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Literature Review on Photoluminescent Material Used as a Safety Wayguidance System

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EXECUTIVE SUMMARY

Photoluminescent pigment is characterized as being photoluminescent due to the excitation it undergoes when exposed to a light source and its ability to store light photons, consequently becoming luminescent. In black out situations resulting from power failures or fires, photoluminescent safety markings can aid evacuation by guiding and directing people to a safe location. This literature review, prepared by the National Research Council Canada, looks into research studies that have been carried out on the use of photoluminescent material as a safety wayguidance system. Experimental procedures and methodologies are highlighted as well as findings and conclusions attained by these early studies in order to better understand photoluminescent material and its applications. This review will serve as background information to aid and to guide future research into this area.

Preliminary studies on photoluminescent material were initiated in the middle of the 1970s to present the idea of using photoluminescent safety markings as an aid or an alternative to emergency lighting. However, phosphorous pigments existing at the time were weak photon absorbers and the material had to be supported by an electrical power supply. With the advent of stronger pigments such as zinc sulphide crystals in the early 1980s, studies began comparing different types of emergency lighting with photoluminescent systems. Comparative studies found that photoluminescent material could provide an acceptable alternative to conventional emergency lighting. Findings also indicated that the material provided a high level of performance when installed in stairwells. It was also found that low-level lighting wayguidance systems performed better than conventional emergency lighting. Studies with smoke concluded that the continuity of information of photoluminescent lines ensured an uninterrupted visual reinforcement, which provided a significant advantage over conventional emergency lighting, which became obscured by the smoke. Other advantages of the material were its easy installation in new or existing buildings, its cost-effectiveness and its low maintenance. Conversely, studies found that the disadvantage with the material was its relatively low visibility.

Only one study has installed the material compliant with one of the several existing standards regulating the material’s usage. Therefore it can be argued that

insufficient research has been conducted to fairly assess the material. Future research on photoluminescent material should consider meeting an actual standard to be more practical and equitable. Also, in most studies, the material was compared to electrically powered lighting to assess visibility. It is argued, that this comparison is not fair as photoluminescent material may not need to be as bright as lit systems to provide appropriate support to evacuating occupants since the principal benefits of this system is to provide continuous wayfinding information along an escape route.

Newer and brighter photoluminescent materials with pigments based on heavy metals such as strontium aluminates have not yet been studied to assess their performance in emergency situations. These new materials have great potential in supporting the safe evacuation of building occupants. It is concluded that there is more research needed on photoluminescent material for use as a safety wayguidance system to properly assess its current stage of technological development.

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1 INTRODUCTION

Photoluminescent material or PLM is made of inorganic chemical compounds, referred to as photoluminescent pigment, encased in a flexible or rigid strata, or diluted in a liquid such as paint [1]. The photoluminescent pigments consist of crystals of aggregated elements and other agents. The crystals are characterized as being photoluminescent due to the excitation they undergo when exposed to a light source and their ability to store light photons, consequently becoming luminescent. After the crystals have been charged by a light source, the light can be cut off, and the crystals will remain excited and continue to emit light. As time progresses, the energy stored in the crystals will continuously exhaust until its complete depletion: the material can be recharged by re-exposing it to light. Certain terms and units are commonly used to characterize the material. Luminance is the luminous intensity or the brightness of a light source. It is measured for photoluminescent material in millicandelas (mcd) per unit area (square feet or square meters). Illuminance is the amount of light that reaches a surface. It is measured in lumens per square foot (foot-candles) or lumens per square meter (lux or lx) [2]. One lumen per square meter is one lx. One lumen per square foot is one foot-candle. A lumen is a unit that measures the number of photons a light source emits. It is the amount of light produced by a light source [3].

Photoluminescent material 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 black-out situations resulting from power failures or fires, photoluminescent safety markings in the form of paint, plastic strips and signs can aid evacuation by guiding and directing people to safer locations; see Figure 1.

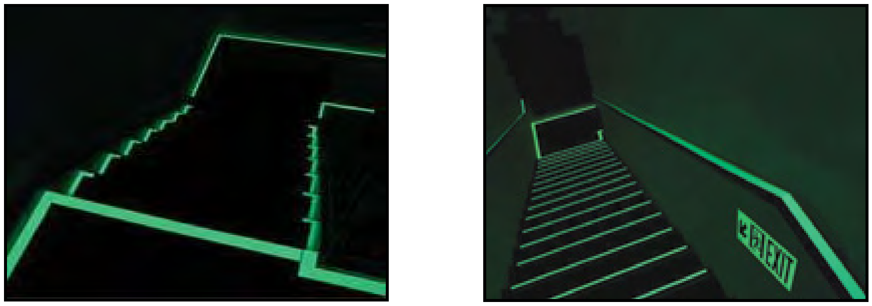

Figure 1: Examples of photoluminescent safety marking in stairwells [4]

Photoluminescent material was first used in remote locations such as offshore platforms and the underground power plant industry. Recently it has been installed in office buildings such as the former World Trade Center towers. It has also recently been implemented in building codes, such as the New York City Building Code [5]. The material will continue to be developed and used. Although international standards exist to regulate the material's usage only a few research projects have studied the performance of PLM.

This literature review, prepared by the National Research Council Canada, looks into empirical studies that have been carried out on the use of photoluminescent material as a safety wayguidance system. Experimental procedures and methodologies are highlighted as well as findings and conclusions obtained in these early studies in order to better understand photoluminescent material and its applications. This will serve as background information to aid and to guide future research into this area.

2 EARLY STUDIES

Initially, German and British scientists researched PLM. In its early stage of development, PLM was made with a phosphorous-based pigment and needed a continuous excitation source to emit light [6].

In 1974, the first regulatory standard for PLM was developed. German norm DIN 67510 specified a test method to evaluate the material's luminance decay [7]. Preliminary studies on PLM were initiated in the middle of the 1970s to present the idea of using photoluminescent safety markings as an aid or an alternative to emergency lighting.

One French study explored different methods of providing evacuation lighting for underground structures [8]. The study was undertaken because underground workers are exposed to high danger. The distance between their worksite and the nearest exit often reaches 1 km. The study presented phosphorent (phosphorous pigment) lighting amongst other suggested types of emergency lighting running on either electricity or radioactive gas to illuminate a 45,000 m^2 underground power plant. The 50 to 200 lumens, the electrical emergency lighting system would produce were regarded as being too low to meet the required illuminance value of 10 to 20 lx. The installation and maintenance of additional lamps to attain this value was considered too costly. The radioactive gas was also considered a potential hazard in case of a lamp break. The study involved 60 glass encased phosphorent arrows 1.25 m in length suspended 5.5 m above floor-level. This seemed a good solution as it was a cheap, instantaneous alternative and less prone to defect compared to conventional emergency lighting. The arrows would have the shape of a pyramid having an equilateral triangle base with sides 0.38 m in length and would point towards the exit. The recommended glass case had two coats of phosphorent paint with the word “Evacuation” painted on it and contained two 110 W light tubes, one tube being connected to local electrical power, the other to a back-up electrical generator. This dual connection would charge the phosphorent pigment with two power sources, making the lighting more reliable. The system would be complemented with 40 other lamps to attain the required illuminance value. The lighting would provide an average illuminance of 9 to 10 lx on a circular surface of 113 m^2. The lighting would provide an illuminance of 14, 11, and 10 lx after 1, 3 and 10 minutes of operation, respectively. After 30 minutes of operation, the illuminance would stabilize to a value of 8 to 9 lx. The study attempted to find an emergency lighting system that was as independent of power sources as possible. However, phosphorous pigments were weak photon absorbers, hence the system would have to be complemented with a continuous light source to emit enough light to meet the required illuminance value of 10 to 20 lx.

3 COMPARATIVE STUDIES

With the advent of stronger pigments such as zinc sulphide crystals in the early 1980s, the need for a continuous power source complementing PLM ended, as it needed to be charged only to emit light. At this point, studies began looking into other properties of PLM, namely luminance to assess whether or not the material could attain emergency lighting illuminance requirements stated in codes and standards. Researchers also initiated studies comparing different types of lighting systems with photoluminescent marking.

Major research contributions came from G. M. B. Webber of the Building Research Establishment in the UK (BRE). In one of his studies published in 1988, he investigated the movement of 84 adult subjects on a simulated emergency escape route under five different lighting conditions [9]. The lighting types included three uniform illuminations: one approximating to, one above, and one below the British standard BS 5266 minimum illuminance requirement of 0.2 lx [10]. The two others were a non-uniform illumination condition and photoluminescent marking. The study took place in a BRE test facility simulating an office building floor. The facility was made up of two sections: an L-shaped corridor and a stairwell. Both were equipped with video cameras to capture subject behaviour. The five lighting conditions were tested individually in each section. The PLM used in the study had a powder-based pigment made of zinc sulphide phosphor with copper and cobalt activating agents. As shown in Figures 2 and 3, photoluminescent paint was used in the corridor along the lower edges of the walls right above where the floor and wall met (skirting board) to highlight the outline of the corridor. Paint was also used on the diagonal lower edge and on the risers of each step. One protective coating was applied on all painted surfaces. Photoluminescent tape was used on the stairwell handrail. Rigid plastic safety signage and exit signs complemented the entire set-up. Exit signs with arrows were placed in the corridor. An exit sign was placed on the exit door. The rigid plastic signs used for the tests were all 150 x 300 mm in size with a green background colour for lettering having a minimum height and width of 80 mm and 12 mm, respectively.

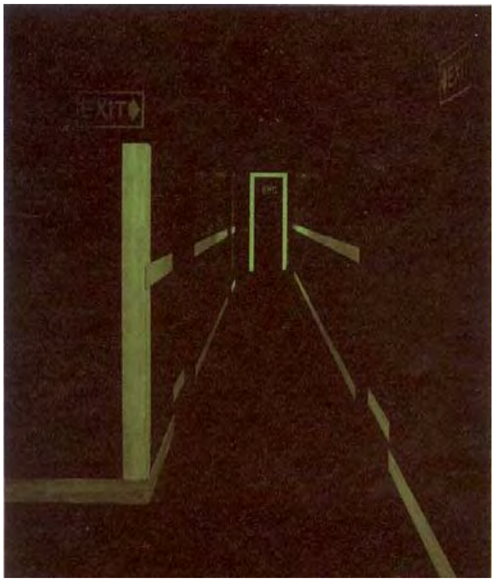

Figure 2: PLM in corridor, BRE study [11]

Figure 3: PLM in stairwell, BRE study [11]

The PLM in the corridor was excited by nine fluorescent lamps. The PLM on the skirting board in the corridor was excited in a separate room by tungsten lamps with diffusers and was then placed in the corridor immediately before the tests. The PLM in the stairwell was excited in a separate room by tungsten lamps and was excited by fluorescent lamps after its installation before each test. Subjects were brought into the test facility through an outside door. A desk was located in an adjacent room designated as the starting point. Subjects were allowed to adapt to normal room lighting at approximately 500 lx for five minutes after which a power failure was simulated. Subjects had to find their way from the desk, go through the L-shaped corridor, turn around and find their way back to the desk. The same adaptation procedure was used in the stairwell as subjects had to perform an ascent and a descent. Each subject was tested individually for all five lighting conditions and for both sections. Their opinions with regards to the five lighting conditions were obtained by means of a questionnaire. In addition, the subjects' mean movement speeds under each lighting condition for each section were compared to get an overall impression of the mean speeds as a function of mean illuminance. From the corridor tests, it was found that speeds under the BS 5266 standard lighting condition of 0.2 lx were found to be quicker. The photoluminescent condition was regarded as being the least favourable in terms of satisfaction. The findings from the stairwell tests showed that speeds for both ascent and descent of the stairwell were quicker for the photoluminescent lighting condition. It was considered less difficult and was regarded as being more favourable in terms of satisfaction by subjects. It was concluded that the British requirement of 0.2 lx was an adequate illumination level for emergency lighting in corridors but that a higher illumination of 1.0 lx would be beneficial and preferred on the stairwell.

Researchers at BRE also carried out their own photometric tests on samples of photoluminescent products exposed to white fluorescent and tungsten lamps. It was found that luminance decreases with time according to a power law and it was suggested that appropriate photometric tests should be developed for measurement and specification of photoluminescent products. The DIN 67510 luminance decay test was judged inappropriate, as it did not use lighting to charge PLM typical of stairwells and corridors [7]. DIN 67510 uses a 1000 lx xenon lamp for five minutes before measuring luminance decay. The PLM used in the study was Hoeschst's Lumilux Green N pigments. Material properties provided by the manufacturer indicated that using a deuterium lamp with a peak output range of 310 and 320 nm as an excitation source, the material would reach a saturated excitation level in about 2 minutes for an excitation of 70 lx and over, and 10 minutes for an excitation of 20 lx. Through photometric tests conducted by the BRE, it was found that using fluorescent lamps to excite PLM resulted in a higher luminance compared to excitation with tungsten lamps (see Figure 4 as an example illustration [11]). It was also observed that a linear relationship exists between the excitation illuminance and the luminance of the material for levels of excitation illuminance above 10 lx. Further, diffusers on excitation sources were found to lower the luminance of PLM. A 40 lx excitation of PLM by tungsten lamps with and without diffusers yielded luminance values of 40 and 58 mcd/m^2 respectively, 1 minute after the light was switched off. For corridors, the recommended minimum level of illuminance by the Chartered Institution of Building Services Engineers (CIBS) code was 100 lx on the floor [12]. This lighting level was simulated in the BRE corridor by tungsten lamps with diffusers. The PLM produced an estimated luminance of 20 mcd/m^2 1 minute after the light was switched off. This value was found to provide adequate cueing for a narrow corridor. The CIBS code required a minimum illuminance of 100 lx in stairwells as well. Using the same excitation source as the one used in the corridor, the PLM produced a luminance of 30 mcd/m^2 1 minute after the light was switched off. This luminance value was also considered adequate to provide cueing for a stairwell. For an excitation of 200 lx by tungsten lamps with diffusers, the photoluminescent exit signs produced an estimated luminance of 40 and 5 mcd/m^2 1 and 10 minutes after the light was switched off, respectively. Observations and suggestions with regards to the use of photoluminescent safety markings were also outlined. The study noted that the effective application of photoluminescent safety markings depends on sufficient provision of visible cueing of the escape route, using at least 80 mm width of material on both risers and treads of stairwells, highlighting handrails, marking obstacles with tape 40 mm in width and using exit signs to distinguish exits from internal doors. Door handles, important switches and panic bolts could also be marked with PLM. In general, the study's findings indicated that PLM could provide an acceptable alternative to the recommendations of BS 5266. The experimental findings showed that people's movement speeds were comparable for all the conditions tested. Findings also indicated that subjects' movement speeds were faster in stairwells illuminated by PLM and that this condition was found to be more satisfactory by subjects. These results indicated that the use of PLM should be considered by designers in the future.

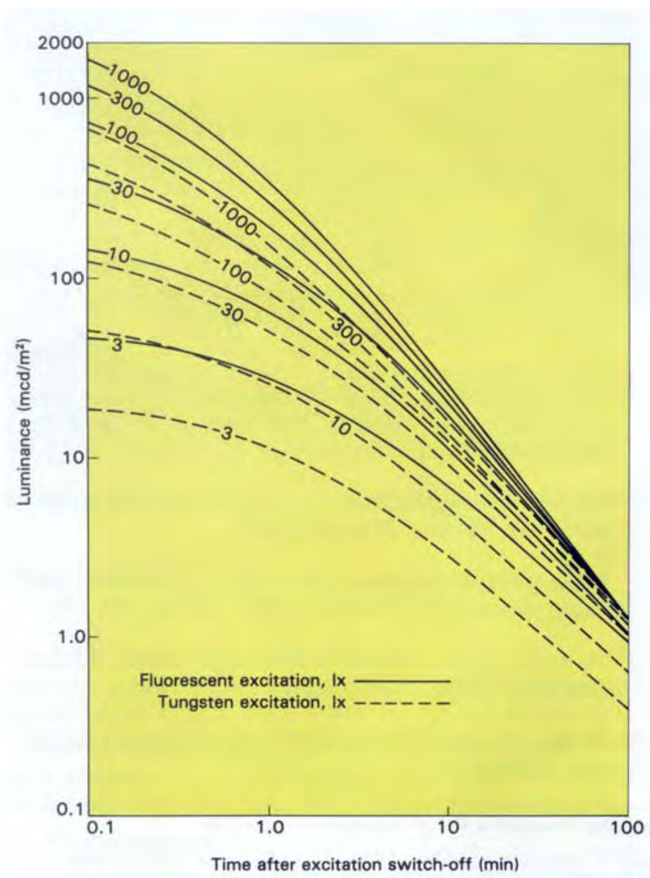

Figure 4: Luminance decay curves, BRE study [11]

BRE conducted another similar study in 1993 [13]. The study evaluated a new approach to emergency lighting based on providing wayfinding information with low level lighting (LLL) wayguidance systems, also referred to as LLL tracks. In addition to directional signage, exit signs, door markings, wall markings and other components that compose a safety wayguidance system, LLL provides information at floor proximity such as luminous lines outlining the lower edge of a corridor at the skirting board level. The impetus behind the development of such systems was the concern regarding evacuation in smoky conditions. LLL tracks are mainly used in building corridors, cinemas and aircrafts. The BRE study tested three systems: the first was a track of electro-luminescent lamps, the second was a track of miniature incandescent tungsten filament lamps (see Figures 5 and 6) and the third system was PLM marking. Conventional emergency lighting compliant with BS 5266 was also tested.

Figure 5: Electroluminescent system, BRE study [14]

Figure 6: Incandescent system, BRE study [14]

These systems were tested in a two-storey BRE test facility in which all windows were blackened out and external doors were light-tight. Within the building there was a simulated emergency escape route consisting of an L-shaped corridor on the ground floor leading to the 1st floor via a stairwell. The test route started on the ground floor, went through the L-shaped corridor, went up to the 1st floor via the stairwell and returned to the beginning of the route. As opposed to the previous BRE study, the escape route included four obstacles: a dummy, a storage bin, a stool and a filing cabinet. Some corridor and stairwell walls were constructed out of perforated screens to position three video cameras using infrared floodlighting behind them to record subject behaviour. Infrared beams were used to capture the subject movement speeds. The photoluminescent system was the same as the one used in the previous BRE study. PLM was mounted at the skirting board level and at a handrail height of 900 mm along the corridor. On the stairwell, the nosings as well as the line at the handrail height on both sides were marked. The lower diagonal line, outlining the slope of the stairwell right above each step, was also marked. PLM 100 mm in width was used to outline the doorway at the beginning of the route and the final exit door. The corridor's corner was marked vertically to avoid having subjects run into it. Generally, the PLM was paint, which was sprayed on surfaces or on mounted wooden boards 100 mm in width. Photoluminescent plastic foil was used on the stair nosing. The material was excited by tungsten lamps with diffusers. The mean excitation illuminance was 64 lx at the floor level in the corridor and 53 lx at the stair nosing level in the stairwell. The PLM used in the study had phosphorous pigments, which could be excited by natural or artificial light at a wavelength of 500 nm or below. Forty-eight subjects were tested individually for all four lighting conditions and were asked to fill out a questionnaire with regards to their performance. The wayguidance systems were considered by the subjects to be much easier to navigate compared to the conventional emergency lighting. Of the LLL systems, the photoluminescent marking provided the least amount of visibility. The PLM used in this study had a weaker phosphorous pigment compared to the zinc sulphide pigment used in the previous study. This could explain why the PLM performed poorly. In terms of the movement speeds in the corridor, all systems including the emergency lighting showed similar patterns. The speeds for the electroluminescent and photoluminescent systems were the slowest of the four. For the stairwell, the incandescent tungsten filament lamp LLL track provided the highest subject movement speed. Similar speeds were observed on the stairwell for the three other conditions. It is also interesting to note that the mean speeds under the PLM system were 20% higher in the corridor compared to the PLM system used in the previous study. The subjects were also asked to identify the locations of any signs they had seen after the tests. Subjects identified the highest percentage of signs, namely an average of 63%, under the photoluminescent marking condition. The study concluded that the use of emergency lighting, as the only design parameter for emergency situations in buildings, is questionable and that LLL wayguidance systems need to be seriously considered by designers.

As the effectiveness of PLM in stairwells became apparent through previous studies, the NRC in collaboration with PWGSC, researched this matter. A study was conducted in 1998 to assess the potential use of PLM as a safety wayguidance system to support office occupant evacuation [15]. An experiment was conducted in a 13-storey office building. The four identical emergency stairwells of the building were equipped with different lighting conditions, as presented in Figure 7. Stairwell A had emergency lighting adjusted to 57 lx to obtain an output above the Canadian Occupational Safety and Health (COSH) requirement of 10 lx and not less than 3.3 lx [16]. Stairwell B was the control stairwell having full emergency lighting at 245 lx. Stairwell C had no lighting while Stairwell D had emergency lighting reduced to 74 lx. Stairwells C and D were equipped with photoluminescent safety wayguidance systems installed compliant with the Photoluminescent Safety Products Association (PSPA) standard 002 Part1 1997 [17].

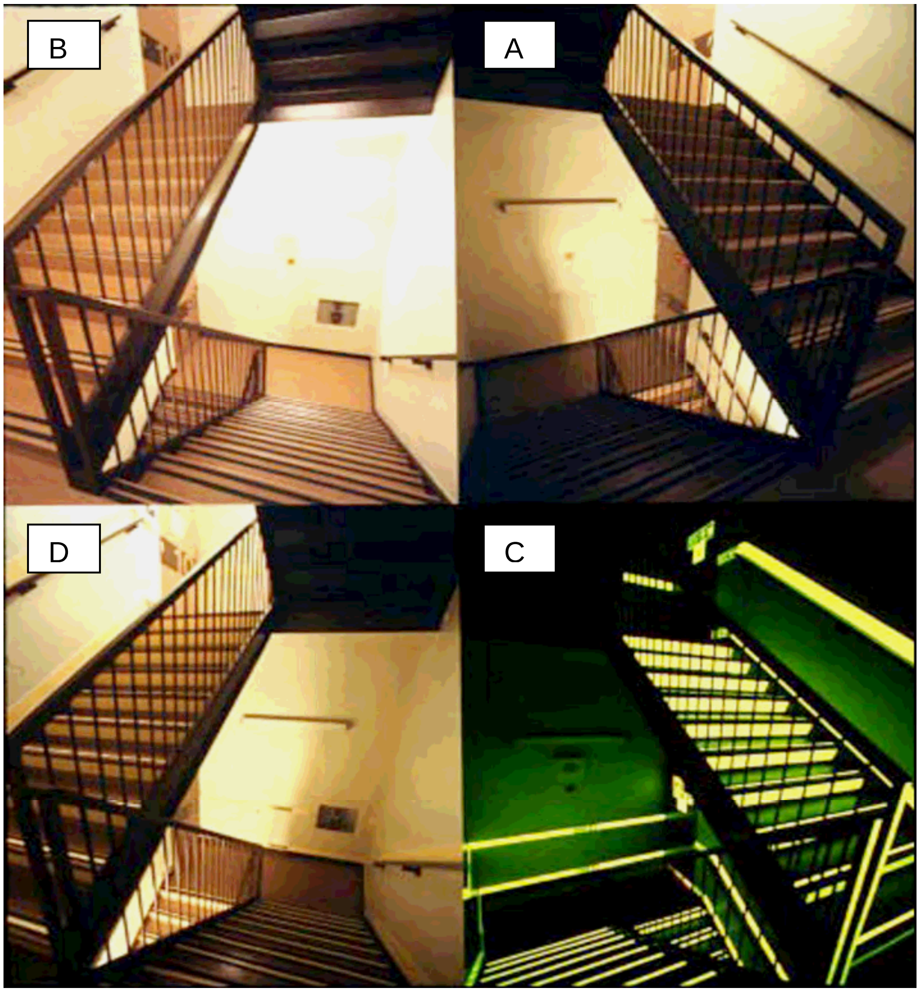

Figure 7: Four experimental stairwells, NRC-PWGSC study [15]

The two stairwells with PLM (C and D) were equipped with two continuous wayguidance lines of 100 mm in width: one line was at the skirting board and the other 1 m from the floor. Directional signs were enclosed within these continuous lines. A 20 mm strip of PLM was fixed on the tread of each step and a 100 mm piece was positioned on 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. In addition, directional signs were also placed at each decision point, each door and at mid-landing at 1.7 m from the floor. These signs presented the “running man” pictogram, which is an ISO standard [18].

The PLM used in the study was made of zinc sulphide pigments; it was provided by Jalite PLC UK. The PLM went through photometric tests before and after its shipment from the UK and after its installation in the test building for luminance at 2, 10, 30 and 60 minutes after lights off. An excitation illuminance of 1000 lx for 5 minutes according to DIN 67510 was used to assess the material's luminance decay before and after its shipment. After installation, an excitation illuminance of 50 lx by cool white fluorescent light was used to assess this property. The following Table 1, indicates that there was no observed change in the material's properties for the 3 tests after elapsed times of 10, 30 and 60 minutes.

Table 1: Material Luminance in mcd/m^2, NRC-PWGSC study [15]

Test Date	Elapsed Time in min			
	2	10	30	60
Before shipment, March 1997	142	26.7	8.1	3.6
After shipment, Dec. 1998	143	27.1	8	3.6
After installation, Dec. 1998	89.1	21.7	7	3.2

Cameras were used to gather behavioural and time data. Infrared cameras were used in both stairwells having the PLM marking. An unannounced evacuation drill was carried out on Floors 9, 10 and 11 of the building. A questionnaire was distributed to the 500 evacuees after their evacuation. Results from the questionnaire indicated positive results for the use of PLM in stairwells. The majority of evacuees (70%) who descended the PLM equipped stairwells judged the lighting quality as very good or acceptable. These results indicated that most people consider it perfectly acceptable to evacuate down a stairwell with the only lighting being provided by a photoluminescent safety wayguidance system meeting a specific standard. From the video recordings, the results showed that irrespective of the lighting condition tested, speeds of movement measured for the four stairwells were similar. The stairwell equipped with the photoluminescent safety wayguidance system only had the slowest speed of movement of 0.57 m/s; this stairwell also had the largest crowd, the highest density and disruption due to the upward movement of 3 firefighters who participated to slow down the descending occupants. The stairwell with the full lighting was the second slowest at 0.61 m/s; it was the second most crowded of the four stairwells. Evacuations in the two stairwells with reduced emergency lighting were faster with 0.70 m/s and 0.72 m/s for the one with PLM and reduced lighting. These stairwells had the fastest overall speed as well as the lowest density. To further explore the speed movement in relation to the density of occupants on the stairs, the expected speed of movement was calculated using Pauls equation [19] $s = 1.08 - 0.29d$, where s is the speed of movement in m/s an d is the density in p/m^2. Results of the calculated speed of movement are presented in Table 2. The calculated speeds of movement are slightly higher than the observed speeds for stairwells A, B and D. For stairwell C, the calculated speed is lower then the observed speed. The study concluded that the decrease in speed of movement is correlated to the increase in crowd and density of the occupants rather than the lighting conditions.

Table 2: Speed and density in the four stairwells, NRC-PWGSC study [15]

Stairwell	Density p/m^2	Observed Mean Speed m/s	Calculated Speed m/s
A	1.25	0.70	0.72
B	1.30	0.61	0.70
C	2.05	0.57	0.49
D	1.00	0.72	0.79

To further explain the occupant speed of movement in the stairwells, it was suggested that the occupants were probably experiencing PLM marking for the first time. Education and training with such systems, in particular evacuation drills carried out under such conditions, would remove the normal reaction to the unknown. It was also concluded that the luminance of the PLM components should be increased. It was pointed out that the luminance properties of the PLM used was not the highest that may have been technically achievable. At the time of the experiment in 1998, Jalite PLC UK, as well as some other manufacturers, were producing PLM having brightness levels up to 5 times greater than the tested material. However, the brighter material was not used since the project was started in 1997 with the old product. It is expected that a brighter product would satisfy some of the criticisms obtained. It was also stated that the amount of material installed could be increased. In an attempt to maintain the amount of material to the minimum required under the PSPA standard, the quantity of material used might have been too little for the location. An immediate improvement could be to install wayguidance lines on both sides of the stairs instead of just the wall side. Several evacuees wrote on their questionnaire that they had difficulty finding the handrail; others complained that the last step to the landing was not identified with PLM. Handrails on both sides, as suggested by previous studies, could have been marked. The landing and mid-landing could have also been identified. The study finally emphasized the potential of PLM to support occupant evacuation. The material properly installed can address deficiencies in the traditional approach to emergency lighting associated with power failure or smoke-logging of high-mounted luminaires. The installation of a PLM wayguidance system appeared to be a cost-effective addition or even a potential replacement for traditional electrical emergency lighting since it does not consume energy, requires no wiring, needs minimum maintenance and is reliable.

The methodology of this study was different from that of previous studies as it used a natural setting and a large number of evacuees. The test facility and the unannounced evacuation drill better simulated a real emergency. In addition, the photoluminescent wayguidance systems were installed compliant to an actual installation standard, which had not been done in previous studies.

4 STUDIES WITH SMOKE

Researchers also focused on assessing PLM in more challenging situations, particularly its performance in smoke. An apparent name in such studies is that of Geir Jensen's from the Norwegian InterConsult Group. His extensive study “Evacuating in Smoke” consisted of four reports [20]. The first report is a literature review on safe evacuation in smoke. The second is a full-scale test series and the third discusses decisive factors in safe escape from smoke. The fourth report presents a method of calculating visibility in smoke. The full-scale test series report evaluated the performance of seven types of safety wayguidance systems in two optical densities of smoke, namely 1.0 m^{-1} and 1.5 m^{-1}. The systems included: three different arrangements of photoluminescent wayguidance systems, two continuous electrically powered LLL tracks, and one semi-continuous “distinct green” cold cathode tube light fixture LLL track. The seventh system was conventional emergency lighting. The PLM used was made of zinc sulphide pigments. The first arrangement of PLM consisted of strips of PLM forming a continuous line 114 mm in width installed at the skirting board level and around the doorframes. The second was strips of PLM forming a continuous line glued to the floor at the center of the path. Both set-ups had directional arrows on their strips. Distances to exits were also printed on these strips. The third set-up consisted of strips of PLM forming a continuous line 25 mm in width imbedded in a mechanically-mounted directional rail, which outlined the surface of the wall at a height of 750 mm from the floor. The flat surface of the handrail containing the photoluminescent strip was tilted at an angle of 60º away from the wall to direct it towards the evacuee.

In a test facility, 84 subjects, including six blind persons, were asked to find their way from a starting room to an exit using whatever means of information they could find. The escape route was 48 m in length. Fourteen tests were conducted having six subjects each to evaluate all systems. Video cameras were used to capture movement speeds. In addition, equipment to measure illuminance and smoke density was used. As opposed to a questionnaire, a jury of safety officials attended the tests to make observations and to assess the performance of each system. Extensive tests were carried out to draw a correlation between visibility and smoke. Numerous conclusions regarding visibility, tenability and survivability in smoke were drawn.

It was observed that non-electrically powered wayguidance systems perform highly in guiding people through smoke. The best system in terms of visibility was found to be the “distinct green” cold cathode tube light fixture LLL track. Subjects using this system made the least amount of erroneous moves and had the highest movement speeds. It was found that PLM was visible in high smoke densities, however printed information on photoluminescent signage such as exit signs and arrows was difficult to read in such conditions. Viewing distance, not luminance, was found to be the crucial factor in high smoke densities. This is due to the fact that the luminance of any type of lighting eventually becomes zero at 100% smoke obscuration. It was found that a strip of PLM at a distance of 0.5 m from the eye is more visible than the most powerful luminaires at 1.5 m away from the eye. It was also found that conventional emergency lighting produces scatter in high smoke densities. The higher luminance provided by powered systems compared to the non-powered ones such as photoluminescent systems was marginal in high smoke densities. Thus, it was suggested that the increase maintenance and installation costs of powered systems were not justified. The photoluminescent systems were found to be more reliable in terms of providing visual information, as they were continuous, providing guidance all along the escape route and at a closer proximity to the evacuee. This was regarded as being essential in smoky conditions since evacuees usually crouch down or crawl to avoid inhaling smoke higher above them. It was recommended that photoluminescent markings should be placed at a low location, below 1000 mm from the floor. An optimum system would be one that has continuous markings at waist height, at the skirting board level and along the centerline of the escape path. It was also found that photoluminescent continuous markings have a distinct advantage over conventional emergency lighting, which offers spaced point sources of light. It was emphasized that lighting systems were not intended for use in smoke. Conventional emergency lighting was useful for optical smoke densities of less than 0.1 m^{-1}, however, at higher smoke densities, when viewing distance became a prevailing factor for visibility, the point sources needed to be more closely spaced. It was concluded that photoluminescent wayguidance systems have a potent advantage over powered lighting systems in terms of visibility in smoke, reliability, simplicity in installation and maintenance, long operational hours (exceeding 8 hours for this study) and cost-effectiveness.

Webber also conducted studies on wayguidance systems in smoke. In 1993 and 1994, Aizlewood and Webber carried out two similar studies testing a newly-developed methodology by BRE for evaluating the performance of such systems and their components in smoke [21, 22]. One of the aims of the studies was to examine the effects of viewing distance and viewing angle over a range of smoke densities. The two studies together tested 10 wayguidance systems at the BRE Emergency Lighting test facility; see examples in Figures 8, 9 and 10. The systems included:

- one photoluminescent LLL system consisting of an exit sign mounted at a height of 1150 mm on the door, doorframe with markings 50 mm in width and a wall track 100 mm in width mounted at the skirting board level in the corridor (excited by tungsten lamps for at least 5 minutes prior to each test);
- two different types of exit signs operated by fluorescent lamps;
- one electroluminescent LLL system consisting of an exit sign, doorframe and wall track, see Figure 8;
- one incandescent miniature tungsten filament lamp operated LLL system consisting of a doorframe and wall track, see Figure 9;

- three different arrangements of light emitting diode (LED) LLL systems each consisting of an exit sign, doorframe and wall track, see Figure 10;
- one gaseous tritium light LLL system consisting of an exit sign, doorframe and wall track;
- one un-operated LED system consisting of an exit sign and directional signage reflecting emergency lighting.

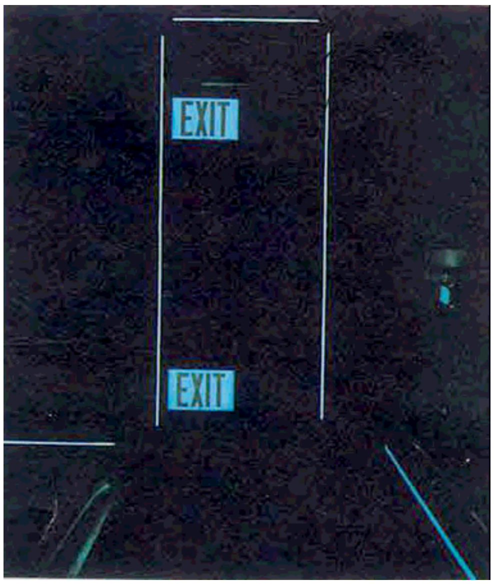

Figure 8: Electroluminescent system, BRE study [23]

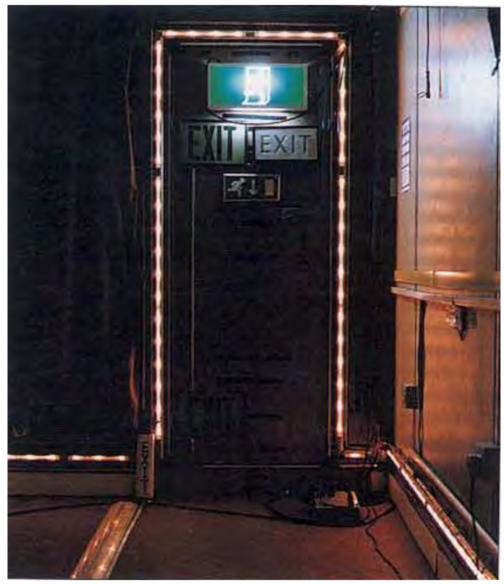

Figure 9: Incandescent system, BRE study [23]

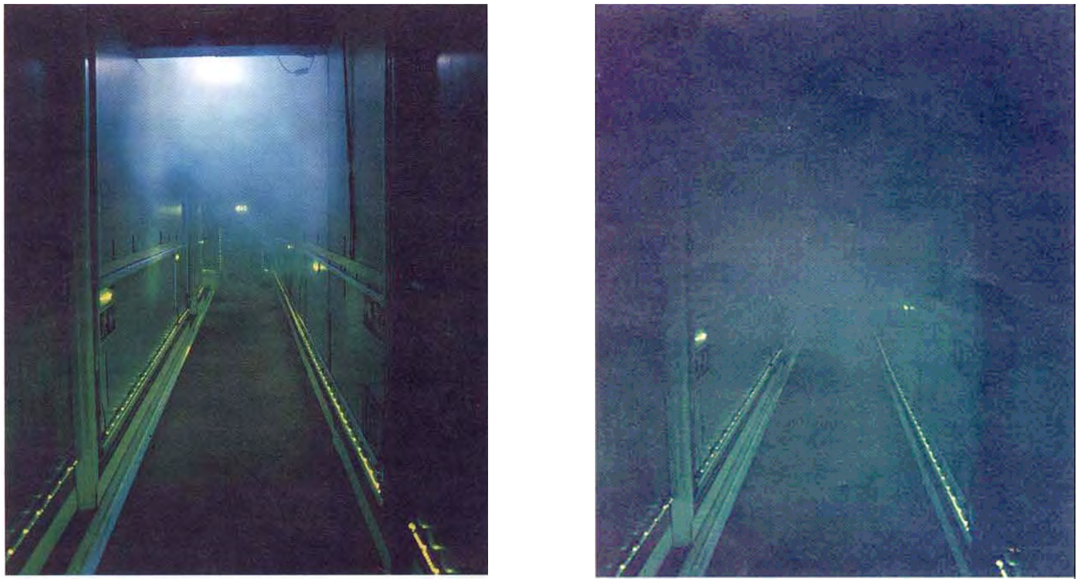

Figure 10: LED system progressively obscured by simulated smoke, BRE study [24]

The PLM pigments were made of zinc sulphide phosphors. The exit sign was excited by 150 lx tungsten lamps with diffusers. The doorframe and the wall track were excited by the same source at an excitation illuminance of 210 lx and 40 lx, respectively. The exit sign and the doorframe had a luminance of 42 mcd/m^2 and 17 mcd/m^2 respectively, 1 minute after the light was switched-off.

The methodology used for both studies was to run a series of tests each at a different smoke density. Each series consisted of several runs and each run consisted of around a dozen observations. The tests were conducted in a corridor ending with a door marked by an exit sign. One subject was tested at a time in different ranges of smoke densities all greater than 0.18 m^{-1} and at different viewing distances from the door with a maximum distance of 13.7 m. At the beginning of each test, the subject was allowed to adapt to an illumination of 2 lx outside the test corridor. After which the subject was moved into the corridor illuminated by one of the tested systems. The subject had to move forward in the smoke filled corridor until the exit sign placed at the end of the corridor was visible. This position was marked. The observer then had to move to a second position where the exit sign was readable. This position was also marked.

It was observed that the exit signs and doorframes of LLL systems were generally visible from a greater distance in smoke compared to the wall tracks. The LED LLL systems were the most visible, with the un-operated LED system having the lowest distance for recognition. The results of these studies showed that electrically powered wayfinding components had a higher visibility performance in smoke than photoluminescent components. However, with no other lights on, the PLM was perceived in smoke after elapsed times of more than 15 minutes.

It was also observed that point light sources such as the LED systems were more visible than planar light sources such as the photoluminescent and electroluminescent systems. Further, the presence of other lighting such as conventional emergency lighting reduced contrast by producing scatter, consequently making it harder to distinguish escape route elements. It was finally concluded that electrically powered wayguidance systems were more visible in smoke than conventional emergency lighting.

5 SPECIAL CASE STUDIES

Other studies focused on PLM for situations that are more particular. Webber alongside other researchers initiated an ongoing five-phase study in 1996 looking into safety wayguidance systems for the visually impaired. Preliminary findings have been published [25, 26, 27]. The final phase of the study will offer design guidance for systems intended for the visually impaired to those involved in the development of standards [28]. The test facility and the methodology used were the same as the ones used for Webber's previously discussed study "Escape route lighting: comparison of human performance with traditional lighting and wayguidance systems, 1993." The only difference was that the subjects were partially sighted. The six different lighting systems tested were: a zinc sulphide based photoluminescent wayguidance system, conventional emergency lighting, normal lighting at 70 lx, an electroluminescent wayguidance system, an LED wayguidance system and an incandescent miniature tungsten filament lamp operated wayguidance system.

In the corridor, the photoluminescent wayguidance system consisted of 100 mm wide continuous lines placed at the skirting board level fixed on both sides of the corridor and strips 50 mm wide placed on the walls at a height of 1000 mm above floor level.

Doorframe markings were 15 mm in width. In the stairwell, 80 mm wide strips were placed at the stair nosing, with a diagonal strip on the wall adjacent to the stairwell 10 mm above the nosing. The handrail had a 35 mm strip of material.

A similarity between the mean walking speeds for all six lighting conditions was observed. It was found that movement speeds are slowest with the photoluminescent wayguidance system. In addition, the subjects ranked this system as the most unsatisfactory. Normal lighting was ranked the most satisfactory. Thus, it was concluded that luminance plays an important role with the visually impaired.

Most studies discussed thus far have looked into PLM applications for buildings. Although the material was initially intended and used for remote structures such as offshore platforms and the underground power plant industry, few studies have looked into this matter. Webber reviewed the use of wayguidance systems on offshore platforms [29]. His report presented different types of wayguidance systems including photoluminescent ones for use on oil platforms. It also discussed existing standards and codes relevant to the installation of such systems and made recommendations based on previous research findings particularly studies involving smoke. Consistent with the findings from his previous studies in smoke, Webber emphasized that electrically-powered wayguidance systems are more visible in a given density of smoke compared to non-electrically powered systems. In cases where non-electrical systems were to be used, technical recommendations such as installation guidelines were presented. With regards to PLM, it was suggested that the door frames of emergency doors should be marked with material at least 50 mm wide. Locations of firefighting and safety equipment could also be marked. It was also stated that the PLM used should not increase flame spread, thus the material should not be flammable. Further, the PLM should be tested against ultra-violet radiation, humidity and salt spray, and the results should be documented. Finally, it was proposed that the photometric performance of the installed PLM should be checked annually by conducting brightness and luminance decay tests.

Transport Canada published in 1999 a document for the evaluation of photoluminescent wayguidance systems for aircrafts [30]. The document pointed out important aspects of Advisory Circular 25.812-2, the standard for the installation of PLM safety markings on aircrafts [31]. It also makes installation recommendations to complement the standard. It suggests that photoluminescent floor markings outlining both sides of the aircraft aisle should be continuous and should be combined with battery powered exit markers. The review emphasized that PLM using strontium aluminates, although it takes slightly longer to charge, provides a much longer luminance time.

6 FEATURES AND APPLICATION EXAMPLES OF PLM

Some articles on PLM, found in fire-safety and fire protection engineering journals, present the material's features and its applications with examples.

Examples of its features are the material's non-toxic and non-radioactive properties, its easy installation for new and existing facilities, its cost-effectiveness, and its low maintenance. The material is almost maintenance free once installed [32, 33, 34]. PLM activates automatically after the light is switched off and does not depend on power sources to function as opposed to conventional emergency lighting, which runs on electrical power and back-up batteries. Traditional emergency lighting entails high maintenance costs, as it needs to be routinely checked, particularly generators for emergency power supply need to be verified. Alternatively, for battery-operated systems, batteries need to be drained, charged or replaced [34]. Thus, back-up emergency lighting systems for buildings are relatively more expensive, require more maintenance and are more complicated to install and upgrade compared to photoluminescent safety wayguidance systems. PLM has an advantage in smoky conditions also. In a smoke-filled building, people tend to crouch down or crawl to evacuate. Photoluminescent wayguidance systems provide low level marking in the form of continuous lines. These lines help evacuation by providing continuous information along an escape route. The continuity of information of photoluminescent marking ensures an uninterrupted visual enforcement and is a significant advantage over conventional emergency lighting, during power failure or when an escape route is obscured by smoke. PLM markings can also guide firefighters in a burning building and help them identify firefighting equipment inside the building [34].

Several articles present examples of PLM use in structures. PLM is well used in the underground power plant industry. For example, in Europe, most of Norway's 863 hydro power plants are equipped with photoluminescent safety markings. In an underground power plant fire in Sweden, two survivors reported that photoluminescent lines saved their lives [35]. Norway's Gardermoen airport is also equipped with photoluminescent markings in its underground areas, train terminal and tunnels [35]. In Australia, New Zealand and the United States photoluminescent markings have been installed in arenas, theatres and office buildings [36]. After the World Trade Center bombing in 1993, a photoluminescent safety wayguidance system was installed in over 110-storey high stairwells. Photoluminescent paint was used to highlight the location of stairwell treads, landings, handrails and exit doors. A survivor of the 2001 World Trade Center attacks reported that PLM provided continuous guidance and reassurance that the stairwell was leading to an exit [36]. In addition, the NIST investigation into the World Trade Center attacks found that 33% of WTC 1 and 17% of WTC 2 survivors reported that the photoluminescent markings helped them evacuate the building [37]. The material has been installed in the neighbouring buildings to the WTC such as Nasdaq, Merchant and the Rockefeller Center [38]. In 2004, installation of photoluminescent material became a requirement of the New York City building code. NYC Standard 6-1 requires that all new or existing office buildings taller than 75 feet must have photoluminescent markings on exit doors and in emergency stairwells [5].

With the recent advent of earth-borne pigments made of heavy metals such as strontium aluminates, it has been found, by PLM manufacturers and researchers alike, that these new pigments provide an even stronger luminance for a longer period. Jensen's article pointed out that new PLM based on earth borne pigments offers a higher margin of safety [39]. New PLM outperforms conventional zinc sulphide PLM significantly by providing luminance for up to three days compared to 5 to 10 hours attained by the old material. Due to its recent introduction, the new PLM, although tested in laboratories to determine its properties, has not been the subject of studies assessing its performance with occupants.

7 DISCUSSION & CONCLUSION

Like any other practical technology, photoluminescent material was created by a necessity. It was initially used by industries operating in remote locations and working in dangerous situations such as mines, industrial factories and oil platforms; places where power could fail and workers could have difficulty finding an exit or an area of safety.

Studies and articles on PLM have provided an understanding of the material's advantages and disadvantages. The material's advantages are its easy installation, its cost-effectiveness and its low maintenance. It does not rely on power sources, thus the material is relatively fail-safe and can entail energy savings compared to conventional emergency lighting. In addition, photoluminescent wayguidance systems provide low level marking in the form of continuous lines. These lines help evacuation by providing continuous information along an escape route in any condition. The continuity of information of photoluminescent lines ensures an uninterrupted visual enforcement, which is a substantial advantage over conventional emergency lighting. In smoke conditions, PLM installed low as a continuous line can provide better guidance then emergency lighting, which are usually located high up near the ceiling.

In the studies consulted, the main disadvantage of PLM was its low luminance. Jensen's studies found that PLM needed improvement, namely a higher level of luminance. Webber's work demonstrated that PLM in stairwells led to efficient movement speed although the subjects tended to judge the system not bright enough. Webber's and Aizlewood's work showed that LLL wayguidance systems were more effective in smoke compared to conventional emergency lighting. However, it was again found that the photoluminescent system used provided the least amount of visibility amongst the systems tested. Conversely, the NRC-PWGSC study showed comparative speed of movement under different test conditions although it was suggested that more material and brighter material would improve comfort and performance of evacuating occupants. More research needs to be conducted to assess the performance of the new generation of PLM, which offers brighter output for a longer duration.

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