people holding the handrail was recorded at some floors. Overall over 80% of the evacuees were holding the handrail while descending or when they were stopped waiting for movement to resume.

Second Study Conclusions

Evacuees in this study provided comparable judgements on several attributes of the 4 tested stairways. There was, however some systematic evaluation that differentiated the stairways. It appears that respondents judged Stairways A (L marker) and C (37 lux) similar on several questions while these two stairways appear less appreciated than Stairway E and G (1” and 2” across). In Stairway A, visibility was judged good by half of the respondents and not good by the other half. Two important issues for several evacuees of Stairway A are that each step in the stair, and the last step of each flight, were difficult to locate. The overall evaluation of Stairway A and C was not as good as for Stairway E and G. Stairway E obtained the best appreciation from the respondents.

The results show that the mean speed of movement in the 4 stairways varied significantly. The mean speed of movement for Stairways A and C was 0.66 m/s; it was 0.57 m/s in Stairway G and 0.40 m/s in Stairway E. The results indicate that Stairway E had significantly slower speed of movement. Close study of the raw data showed that Stairway E had two individuals with mobility limitations who had a major impact on the evacuation movement slowing down all the evacuees who were behind them. The results also show that occupant density on the stairs was fairly high and very similar for each stairway ranging from 1.56 to 1.60 p/m^2 for the 5 busiest minutes of the evacuation. The driving factor for the speed of movement in the stairways was not the installation tested but the occupants' density. From the speed of movement alone it is not possible to conclude which installation is the best.

One interesting observation is the fact that over 80% of the evacuees were holding the handrail in the stairway with PLM marking. This fact supports the research team decision to mark the handrail as evacuees seemed to rely considerably on the handrail during movement down as well as during times when the crowd was stopped.

Density can be represented by showing positions of evacuees in the stairs, as in Figure 9, which shows density in Stairway A (L marker) on floor 3, at 2, 3, 4, 5 and 6 minutes from the alarm. Such drawings are helpful when analyzing the behaviour of the evacuees as they descend. The representation at 5 min shows the most crowded time of the evacuation, with 6-7 evacuees on one flight of stairs, representing 1.98 p/m^2. In this kind of crowd it is important to understand that each evacuee has a limited view of the PLM marking as other evacuees are hiding some of the marking. This explains why many mentioned the difficulty identifying the last step of each flight. In a dense crowd evacuees could not see the demarcation line marking the landings and mid-landings so the last step was difficult to identify.

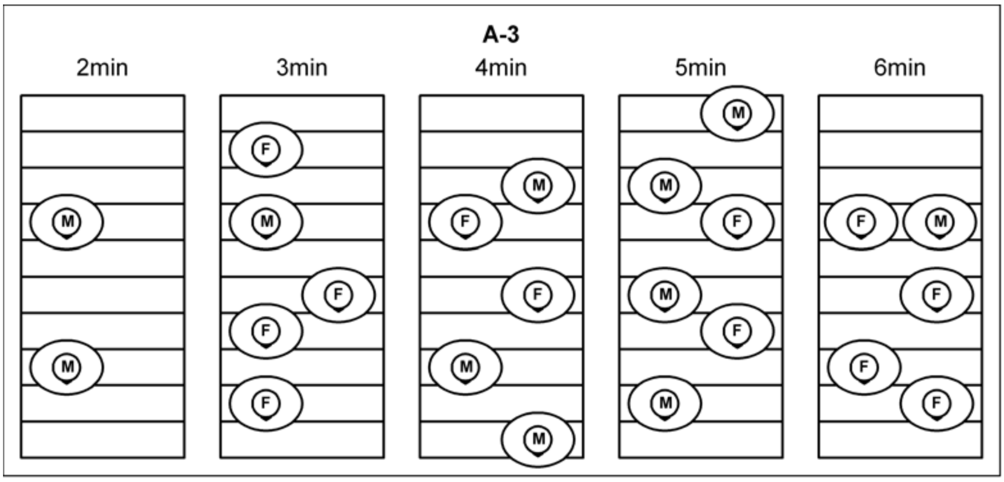

Figure 9. Representation of densities on 3rd floor of Stairway A at different times

Overall respondents favoured the installation of Stairway E with the 1" strip marking across each step. The larger 2" stair strips of Stairway G, combined with the "L" shaped marking as well as the 2" demarcation line did not seem to play a role for a better evaluation by the respondents when compared with Stairway E. It appears that Stairway A with the L shaped markers was the less appreciated as it was difficult for evacuees to differentiate each step. Respondents' evaluation of Stairway C, with 37 lux, is comparable to Stairway A, although these two stairways were illuminated differently. Close to half of the respondents who used Stairway C said that it was difficult to see around because of the poor lighting.

Overall, the conditions experienced in the 4 studied stairways were judged as fairly difficult by the evacuees as several considered that the lighting was poor, the steps were difficult to identify and it was crowded and slow. A majority agreed, however, that they would feel comfortable evacuating under such conditions if there was an emergency.

DEVELOPMENT OF AN INSTALLATION GUIDE

In light of the interest of installing PLM signs and markings in buildings, a Guide for the Installation of Photoluminescent Exit Stairway Markings in Buildings was developed [16]. The Guide is based on the 2 field study results as well as on available standards, technical guides and regulations. The purpose of the Guide is to provide information about the best practice for the installation of PLM markings in buildings and the requirements for a satisfactory performance.

The Guide describes some general basic principles that every PLM system should have. For instance continuity of the marking is essential. The marking should be placed as continuous strips, at low location, along the evacuation route to serve as a proximity guide for evacuees. PLM signs should also be part of the installation to identify destination and directions and to serve as visual reinforcement. It is recommended that all PLM marking used, as a safety wayguidance system should have the same colour so installation in different buildings and different jurisdictions would always be the same colour. The marking should be installed to avoid confusion and direct evacuees toward places of safety. It is suggested to install PLM marking in the means of egress and also to identify emergency equipment and floor plan layout to ensure that occupants can find these essential elements in case of an emergency.

The performance of the PLM marking to be installed is paramount. The material selected to support the safe evacuation of building occupants should comply with specific certifications regarding brightness rating and be subjected to tests to ensure for example their washability, toxicity, radioactivity and flame spread. The performance evaluation process should be conducted by a certified laboratory.

The Guide details the installation of the material from the door leading to an evacuation stairway, within the stairway enclosure, to the final exit to safety. On every floor of the building, it is proposed to mark the exit doorframe with PLM as well as the door hardware to help identify the means of egress. Inside the exit stairway the marking suggested is in line with the marking of Stairway E of the Second Study, which occupants judged the best. Marking of 1" across each step, with demarcation line on the landing and mid-landing of 1" are recommended. Since the studies demonstrated the high usage of the handrail while descending and since it was one of the criticisms obtained in the First Study that the handrail was not properly identify, the Guide requires marking on all handrails.

It was felt that the Guide needed to address the issue raised by the evacuees of the Second Study regarding the difficulty of finding the last step of each flight of stair. The decision was made to propose the installation of a landing marking similar to the line painted at the WTC after the 1993 bombing which seemed to work well when the stairway is crowded, as it would be the case in most high-rise office building evacuations. Figure 10 shows a drawing of a stairway with a complete installation.

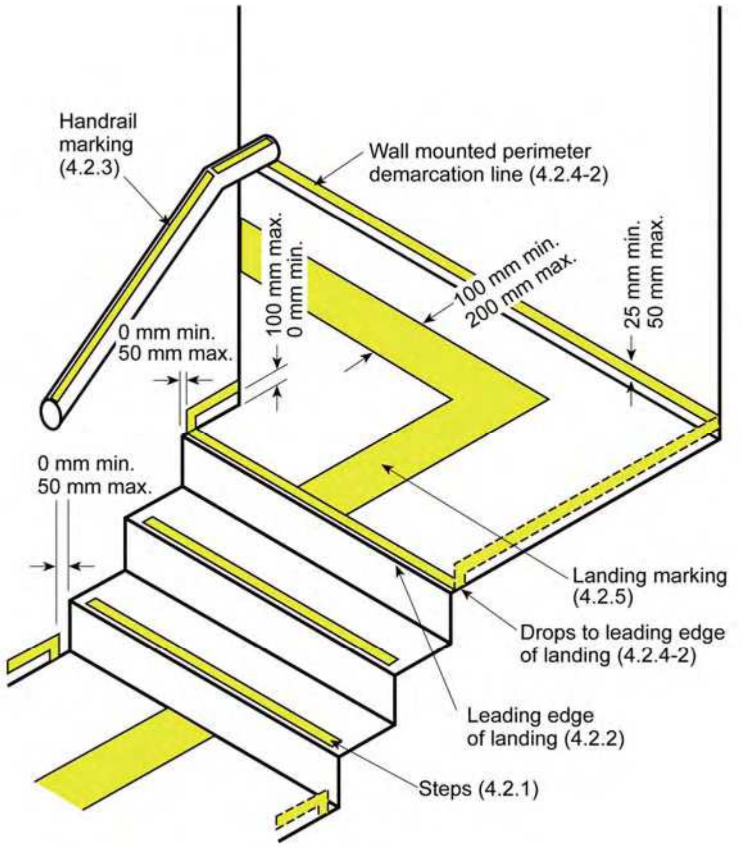

Figure 10: Recommended installation for stairway from the installation Guide

The Guide recommends marking any obstacle below 1980 mm in height and projecting more than 100 mm. The marking of an obstacle should be made with a zebra pattern of PLM and black marking.

Intermediate exit door and final exit door should be marked with PLM on the doorframe and the door hardware. In addition, PLM signs should indicate where the door leads and if evacuees have reached the final exit.

Additional marking is also suggested to indicate the floor number and stairway identification on every floor inside the stairway enclosure. Further, directional signs should be posted to indicate transfer floors, doors that are not an exit and if there is no roof access.

One of the great advantages of a PLM system is that it requires almost no maintenance. The Guide suggests conducting a visual inspection once a year to ensure that no marking is missing or damaged. Just as important in to verify that no fluorescent lights are missing or defective is order to replace them right away to ensure that the PLM marking is properly charged.

Although the Guide was developed with high-rise office buildings in mind, the installation suggested could be implemented in any emergency stairway enclosure of buildings of any type of occupancy.

ACKNOWLEGMENT

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REFERENCES

1. M.S. Isner and T. J. Klem, "World Trade Center Explosion and Fire New York, New York, February 26, 1993," Investigation Report, National Fire Protection Association, Quincy, MA, 59 p. 1993

2. R. F. Fahy and G. Proulx, "Collective Common Sense: A Study of Human Behavior During the World Trade Center Evacuation", *NFPA Journal*, Vol. 9, No. 2, National Fire Protection Association, Quincy MA, pp. 59-67, 1995.

3. J. D. Averill; D. S. Mileti, R. D. Peacock, E. D. Kuligowski, N. Groner, G. Proulx, P.A. Reneke, and E. H. Nelson, "Federal Building and Fire Safety Investigation of the World Trade Center Disaster : Occupant Behavior, Egress, and Emergency Communications", 174 p., 2005. http://wtc.nist.gov/oct05NCSTAR1-7index.htm

4. New York City Building Code, RS 6-1 and RS 6-1 A, "Photoluminescent Exit Path Markings", Local Law 26, New York City, U.S.A., 2005. http://www.nyc.gov/html/dob/downloads/pdf/rs_6-1.pdf

5. G. Proulx, D.K. Tiller, B. Kyle, J. Creak, "Assessment of Photoluminescent Material During Office Occupant Evacuation", Internal Report 774, Institute for Research in Construction, National Research Council Canada, Ottawa, 38 p. 1999. http://irc.nrc-cnrc.gc.ca/pubs/ir/ir774/

6. J. Pauls, "Movement of People", *SFPE Handbook of Fire Protection Engineering*, Second Edition, Chapter 3-13, SFPE USA, pp. 263-285, 1995.

7. J. L. Bryan, "Behavioral Response to Fire and Smoke", *SFPE Handbook of Fire Protection Engineering*, Second Edition, Chapter 3-12, SFPE USA, pp. 241-262, 1995.

8. J. J. Fruin, Pedestrian Planning and Design, Metropolitan Association of Urban Designers and Environmental Planners, New York, 1971.

9. PSPA, "Standard 002 Emergency Way-finding Guidance Systems, Part 1 Code of Practice for the Installation of Emergency Way-finding Guidance (LLL) Systems Produced from Photoluminescence for Use in Public, Industrial and Commercial Buildings", Photoluminescent Safety Products Association, UK, 1997.

10. G. Proulx and J. Pineau, "Differences in the Evacuation Behaviour of Office and Apartment Building Occupants", *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting*, Vol. 2, HFES, Santa Monica, CA, pp. 825-829, 1996.
11. R. Tonikian, G. Proulx, N. Bénichou, I. Reid, "Literature Review on Photoluminescent Material Used as a Safety Wayguidance System", Research Report 214, Institute for Research in Construction, National Research Council Canada, 31p., 2006.
12. ISO 16069, "Graphical symbols – Safety signs – Safety way guidance systems (SWGS)", 2004.
13. ASTM E 2030 – 04, "Guide for recommended uses of photoluminescent (phosphorescent) safety markings", 2004.
14. G. Peckham, "Photoluminescent Directional Egress Path Marking Systems", *Archi-Tech Magazine*, Dec. 2005. Photos used with permission © Jalite USA, 2005.
15. G. Proulx, N. Bénichou, J. K. Hum, K. N. Restivo, "Evaluation of the Effectiveness of different Photoluminescent Stairway Installations for the Evacuation of Office Building Occupants", Research Report 232, Institute for Research in Construction, National Research Council Canada, 72 p., 2006. http://irc.nrc-cnrc.gc.ca/pubs/rr/rr232/
16. G. Proulx, N. Bénichou, B. R. Kyle, S. Foo, "Guide for the installation of photoluminescent exit stairway markings in buildings", 22 p., August 01, 2008. http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc50818/