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A Study on the Solar Illumination Provided by a Water Bottle

Tejit V. Pabari

Student, The Doon School
E-mail: 272@doonschool.com

Abstract—*This paper provides experimental evidence to show that the "Litre of Light" (LOL) bottle is a better option than a glass plate covering the hole in the ceiling for providing sufficient illumination during daytime in congested settlements with insufficient illumination (slums). To model the room, a 70cm x 70 cm x 70 cm wooden box was constructed, and a 2liter coke bottle filled with drinking water was fixed to the roof of the box with 1/3rd of the bottle outside the box. The illuminance profile of the box floor was measured using a light sensor for different positions of the Sun in the sky from sunrise to sunset (by covering the roof hole first with LOL bottle, and then with glass plate). It was found that less than 0.7% of incident illuminance reaches the box floor after passing through the LOL bottle and less than 1.2% after passing through the glass plate. The LOL bottle was found to provide sufficient illumination for reading over a larger area of the room for a longer part of the day than a glass plate, in spite of the fact that the loss in illuminance when direct sunlight passes through a glass plate or a LOL bottle is very high. The peak intensity region was found to lie on diametrically opposite corners of the floor as compared to that found with a glass plate. This indicates the possibility of total internal reflection happening inside the LOL bottle.*

1. INTRODUCTION

Liter of Light (LOL) [2-14] is an initiative designed to provide cheap daytime lighting in congested settlements (slums) suffering from insufficient illumination due to the absence of windows.

Fig. 1: Liter of Light Bottle top view [1]

They do so by the use of a plastic bottle filled with water. This paper proves that the concept of using a water-filled plastic bottle as a substitute for a light bulb during daytime is feasible, and efficient enough to allow a person to read (illuminance > 10 lux) at a distance of 2 m from the LOL bottle for the major part of the day.

Before taking up this idea seriously and implementing it on a large scale, it is necessary to have a better understanding of the processes taking place inside the LOL bottle and explore ways of maximizing the efficiency of the LOL bottle in terms of increasing its illuminance over a larger floor area for a greater part of the day.

Existing literature on this topic [15-17] propose that the dominant processes taking place inside the LOL bottle are just reflection and refraction of light happening at the air-plastic, plastic-water, water-plastic, and plastic-air interfaces, which cause the light to spread out more inside the room as compared to just a hole in the roof, where the light would be concentrated in a smaller area like a spotlight.

Fig. 2: Liter of Light Bottle bottom view [1]

So the purpose of the LOL bottle is to channel more light into the room than is possible with just a plain glass plate covering the hole inthe roof, andto scatter the lightenteringthe room so as to cover a larger area of the room. This paper demonstrates how effective the LOL bottle is in meeting these objectives.

2. METHOD

A wooden box of dimensions 70cm×70cm×70cm was constructed. A hole of the bottle's diameter (11.00 cm) was made on one side (the roof) of the box. On the opposite side

(floor) 49 holes – 7 holes × 7 holes, equi-spaced – were made, of the diameter of the light sensor (1.46 cm). These holes were labeled according to Cartesian coordinates, with the center hole being (0, 0). The box was supported on the four corners by four stools, such

that a person could go under it and measure the illuminance reaching the floor of the box by inserting a light sensor(Vernier) through the holes. The experiment was conducted on a roof. The time was recorded at the start and end of each set of measurements, which consisted of measuring the illuminance profile of the box floor, first with a glass plate covering the hole, and then with a 2 litre coke bottle filled with pure drinking water with its top one-third protruding out of the hole. Thus, the illuminance profile of the box floor was recorded at 11:35 am, 1:29 pm, 2:25 pm, 3:56 pm, 4:53 pm, and 5:40 pm on the 15th of May, 2016, at Dehradun, India, for the hole in the roof covered by a glass plate and the LOL bottle. The maximum incident illuminance of sunlight reaching the surface of the glass plate or the LOL bottle was recorded before each measurement, by pointing the light sensor directly towards the Sun. The angle of sun rays with the horizontal was also recorded at the time of each measurement, by using a pin on a glue stick as a sundial. This setup was placed on a graph sheet, and the length of the shadow was calculated by Pythagoras theorem. Using the height of the sundial and the length of the shadow, the angle of the Sun's rays with the horizontal was calculated. Finally, the illuminance profile obtained from the box floor, for different times of the day, was extrapolated to a room of dimensions 2 m x 2 m x 2m, by using the fact that the illuminance decreases as 1/r2 with increasing distance (r) from the light source (LOL bottle). The sealed wooden box ensured that no ambient light entered the box. The gaps between the bottle surface and the edges of the hole in the roof of the box were sealed with clay to make it light-proof. A new, clear, scratch- free coke bottle filled with RO purified drinking water was used for the experiment. The glass plate used in the experiment was clean and scratch-free. All measurements were taken under direct sunlight and clear skies.

Results and Discussion

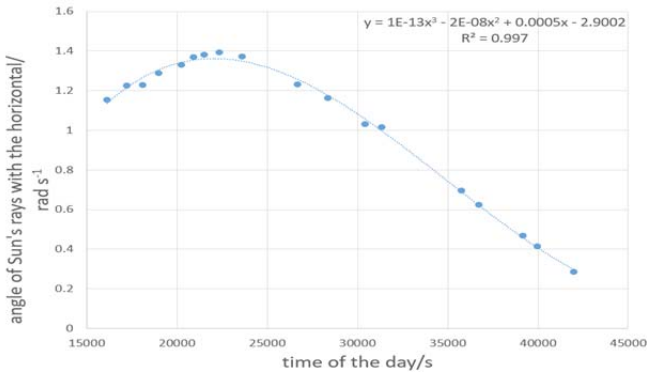

Fig. 3: Angle of the Sun's rays with the horizontal vs time of the day (6 am = 0 s)

The angle of the sun's rays with horizontal as a function of the time of day was obtained (Fig. 3)by analyzing the shadows of the sundial. Using this graph, we can predict the angle of the Sun's rays with the horizontal at any time of the day. The time of day in seconds was calculated by taking 6 am as 0 s. Notice that the peak of the best fit is at 1.4 radians ~ 80° - an indication that Dehradun, is not near the equator.

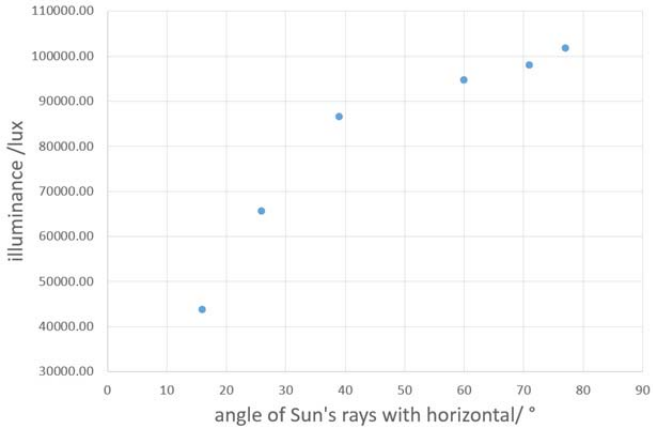

Fig. 4: Maximum illuminance incident over the bottle profile vs angle of Sun's rays with horizontal

Fig. 4: shows that the incident illluminance on the bottle surface is maximum when the Sun's position in the sky is closest to the vertical (80°) and minimum when the Sun is closest to the horizontal.

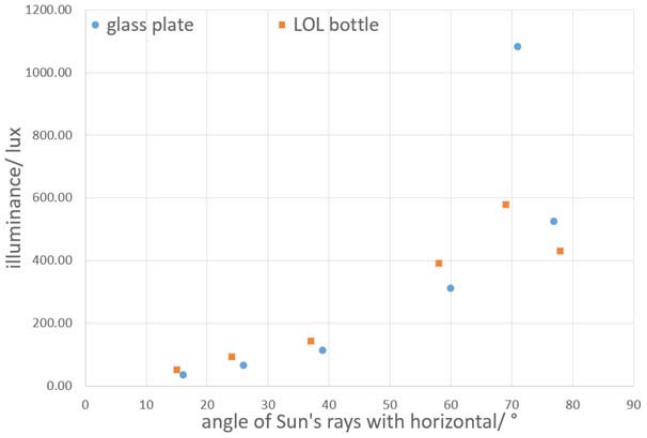

Fig. 5: Comparing the average illuminance reaching the box floor after passing through glass plate and LOL bottle for different angles of Sun's rays with the horizontal

The average illuminance reaching the box floor increases as the Sun rises in the sky as expected, but there is an anomalous data point at 1:29 pm corresponding to the angle of Sun's rays with horizontal being 71°

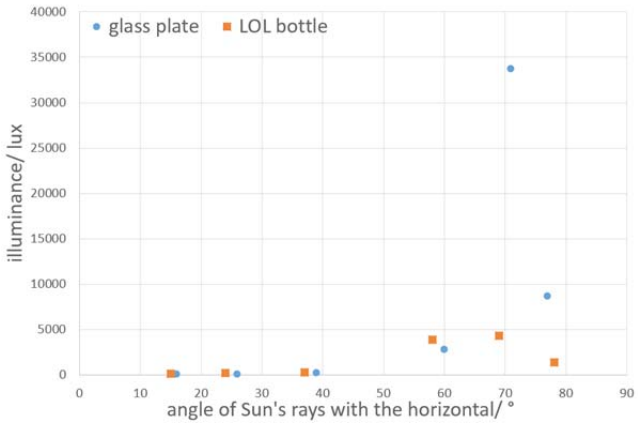

Fig. 6: Comparing the maximum illuminance reaching the box floor after passing through glass plate and LOL bottle for different angles of Sun's rays with the horizontal

The average illuminance and maximum illuminance reaching the box floor through both glass plate and LOL at 1:29 pm (when the Sun's position makes an angle of 71° with the horizontal) is much greater than the values for the bigger angle of 77°. This is puzzling because steeper the angle, more light should be able to enter the box and reach the floor. This anomaly cannot be attributed to sudden unusually clear skies or solar flares because the incident illuminance at the glass plate and bottle surface is showing the normal trend of increasing with increase in angle of Sun's rays with horizontal. So efficiency of transmission of illuminance (illuminance reaching the box floor/incident illuminance on bottle profile) is unusually high at this anomalous point (71°) for both glass plate and LOL. This measurement must be repeated to find an explanation for this anomaly.

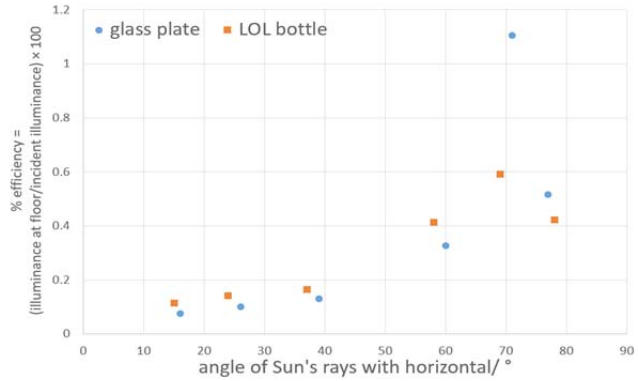

Fig. 7. Comparing the % efficiency of the average illuminance reaching the box floor after passing through glass plate and LOL bottle for different angles of Sun's rays with the horizontal

When the Sun's position in the sky is lower than 63° with the horizontal, most of the sunlight entering the box hits the wall of the box instead of the floor. Hence, though both glass plate and LOL bottle show a decrease in % efficiency as the Sun moves lower in the sky, the LOL bottle's % efficiency gets better than that of the glass plate. This is because while most of the incident light is lost to the wall and doesn't reach the floor in the case of the glass plate, the LOL bottle scatters more light onto the box floor. The Illuminance profile of the box floor obtained with the roof hole covered with glass plate, and the LOL bottle at different times of the day are shown below:

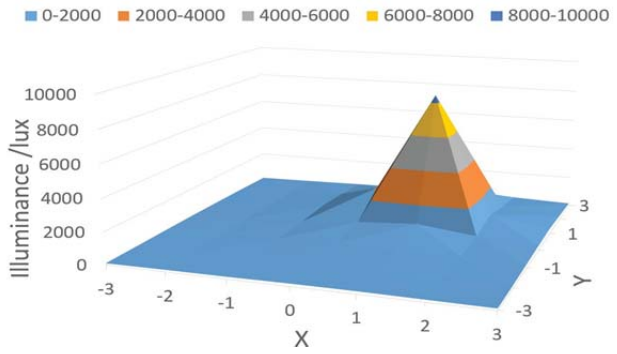

Fig. 8.1a. Illuminance profile of box floor for glass plate from 11:35 am to 11:48 am (Sun at 77° with horizontal)

Peak illuminance is at the rear right of the box floor.

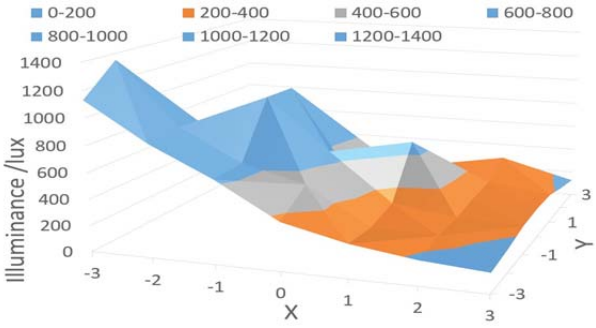

Fig. 8.1b. Illuminance profile of box floor for LOL bottle from 11:56 am to 12:08 pm (Sun at 77° with horizontal)

Whenthe glass plate was replaced with LOLbottle, the peak illuminance position shifted to the front left corner of the box.

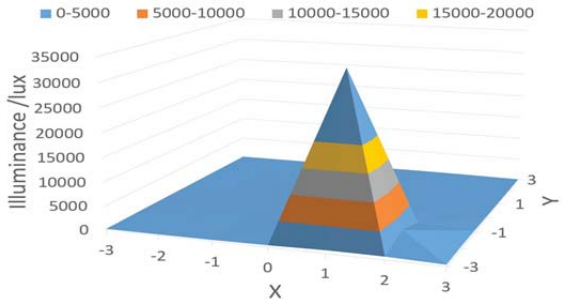

Fig. 8.2a: Illuminance profile of box floor for glass plate from 1:29 pm to 1:39 pm (Sun at 71° with horizontal)

With the change in the position of the Sun in the sky, the peak illuminance position for glass plate has now shifted to front right of the box floor.

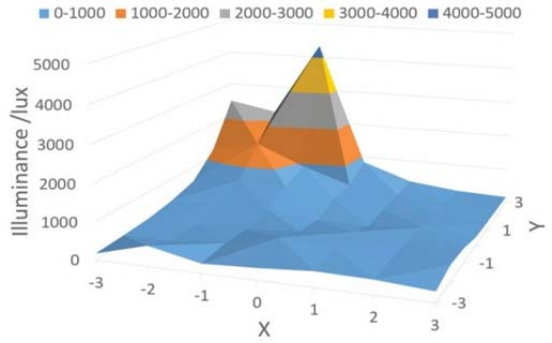

Fig. 8.2b. Illuminance profile of box floor for LOL bottle from 1:41 pm to 1:51 pm (Sun at 71° with horizontal)

With LOL bottle, again the peak illuminance position has shifted to the diametrically opposite corner of the box floor - rear left corner.

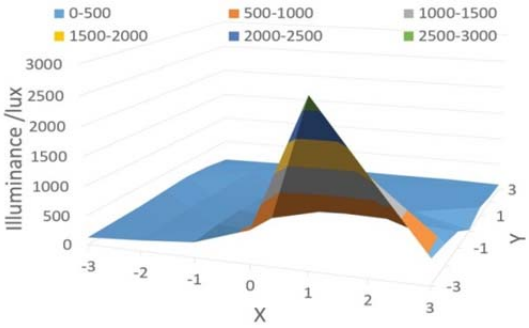

Fig. 8.3a. Illuminance profile of box floor for glass plate from 2:25 pm to 2:32 pm (Sun at 60° with horizontal)

As the Sun moved lower in the sky, the sunlight entering the box through the glass plate, hit the wall and hence the peak illuminance on the floor has decreased.

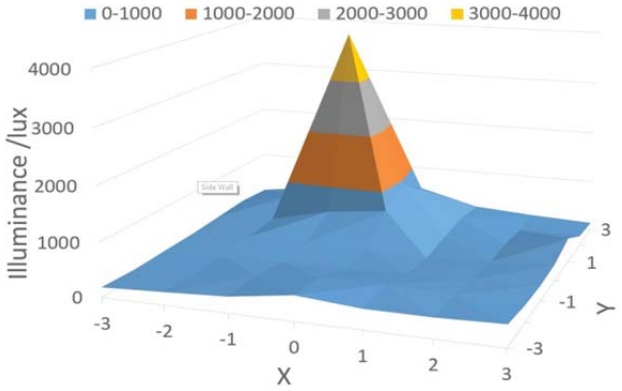

Fig. 8.3b. Illuminance profile of box floor for LOL bottle from 2:34 pm to 2:41 pm (Sun at 60° with horizontal)

Yet again, when the glass plate was replaced with LOL bottle, the position of peak illuminance shifted to the diametrically opposite corner (rear left) Notice that the peak illuminance values for LOL bottle are now greater than that for the glass plate.

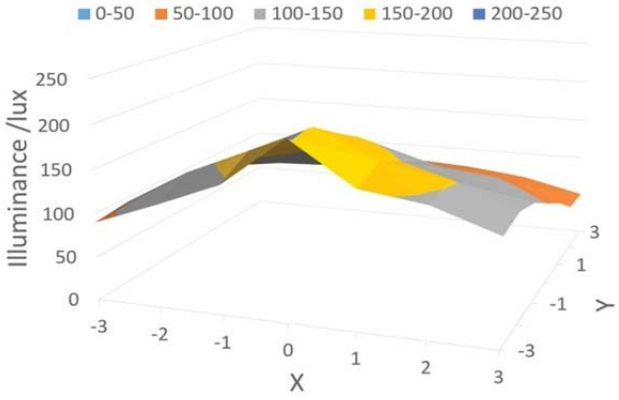

Fig. 8.4a. Illuminance profile of box floor for glass plate from 3:56 pm to 4:05 pm (Sun at 39° with horizontal)

The peak illuminance position for glass plate has now shifted to front centre, and almost all the sunlight is now incident only on the wall.

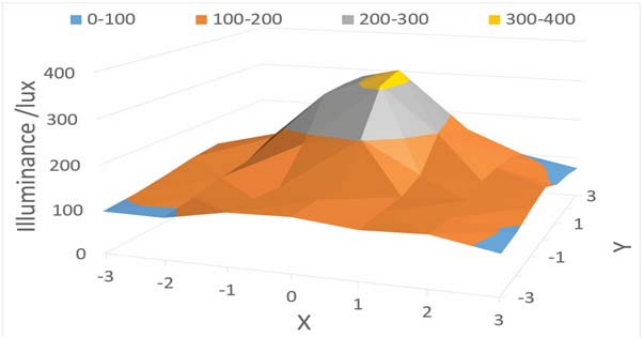

Fig. 8.4b. Illuminance profile of box floor for LOL bottle from 4:06 pm to 4:12 pm (Sun at 39° with horizontal)

On replacing with LOL bottle, the peak illuminance position has shifted to rear centre as expected.Again, the peak value for LOL bottle is greater than that for the glass plate.

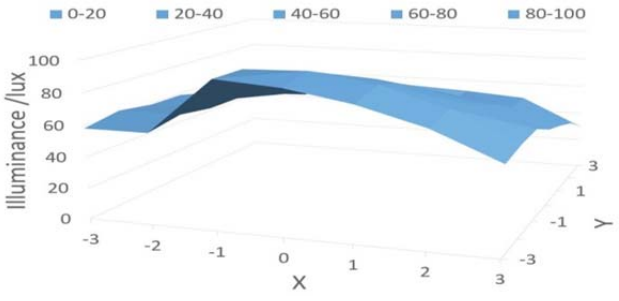

Fig. 8.5a. Illuminance profile of box floor for glass plate from 4:53 pm to 4:58 pm (Sun at 26° with horizontal)

The spot on the front wall where the sunlight hits after passing through the glass plate, has moved up. Thus, only reflected light from the wooden wall reaches the floor now, causing low illuminance on the floor.

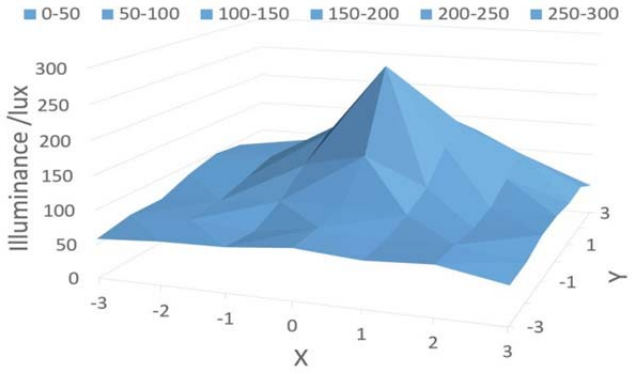

Fig. 8.5b. Illuminance profile of box floor for LOL bottle from 5:00 pm to 5:06 pm (Sun at 26° with horizontal)

The peak illuminance position is at rear centre and its value is much greater than that for the glass plate.

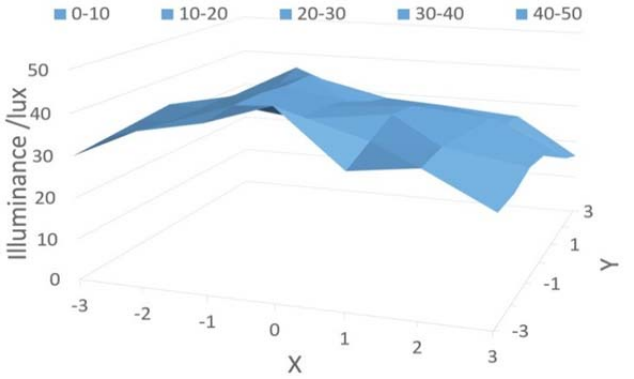

Fig. 8.6a. Illuminance profile of box floor for glass plate from 5:40 pm to 5:48 pm (Sun at 16° with horizontal)

The illuminated spot on the front wall has moved further up for the glass plate, and is now farther away from the box floor, resulting in very poor illumination on the box floor.

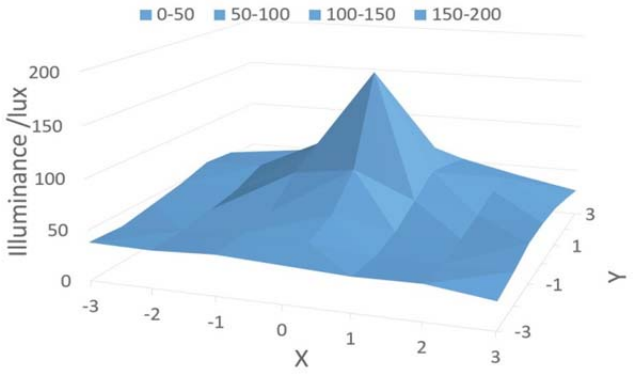

Fig. 8.6b. Illuminance profile of box floor for LOL bottle from 5:50 pm to 5:57 pm (Sun at 16° with horizontal)

For LOL bottle, the peak illuminance position is still at the rear center of the box floor. The floor illumination provided by the LOL bottle is much better than that provided by the glass plate. The illuminance profiles of the floor of a 2m x 2m x 2m room obtained by extrapolating the illuminance data measured for a 70 cm x 70 cm x 70 cm box are shown below. The parts of the floor having illuminance less than 10 lux have been indicated using smaller font (and red color) for the values. The parts of the floor having adequate illumination for reading (>10 lux) have been indicated using larger font (and green color) for the values.

Glass Slab	-3	-2	-1	0	1	2	3	Water Bottle	-3	-2	-1	0	1	2	3
-3	12	15	16	20	21	18	15	-3	138	104	77	44	31	23	18
-2	15	19	22	27	28	23	19	-2	166	108	79	64	30	28	22
-1	19	22	31	42	46	36	27	-1	95	96	129	82	38	29	27
0	21	27	44	87	116	63	36	0	61	82	128	47	83	33	28
1	21	30	61	254	1036	110	43	1	37	53	51	62	49	35	27
2	20	28	53	127	187	64	31	2	28	31	33	39	29	48	21
3	17	24	32	38	39	31	19	3	21	24	26	24	21	21	16

Fig. 9.1. Illuminance profile (lux) of 2m x 2m x 2m room between 11:35 AM and 12:08 pm, Sun at 77º with horizontal.

Glass Slab	-3	-2	-1	0	1	2	3	Water Bottle	-3	-2	-1	0	1	2	3
-3	25	27	34	51	82	82	47	-3	21	67	31	38	50	47	34
-2	27	34	41	82	4126	325	63	-2	25	27	40	78	65	48	54
-1	26	38	54	74	172	112	54	-1	32	30	32	44	61	47	48
0	23	33	51	61	63	52	39	0	46	48	52	30	28	43	28
1	20	26	38	66	46	34	27	1	71	89	82	55	34	33	23
2	18	22	27	37	44	23	17	2	149	184	114	59	40	27	21
3	16	20	20	20	29	25	15	3	301	270	531	103	44	25	19

Fig. 9.2. Illuminance profile (lux) of 2m x 2m x 2m room between 1:29 pm and 1:51 pm, Sun at 71º with horizontal.

Both glass plate and LOL bottle provide adequate illumination for reading (>10 lux) at every part of the floor as long as the Sun's position in the sky is greater than 63º for a 2m x 2m x 2m room.

Glass Slab	-3	-2	-1	0	1	2	3	Water Bottle	-3	-2	-1	0	1	2	3
-3	15	22	31	69	337	194	53	-3	23	29	36	56	45	44	49
-2	17	24	34	59	86	83	46	-2	18	24	35	48	50	44	39
-1	18	24	31	43	47	45	34	-1	20	23	24	23	29	32	35
0	22	21	26	33	35	31	3	0	22	27	29	28	21	28	39
1	25	20	22	24	25	23	20	1	26	35	66	82	31	28	57
2	22	20	19	17	18	16	13	2	30	60	478	112	38	23	23
3	13	15	17	13	12	13	11	3	25	44	129	68	32	23	17

Fig. 9.3. Illuminance profile (lux) of 2m x 2m x 2m room between 2:25 pm and 2:41 pm, Sun at 60º with horizontal.

Now the LOL bottle has started providing illumination over a larger area of the floor than the glass plate.

Glass Slab	-3	-2	-1	0	1	2	3	Water Bottle	-3	-2	-1	0	1	2	3
-3	11	14	18	25	19	18	15	-3	12	12	15	15	13	14	11
-2	12	17	20	24	21	19	15	-2	12	13	14	15	14	14	12
-1	11	16	17	22	18	17	14	-1	14	15	13	14	13	14	14
0	11	14	14	19	16	15	12	0	15	16	22	25	16	15	15
1	11	12	12	15	14	12	9	1	16	19	34	38	24	15	12
2	9	10	11	11	11	9	6	2	14	18	35	40	22	15	11
3	7	10	9	10	9	8	6	3	11	16	35	32	19	12	9

Fig. 9.4. Illuminance profile (lux) of 2m x 2m x 2m room between 3:56 pm and 4:12 pm, Sun at 39º with horizontal.

With glass plate, the illumination at the rear edge of the room has become insufficient for reading.

Glass Slab	-3	-2	-1	0	1	2	3	Water Bottle	-3	-2	-1	0	1	2	3
-3	7	7	11	11	10	9	7	-3	7	8	8	9	8	9	7
-2	8	8	11	12	11	9	7	-2	8	9	7	9	8	9	7
-1	7	7	10	11	10	9	7	-1	8	9	10	10	10	8	8
0	7	7	10	10	8	8	6	0	11	11	14	17	12	9	9
1	7	7	9	9	8	7	6	1	12	12	18	32	17	12	8
2	6	6	8	7	6	6	5	2	11	12	18	24	19	14	8
3	5	5	7	7	6	6	4	3	6	11	14	17	16	10	6

Fig. 9.5. Illuminance profile (lux) of 2m x 2m x 2m room between 4:53 pm and 5:06 pm, Sun at 26º with horizontal.

The illumination has become insufficient for reading over large areas of the floor for both glass plate and LOL bottle, but the LOL bottle still provides sufficient illumination over a larger area.

Glass Slab	-3	-2	-1	0	1	2	3	Water Bottle	-3	-2	-1	0	1	2	3
-3	4	5	5	6	4	4	3	-3	5	5	5	5	4	4	3
-2	4	4	5	5	4	4	3	-2	4	5	5	5	4	4	4
-1	4	4	5	5	5	4	3	-1	5	5	6	6	5	5	5
0	4	4	5	5	5	4	3	0	6	6	9	10	6	5	5
1	4	4	5	4	4	4	3	1	7	7	10	21	8	6	5
2	3	4	4	4	4	3	2	2	7	6	10	12	7	6	4
3	3	4	4	3	3	3	2	3	4	6	7	7	6	5	3

Fig. 9.6. Illuminance profile (lux) of 2m x 2m x 2m room between 5:40 pm and 5:576 pm, Sun at 16º with horizontal.

The glass plate has failed now and the floor is very dark now. The LOL bottle however, still provides sufficient illumination for reading near the rear centre of the room.

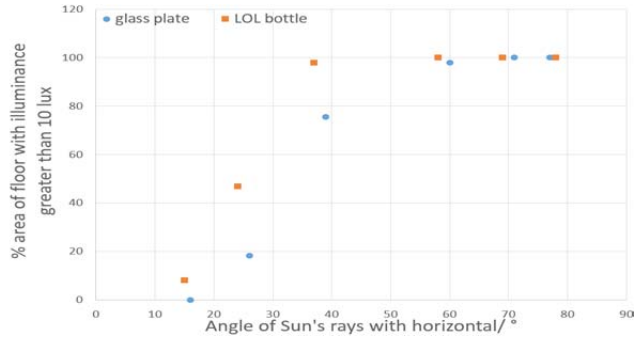

Fig. 10. Comparision between glass plate and LOL bottle for % area of floor of 2m x 2m x 2m room that will have illuminance greater than 10 lux

The LOL bottle performs much better than the glass plate in terms of scattering the light to illuminate a larger area of the floor when the Sun is lower than 63º from the horizontal.

3. CONCLUSION

The loss in illuminance when direct sunlight passes through a glass plate or a LOL bottle is very high, such that less than 0.7% of incident illuminance reaches the box floor after passing through the LOL bottle and less than 1.2% after passing through the glass plate. However, the LOL bottle still provides better illumination than just a glass plate, by scattering the sunlight over a larger area. The exact mechanism of this scattering is not yet clear, though Total Internal Reflection could be playing a major role, since LOL bottle shifts the position of peak illuminance areas to diametrically opposite corners of the room from where the glass plate was producing the areas of peak illuminance. For angles of Sun's rays less than 63º with the horizontal, in a cubical room, the LOL bottle has a clear advantage over the glass plate and starts to outperform the glass plate in terms of % area of floor which has readable illuminance (greater than 10 lux) and even in terms of average illuminance and maximum illuminance.

4. ACKNOWLEDGEMENTS

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