Evaluation and comparison of different installations of photoluminescent marking in stairwells of a highrise building

Bénichou, N.; Proulx, G.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20377815
Interflam 2007, 11th International Conference on Fire Science and Engineering [Proceedings], pp. 183-194, 2007-09-03

Evaluation and comparison of different installations of photoluminescent marking in stairwells of a highrise building

NRCC-49230

Bénichou, N.; Proulx, G.

A version of this document is published in / Une version de ce document se trouve dans: Interflam 2007, 11th International Conference on Fire Science and Engineering, London, UK., Sept. 3-5, 2007, pp. 1-12

EVALUATION AND COMPARISON OF DIFFERENT INSTALLATIONS OF PHOTOLUMINESCENT MARKING IN STAIRWELLS OF A HIGHRISE BUILDING

Noureddine Bénichou and Guylène Proulx
National Research Council of Canada, Ottawa, Canada

ABSTRACT

A field study was conducted to assess the effectiveness of a number of different photoluminescent material (PLM) stairwell installations as a safety wayguidance system to support office occupant evacuation. Four identical stairwells were used in the experiment. Video cameras and a questionnaire were used to gather data on the movement time and behaviour of evacuees, their feelings of comfort and safety in the stairwell, and their overall appreciation of the PLM wayguidance emergency evacuation system.

Results from the study show that between 65 to 75% of the respondents felt comfortable going down the stairwells with PLM markings, with the visibility assessed as "good or excellent" in the two of the stairwells with PLM marking across each step. The average time taken by the first occupants to arrive at each stairwell was 1 min 7 s. Overall, the full evacuation lasted about 12 min. The results also indicate that the mean speed of movement in the stairwells ranged between 0.40 and 0.66 m/s, while the density ranged between 1.56 and 1.60 p/m^2. Occupants' judgement of the installation showed the importance of marking across each step of the stairwell.

INTRODUCTION

Photoluminescent material (PLM) is made of inorganic chemical compounds, referred to as photoluminescent pigment phosphors, encased in flexible or rigid strata or dispersed in a liquid [1]. The photoluminescent pigments consist of crystals of aggregated elements and other agents. The crystals are characterized as being photoluminescent (phosphorescent) due to the excitation they undergo when exposed to a light source and their ability to store light photons, consequently showing luminescence over time. After the crystals have been charged by a light source, they can emit light. In the absence of light, the energy stored will continuously exhaust until its complete depletion. PLM has many applications. In fire safety, the most promising uses are for safety markings such as exit signs, directional signage, door markings, path markings, obstruction identification and other components that compose a safety wayguidance system. In blackout situations resulting from power failures or fires, PLM safety markings can aid occupant evacuation to safer locations; see Figure 1.

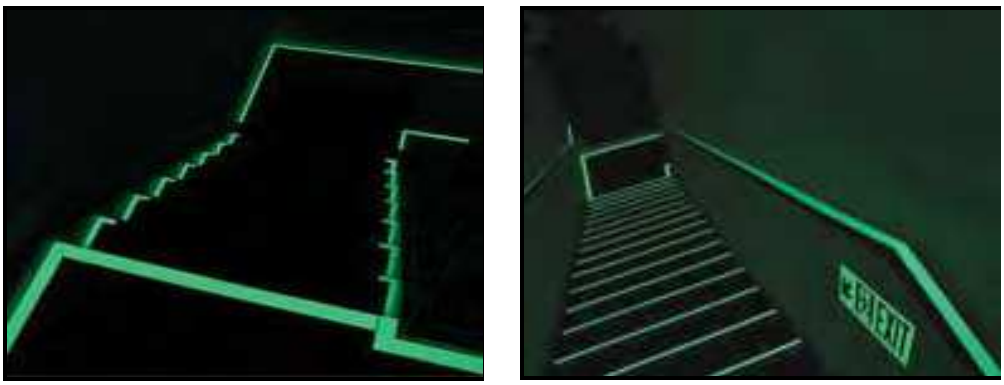
In 2006, the National Research Council of Canada (NRC) prepared a literature review of research studies that have been carried out on the use of PLM as a safety wayguidance system [3]. The review revealed that lessons learned from past tragedies and factual benefits of PLM wayguidance systems have led to the development of requirements, product technical standards and installation guides [4, 5, 6]. However, none of these installation standards have ever been tested with human subjects during an evacuation. Also, it is not known if the installations proposed are excessive, and are costing more than is required for safe and effective evacuation. The review of the PLM technology and its applications has led to three recommendations: 1) PLM signage 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; 3) to ensure that the technology is used properly, a methodology for the installation of PLM wayguidance systems should be developed. As a result of these recommendations, a project was developed to address at three objectives:

1. To assess the effectiveness of 3 stairwell installations of a PLM wayguidance system in an office building environment.
2. To compare the effectiveness of PLM wayguidance systems to a stairwell under emergency lighting condition.
3. To develop, based on the research results, an installation guide for PLM wayguidance system.

Objectives 1 and 2 were pursued through a full building evacuation experiment with human subjects. The findings of this experiment are reported in this paper.

Figure 1. Examples of PLM safety marking in stairwells [2]



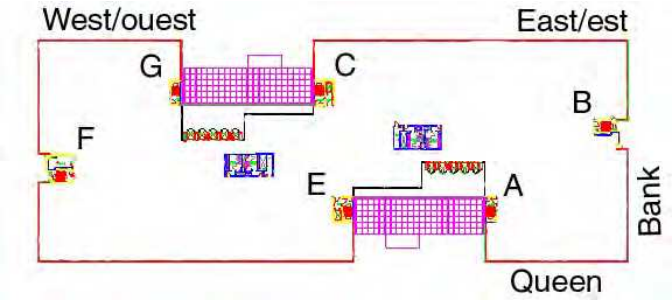
METHODOLOGY

To measure people's movement time, ability to find destinations and to obtain people's appreciation of PLM installations, a study of an evacuation drill in an office building was conducted. Several buildings were considered for this study. A set of criteria was established to identify the building most suitable to meet the study objectives [7]. The C.D. Howe building, located in Ottawa, met the study criteria; see Figure 2. The building was built in 1977 and has 11 floors of office space plus 2 storeys of commercial space, making a total of 13 storeys. There is also one storey of commercial floor underground, a basement level and a 3-storey parking garage. Each office floor area is approximately 8000 m^2, housing around 350 workers. The building has 6 geometrically identical stairwells among which 4 are windowless; see Figure 3. All stairwells discharge directly to the street. The building has a central fire alarm bell system and is fully sprinklered.

Figure 2. Picture of the CD Howe building

The subjects of this study were the employees working at the C.D. Howe Building, although building visitors may have been involved. Around 4,000 employees are expected to 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 condition. 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 3. Stairwells location



Experimental Design

For practical reasons, it was not possible to obtain signed consents from the potential participants to this study. However, an information sheet, detailing the study but not the drill day and time, was sent to all building employees a week prior to the experiment. The drill or experiment was conducted on October 5, 2006 starting at 10:35:23 a.m. In accordance with the emergency procedure, at the sounding of the alarm all occupants, supported by the Floor Emergency Officers, started to move toward their designated or the nearest stairwell. At alarm activation, the 3 PLM stairwells (Stairwells A, E and G) were simultaneously put in total darkness. Stairwell C was under emergency lighting (2 out of 3 double-tube fluorescents were removed a day before the drill) providing an average level of lighting of 37 lux [7]. The current code accepts that the emergency lighting be reduced to an average as low as 10 lux [8]. 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 stairwells to capture the behaviour and speed of movement of evacuees, as well as the overall mood and parts of conversations. Upon exiting the studied stairwells, evacuees were handed a questionnaire to fill out. On location were members of the Building Fire Emergency Organization, research team, observers, firefighters, paramedics and police. The evacuation was completed in 12 minutes after which all occupants were allowed to return into the building.

Three material suppliers, Prolink North America, Jessup Manufacturing Company and Jalite USA, provided and installed the PLM marking and signs for this study. All materials used had received certification in accordance with New York City Standard 6-1 2004 [4]. Three stairwells were equipped with PLM installations. Table 1 summarizes the elements that were installed in the tested stairwells. The 4th stairwell studied, Stairwell C, had no PLM marking but had reduced lighting (37 lux average level) to represent emergency lighting. Figure 4 shows the 4 studied stairwells as experienced by the evacuees. Installation of the material took place in the two weeks prior to the evacuation drill.

Data Gathering

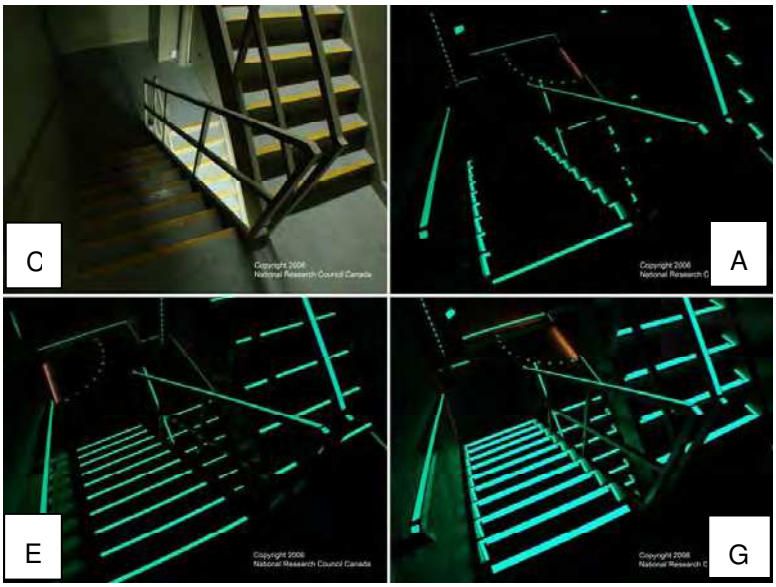
The experimental design offered the advantage of comparing the speed of movement and occupant appreciation of the PLM stairwell installations, which could be compared to a stairwell with emergency lighting. The methodology of using video cameras to record movement and behaviour and a questionnaire to obtain feedback were used in this study. The questionnaire contained questions on the participants' characteristics, specific questions on the comfort and safety felt and overall

appreciation of the PLM wayguidance emergency evacuation systems in the stairwell used (questionnaire details found in [7]). Twenty-eight video cameras, positioned on floors 11, 9, 7, 5, 3, 1 and B level of the stairwells, were used to gather data on movement time and behaviour of evacuees in the stairwells.

Table 1. Experimental installation of the stairwells

Marking	Stairwell A	Stairwell E	Stairwell G	Stairwell C
Steps	L marker 1”	Marking across each step 1” Anti-slip strip 1”	Marking across each step 2” 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

Figure 4. Four studied stairwell installations



FIELD STUDY RESULTS

The evacuation drill unfolded as planned without any unexpected incident to report. Data from the questionnaires and the videos were analyzed and statistical calculations were run using SPSS 13.0.

Questionnaire Results

In total, 489 questionnaires were returned from the 1191 evacuees observed on the video recordings. 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 with a 95% confidence level with a potential variation of 3 points. Among the returned questionnaires, 130 or 27% were from respondents who used Stairwell A, 132 or 27% were from Stairwell E, 128 or 26% were from Stairwell G, and 99 or 20% were from Stairwell C. As shown in Table 2, the sample of returned

questionnaires represents a return rate of 41% which is good for this type of study [9]. A statistical analysis on the number of observed evacuees counted shows that there are no statistical differences between the PLM stairwells. Therefore, it is possible to compare tested stairwells with confidence.

Table 2. Returned questionnaires

Stairwell used	Returned questionnaire	Evacuees observed	Return percent
A	130	345	38%
E	132	287	46%
G	128	281	46%
C	99	278	36%
Total	**489**	**1191**	**41%**

Respondent profile:
Of the 421 respondents, 65% were female and 35% were male. The respondents' age distribution demonstrates a rather mature crowd. 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. Nevertheless, all these respondents evacuated the building using a stairwell since they filled out a questionnaire. The questionnaire provided 8 categories of limitation to choose from as shown in Table 3 (category "others" refers to hand-written comments; one added claustrophobia and another one pregnancy). Out of the 41 respondents who identified a limitation, 4 had multiple limitations all involving being overweight and other conditions. 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 serious mobility limitation who could not use the stairwells to evacuate are not part of this sample. Respondents who reported a disability were well distributed in the stairwells: 8 used Stairwell A and 11 used each of the other 3 stairwells.

Table 3. Limitation that could impede evacuation

Limitations	Frequency	Valid percent
Asthma	12	26%
Overweight	11	23%
Arthritis	8	17%
Heart condition	3	6%
Vision impairment	3	6%
Injury	3	6%
Mobility impairment	3	6%
Hearing impairment	3	6%
Others	2	4%
Total	**48**	**100%**

Alarm and initial response:
Among the respondents, 99% heard the fire alarm at the time of the evacuation. Only 3 respondents stated that they did not hear the alarm in their area. These occupants were located on floors 2, 5 and 6 of the East tower; but somebody rapidly came to warn them. None of them mentioned having a hearing limitation. Of those who commented on the sound level of the alarm, 76% found the alarm "loud enough", however 21% or 102 respondents felt that the alarm was "too loud" and 3% or 14 respondents found the alarm to be "too quiet". Respondents of both genders provided appreciation of the alarm level in exactly the same proportion so no gender difference was found.

When the alarm sounded, 81% of the questionnaire respondents were at their desks, others were in other locations such as meeting rooms, corridors and washrooms. Respondents were asked if they completed any of a list of 8 actions before starting their evacuation. As shown in Table 4, the most

prevalent action before starting evacuation was for 335 or 69% of the respondents to "get dressed". The other three most likely actions were to "gather valuables" with 54%, "secure files or information" 45%, and "follow warden's instructions" 43%. Interestingly, 14 respondents continued working".

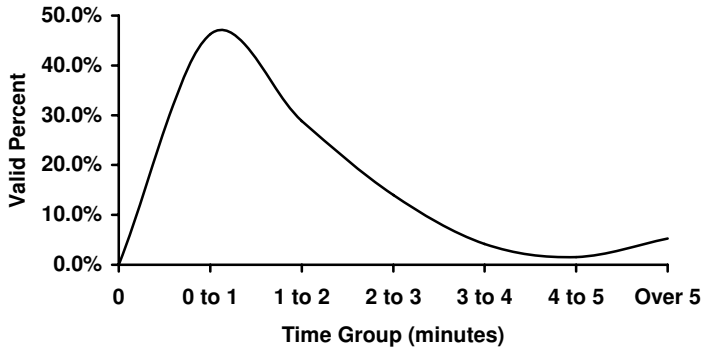
Table 4. Action performed before starting evacuation

Action	Frequency	Percent
Get dressed	335	68.5
Gather valuables	265	54.2
Secure files or information	222	45.4
Follow warden's instructions	208	42.5
Return to office	75	15.3
Discuss with a colleague	56	11.5
Seek more information	23	4.7
Continue working	14	2.9

Evacuation times:

Respondents were asked to estimate how much time they spent from the time the evacuation drill started to the time they decided to leave their floor. As presented in Figure 5, an overall 46% reported starting to leave in less than 1 minute, which is very good. However, some 29% decided to leave between 1 to 2 minutes, 14% decided to leave between 2 to 3 minutes, and 4% decided to leave between 3 to 4 minutes. Over 6% or 31 respondents took more than 4 minutes to start leaving, which is of concern. Among the respondents who took over 4 minutes, 7 returned to their offices after hearing the alarm and completed tasks such as securing files and getting dressed. Another 6 continued working after hearing the fire alarm until they were told to leave. Finally, 6 were Floor Emergency Officers who took time to ensure that their floors were empty before starting their evacuation.

Figure 5. Distribution of time to start evacuation



Respondents were also asked to estimate how much time they spent overall to evacuate the building from the time the drill started to the time they reached the outside. Overall, 47% of the respondents estimated that they took less than 5 minutes to evacuate the building. Another 40% indicated that they took from 5 to 10 minutes, and 13% said that they took over 10 minutes to evacuate the building. The analysis of the video recordings provided exact times with which to compare these estimates which turned out to be very accurate.

Stairwell evacuation:

Once occupants decided to evacuate their floor, they moved toward the different stairwells. The questionnaire had several questions for respondents to express their experience descending the studied stairwells. The questionnaire asked the respondents if they encountered any problems as they entered and negotiated the stairwells. No respondent mentioned furniture obstructing the entry to the stairwell. Approximately 22% of the evacuees in the 4 studied stairwells encountered crowding

around the entry. Only 2 respondents in Stairwell E and 2 in Stairwell C mentioned difficulty opening the exit stairwell door. Difficulty entering the stairwell because too many people were coming down was felt to be a problem by 23% in Stairwell A, 16% in Stairwell E, 20% in Stairwell G and 21% in Stairwell C. It does not appear that finding the handrail was a problem in the 3 stairwells equipped with PLM marking as well as in the stairwell with reduced lighting. The problem that was the most frequently identified was the difficulty seeing because of poor lighting. This problem was mentioned by 52% of the respondents from Stairwell A and as many in Stairwell E, 50% mentioned this problem in Stairwell G and 45% in Stairwell C. The second problem most frequently mentioned was that the people in front of the descending evacuee were moving too slowly. Counter flow did not seem to be a problem in any of the stairwells studied and most respondents had no difficulty in finding and opening the exit door at the base since the last flight of stairs was fully lit.

Evacuees were asked to judge the visibility in the stairwell they used. Table 5 shows the results when combining the judgements "excellent" and "good" versus "not very good" and "poor". Stairwells E and G received substantially more judgement that the visibility in these stairwells was good or excellent while Stairwells A and C received less positive judgement.

Table 5. Judgement of the visibility in the stairwell used

Judgement	Percent of answer in stairwell			
	A	E	G	C
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 attributes that they experienced in the stairwell. The complete results to those questions are presented in Table 6. Overall, the respondents of the 4 studied stairwells considered the handrail to be easy to find. When asked if the first step to each flight was easy to locate, respondents from the 4 studied stairwells were positive toward this statement with Stairwells E and G respondents providing a larger number of people who strongly agree. It was much easier for evacuees to identify each step in Stairwell E and G, while it was difficult to identify each step in Stairwells A and C. This finding is not surprising as Stairwell A had only the "L" shape marking at the extremity of each step to identify the step and Stairwell C had no marking and reduced lighting which made each step more difficult to identify. Respondents were asked about the easiness to locate the last step of each flight. Of all stairwells, Stairwell A received the largest proportion of disagreement that the last step was easy to find. Stairwell E obtained the largest percentage of positive assessment. In terms of sign visibility, Stairwell E scored the best for the visibility of directional signs, although the directional signs were the same in all the PLM stairwells. There was no statistical difference among stairwells for the marking of obstructions, the identification of the crossover floor, or the marking of the final exit. Overall, if we take the stairwell attributes individually and look at the stairwell that received the most favourable appreciations for each feature, Stairwell E is systematically in first place with Stairwell G second; see Table 7. Stairwells A and C are in turn at the third and last position.

Evacuees were questioned on their sense of comfort while going down the stairs during the evacuation. Overall, 65 to 75% of the respondents felt comfortable going down the stairwells with the PLM marking or the reduced lighting. Respondents were asked to judge the density of the crowd in the stairwell they used and Stairwell E was judged the most crowded during the evacuation.

From the questionnaire it appears that respondents judged Stairwells A and C similar on several questions while these two stairwells appear less positively evaluated than Stairwell E and G. Stairwell E obtained the best positive evaluation despite the fact that this was also the stairwell that was felt to be most crowded and that problems such as occupants at the front moving too slowly were identified. Stairwell G seems also to have been positively evaluated but somewhat less so than Stairwell E on some of the attributes. The larger 2" stair stripes combined with the "L" shaped marking as well as the 2" demarcation line of Stairwell G did not seem to play a role in the evaluation

of the respondents when compared with Stairwell E. Visibility was judged good to excellent in these stairwells (E and G) and locating each step appeared to be easier with the PLM marking of each step.

Table 6. Appreciation of wayguidance attributes in the stairwells

Statement		Percent of answer in stairwell			
		A	E	G	C
The handrail was easy to find:	*Strongly agree*	72%	85%	76%	75%
	Somewhat agree	22%	12%	17%	19%
	Somewhat disagree	5%	2%	4%	4%
	Strongly disagree	1%	1%	3%	2%
The first step of each flight was easy to locate:	*Strongly agree*	57%	74%	67%	55%
	Somewhat agree	31%	18%	21%	32%
	Somewhat disagree	8%	7%	6%	9%
	Strongly disagree	4%	1%	6%	4%
Each step was easy to identify:	*Strongly agree*	50%	72%	64%	54%
	Somewhat agree	32%	21%	28%	33%
	Somewhat disagree	11%	7%	5%	12%
	Strongly disagree	7%	0%	3%	1%
The last step of each flight was easy to find:	*Strongly agree*	45%	58%	52%	49%
	Somewhat agree	27%	25%	26%	30%
	Somewhat disagree	15%	11%	13%	17%
	Strongly disagree	13%	6%	9%	4%
Directional signs were visible:	*Strongly agree*	54%	66%	54%	46%
	Somewhat agree	32%	30%	27%	25%
	Somewhat disagree	12%	2%	11%	13%
	Strongly disagree	2%	2%	8%	16%
Obstructions were well marked:	*Strongly agree*	43%	52%	50%	45%
	Somewhat agree	42%	37%	31%	25%
	Somewhat disagree	10%	9%	10%	13%
	Strongly disagree	5%	2%	9%	16%
Re-entry floors were well identified:	*Strongly agree*	50%	57%	61%	52%
	Somewhat agree	39%	33%	24%	30%
	Somewhat disagree	8%	7%	6%	8%
	Strongly disagree	3%	3%	9%	10%
The final exit was well marked:	*Strongly agree*	69%	68%	69%	68%
	Somewhat agree	30%	27%	24%	22%
	Somewhat disagree	1%	4%	4%	8%
	Strongly disagree	0%	1%	3%	2%

Table 7. Rating of the stairwells for each attribute

Attribute	Rating			
	1st	2nd	3rd	4th
Handrail was easy to find	E	G	C	A
First step of each flight was easy to locate	E	G	A	C
Each step was easy to identify	E	G	C	A
Last step of each flight was easy to find	E	G	C	A
Directional signs were visible	E	G	A	C
Obstructions were well marked	E	G	A	C
Re-entry floors were well identified	G	E	A	C
Final exit was well marked	G	A	E	C

Data from the Video Cameras

Recordings from the 28 video cameras used to survey the evacuation were analyzed. A total of 1191 occupants were observed on the recordings.

Time to start:
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 each exit door. The average time for the first person to reach the exit door after the alarm is 1 min 7 s. The average time for the last person to reach the exit door after the alarm is 5 min 29 s. It can be estimated that the true time to start or pre-movement time of each occupant was approximately 10-15 s prior to their arrival at the door. Among the last to enter the stairwells 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.

Speed of movement:
The speed of movement of each evacuee in each stairwell is important data to be obtained from the video recordings. Speed of movement was calculated in metres per second (m/s) for each evacuee with the exact distance travelled in each stairwell. The speed of movement in Stairwell A ranged from 0.33 m/s to 1.39 m/s. In Stairwell E, the speed ranged from 0.17 m/s to 1.03 m/s, in Stairwell G it ranged from 0.14 m/s to 1.53 m/s and in Stairwell C it ranged from 0.38 m/s to 1.87 m/s. The observed mean speed of movement in all stairwells is presented in Table 8. The slowest mean speed of movement was in Stairwell E, which had a speed of 0.40 m/s. Stairwell G had a mean speed of 0.57 m/s and Stairwells A and C shared the highest mean speed of 0.66 m/s. Table 8 also presents the density of occupants descending which varied slightly for each stairwell. Density of evacuees was calculated in people per metre squared (p/m^2) during the five busiest minutes of the evacuation. The last column shows the calculated speed of movement, as defined by Pauls [10], which is similar to the observed speed in Stairwells A, G and C. Stairwell 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 Stairwell E indicated that it was more crowded earlier in the evacuation than the other stairwells. This could help explain the much lower observed mean speed of evacuation. Having most of the evacuees entering the stairwell 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 Stairwell E, it was noticed that two individuals with limitations had a major impact on the speed of movement in that stairwell. At 10:37:41, entering from floor 7, a heavy person started going down the stairwell one step at a time, moving sideways to the stairs, holding the handrail with one hand and a jacket and vest with the other. Almost at the same time at 10:37:38, 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 in the stairwell, and a gap formed in front of them leaving a full flight of stairs empty. The impact on the descending crowd was substantial, stalling the descent for a few minutes.

Table 8. Speed of movement in the four stairwells

Stairwell	Number of evacuees	Density (p/m^2)	Observed mean speed (m/s)	Calculated speed (m/s)
A	345	1.56	0.66	0.63
E	287	1.60	0.40	0.62
G	281	1.58	0.57	0.62
C	278	1.60	0.66	0.62

The videotapes also showed that the number of people entering on any floor tended to be higher at the beginning of the evacuation, and slowly dropped as the evacuation continued for Stairwells A, C and

G. In Stairwell E, however, the number of people who entered peaked at 2-3 minutes from the alarm on all floors, and then fell steeply for the rest of the evacuation. This means that the majority of the evacuees in Stairwell E were all in the stairwell at the same time, causing crowding and congestion.

Observed behaviour:
Observations of the behaviour of the evacuees during the evacuation, such as crowding and holding of the handrails, were obtained from the video recordings. There was significant crowding observed in all of the stairwells. 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 Stairwells A, C and G, and as long as 1 min 20 s in Stairwell E. This large discrepancy between stairwells is attributable to the two evacuees with limitations who entered Stairwell E and slowed down the evacuation behind them.

Holding of the handrail also contributed to crowding and slowing down movement in the stairwells. Evacuees using the handrails were descending at the sides of the stairwell, 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 stairwell. In some areas, 4-5 evacuees were observed in each stairwell 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. As examples, on floor 9, 88% were holding the handrail in Stairwell A, 81% in Stairwell E, 86% in Stairwell G and 71% in Stairwell C. On floor 5, 84% used the handrail in Stairwell A, 87% in Stairwell E, 80% in Stairwell G and 81% in Stairwell C. On floor B, which was fully lit, 31% used the handrail in Stairwell A, 55% in Stairwell E, 33% in Stairwell G and 61% in Stairwell C. Two possible explanations may be offered for the difference between floor B and the upper floors 5 and 9. The first one is the lighting difference between the floors. Evacuees held on to the handrail more frequently on levels with less lighting. The second explanation is the proximity to the exit. On floor B, evacuees were moving well without any crowding because they were heading directly outside. Because they were so close to the exit, evacuees sped up and stopped using the handrail. Many were seen zipping their coat on this last flight of stairs.

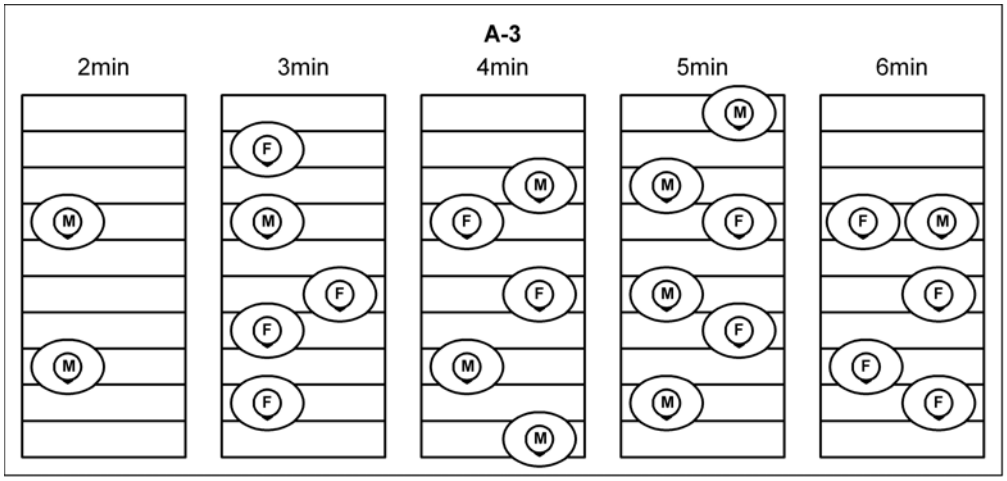
Density can be represented by showing positions of evacuees in the stairs, as in Figure 6, which shows density in Stairwell A on floor 3, at 2, 3, 4, 5 and 6 minutes from the alarm. These representations are helpful when analyzing the behaviour of the evacuees as they descend. For example, it was very rare to see two people descending the stairs side-by-side during this evacuation. There was not enough room in the 1100 mm stairwell for two to fit comfortably shoulder to shoulder, without one violating the other's personal space. This was usually only seen when two friends were speaking to each other while descending. When the stairwell was relatively empty, evacuees kept to their right. This tendency to stay on the right is explained by the fact that the staircase spirals downward to the right; keeping to that side allowed evacuees to descend faster. When the stairwell was more crowded, such as at 5 minutes, the evacuees maintained a scattered pattern to avoid walking too close to each other. 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.

Based on observations from the videotapes, most evacuees were at ease and not alarmed by the PLM marking. Comments such as, "wow" and "this is some lighting" were heard in all three PLM stairwells. One evacuee in Stairwell G commented on the visibility, saying, "you can't see people, all you can see are the stairs." Overall, comments about the PLM marking were positive. Most occupants did not overtly react to the material and just followed the evacuation flow.

SUMMARY AND CONCLUSIONS

A field study was conducted to assess the effectiveness of a number of different PLM stairwell installations as a safety wayguidance system to support office occupant evacuation. Following are the major findings and conclusions of this study.

Figure 6. Representation of density on floor 3 of Stairwell A at different times



Evacuees' Subjective Assessment of PLM Signage

Overall respondents to the questionnaire provided statistically comparable judgements on several attributes of the 4 tested stairwells. There was, however some systematic evaluation that differentiated the stairwells. It appears that respondents judged Stairwells A (L shape marker) and C (reduced lighting) similar on several questions while these two stairwells appear less appreciated than Stairwell E and G (1" and 2" marking, respectively). In Stairwell A, visibility was judged good by half the respondents and not good by the other half. Two important issues for several evacuees of Stairwell A are that each step in the stair, and the last step of each flight, were difficult to locate. The overall evaluation of Stairwell A and C was not as good as for Stairwell E and G. Stairwell E obtained the best appreciation from the respondents.

Occupant Movement

Video recordings provided a complete account of the movement of occupants. The average time taken by the first occupants to arrive at each stairwell was 1 min 7 s. Overall, the full evacuation lasted just under 12 min. It seems that the reduced lighting of Stairwell C and the PLM marking without lighting in the other 3 studied stairwells had no impact on the overall time to evacuate that building since the annual evacuation drill takes typically around 14 min.

The results show that speed of movement in the 4 stairwells studied ranged from 0.14 m/s to 1.87 m/s. The mean speed of movement for Stairwell A was 0.66 m/s; 0.40 m/s in Stairwell E; 0.57 m/s in Stairwell G and 0.66 in Stairwell C. The results indicate that Stairwell E had significantly slower speed of movement. Close study of the raw data showed that Stairwell E had two individuals with limitations who had a major impact on the evacuation movement. The results also show that occupant density on the stairs was very similar for each stairwell ranging from 1.56 to 1.60 p/m^2. The driving factor for the speed of movement in the stairwells was not the installation tested but the occupants' density. From the speed of movement it is not possible to conclude which installation is the best.

One of the most interesting observations is the fact that over 80% of the evacuees were holding the handrail in the stairwell 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.

Comparison of PLM Installations

The overall judgement of the respondents favoured the installation of Stairwell E with the 1" strip marking across each step. It appears that Stairwell A with the L shaped markers was the less

appreciated as it was difficult for evacuees to differentiate each step. Although Stairwell E is the installation that received the best evaluation its better performance is not based on a faster speed of movement on stairs but essentially on the subjective judgement of respondents.

Comparison of PLM with Emergency Lighting

Respondents' evaluation of Stairwell C, with reduced lighting, is comparable to Stairwell A, with L shaped markers, although these two stairwells were differently illuminated. Close to half of the respondents who used Stairwell C said that it was difficult to see around because of the poor lighting.

Overall, the conditions experienced in the 4 studied stairwells 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. However a majority agreed that they would feel comfortable evacuating under such conditions if there was an emergency.

ACKNOWLEGMENT

This study was a joint research project between the National Research Council Canada (NRC) and Public Works and Government Services Canada (PWGSC). The authors would like to thank all the participants in the study including the occupants, Brian Kyle and his team, the building management, PLM manufacturers, and NRC-IRC staff.

REFERENCES

[1] Krokeide, G., 1988, "An Introduction to Luminous Escape Systems", Safety in the Built Environment, pp. 134-147.
[2] Peckham, G., 2005, "Photoluminescent Directional Egress Path Marking Systems, Archi-Tech Magazine, Dec. 2005 Issue. Photos used with permission © Jalite USA.
[3] Tonikian, R.; Proulx, G.; Bénichou, N.; Reid, I., 2006, "Literature Review on Photoluminescent Material Used as a Safety Wayguidance System, Research Report, Institute for Research in Construction, National Research Council Canada, 214, pp. 31.
[4] New York City Building Code, RS 6-1 and RS 6-1 A, 2004, Photoluminescent Exit Path Markings, Local Law 26, New York City, U.S.A.
[5] ISO 16069, 2004, Graphical symbols – Safety signs – Safety way guidance systems (SWGS).
[6] ASTM E 2030 – 04, 2004, Guide for recommended uses of photoluminescent (phosphorescent) safety markings.
[7] Proulx, G.; Bénichou, N.; Hum, J.K., Restivo, K.N., 2006, "Evaluation of the Effectiveness of different Photoluminescent Stairwell Installations for the Evacuation of Office Building Occupants, Research Report, Institute for Research in Construction, National Research Council Canada, 232, pp. 72.
[8] COSH, 1994, Handbook of Occupational Safety and Health, Fifth Edition, Treasury Board of Canada Secretariat, Human Resources Management Office, Occupational Safety and Health Chapter 3-1 Standard for fire safety planning and fire emergency organization, Ottawa, Canada
[9] Shaughnessy J.J., Zechmeister, B.E., 1994, Research methods in psychology, Third Edition, McGraw Hill Inc.
[10] Pauls, J., 1995, "Movement of People", SFPE Handbook of Fire Protection Engineering, Chapter 3-13, SFPE USA, pp. 263-285.