Improved Lighting for **Indian Fishing Communities**

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Abstract

500 million Indians rely on kerosene for their lighting needs. Apart from poor light quality and negative health effects, kerosene lanterns also have a significantly higher cost of ownership than many modern lighting technologies such as CFLs and LEDs. Our work seeks to identify and develop appropriate modern alternatives to fuel-based lighting. We spent several weeks thoroughly identifying the lighting needs of our target community on the Kutch coast of the state of Gujarat in western India. Then we procured several LED and CFL off-grid lighting products to test their quality and appropriateness for the needs of the community. We conducted a thorough economic analysis of each of these products to arrive at a levelized monthly cost of lighting and compared those values to their current cost of lighting. We evaluated each of these products according to the following criteria: light distribution, discharge characteristics, charging time, levelized cost, cultural acceptability, ruggedness, flexibility and portability. We used the test results to inform our recommendations for key design features to succeed in this market. Finally, we designed an efficient underwater fishing light that can be used by the fishermen to improve their catch during night fishing.

Introduction

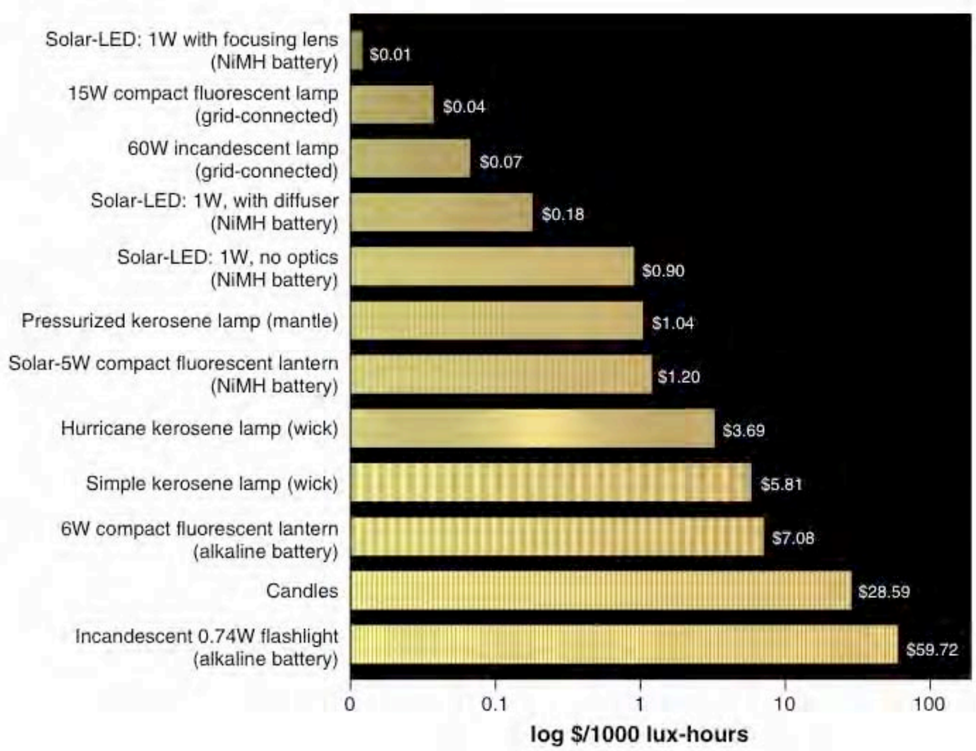
The Challenge: Lighting Energy Services for the Global Poor

In the industrialized world, few give thought to the availability of electric light; except during a rare power outage, it can practically be taken for granted. Yet, worldwide over 1.6 billion people lack access to electricity (IEA, 2002), and nearly a third of this population lives in India alone. For these people – as well as millions of others living in countries with unreliable power generation and distribution systems – a wide range of fuels (such as wood, dung, diesel and kerosene) are used for illumination after dark. In India, kerosene is the dominant fuel used for lighting in rural settings, and is also heavily relied upon by the urban poor (Census of India, 2001.).

Compared with "modern" electric illumination, fuel-based lighting systems typically produce less light at lower efficiency. A typical wick kerosene lantern found in an Asian or African household might provide an average of 5 lux (lumens / m^2) of illuminance over 1-3 square meters, compared to the 50-100 lux that might be found in a typical US home. Wick lamps tend to produce flickering and unevenly distributed light, making it more difficult to use – an important impact on productivity. While modern lighting systems are highly energy efficient, producing well over 50 lumens/watt, a simple kerosene lantern may have a luminous efficacy of 1 lm/W or lower (Mills 2005). Coupled with the high cost of fuel, this dramatic difference in efficiency leads to a very high total cost of ownership for fuel-based lighting systems. Mills (2005) presents cost vs lux-hour (below) produced for a variety of lighting technologies and designs. Light-emitting diode (LED) technology performs the best in this regard due to overall energy efficiency and easy design for task focus. In general, compact fluorescent lights (CFLs) are currently more energy efficient than LEDs and are good for area lighting but are not easily designed for task lighting. They are substantially more fragile and have lifetimes that are less than a tenth of an LED.

Kerosene lanterns have the worst cost per lux-hour figures, yet they are still the dominant lighting technology in much of the developing world. It is instructive to understand the reasons for this. First, there is a significant paucity of good modern lighting products that can function off-grid under the conditions prevailing in these communities. Second, the few such products that exist are unavailable in the rural areas of the developing world. Third, even if such products were procured by the poor, there is no product support. Fourth, even though the total cost of ownership for kerosene lanterns are high, the upfront purchase cost is substantially lower which is crucial driver of decisions in this segment of the population. Finally, many developing countries heavily subsidize kerosene. This is especially true in India where subsidized kerosene is available for $0.2/liter. Each of these barriers needs to be addressed before modern lighting can be brought to these communities.

Comparison of cost / lux-hr of various lighting technologies.



(Source: Mills, 2005)

The Opportunity: Leapfrogging with Efficient Lighting

White light-emitting diodes (WLEDs) and CFLs offer a unique opportunity to improve the quality of indoor air and lighting while simultaneously reducing costs for impoverished communities. With LEDs and CFLs showing such significant advantages over fuel-based light and incandescent lights, there is a real opportunity for many of the poorer communities of the world to leapfrog incandescents to very efficient lights. However, it is crucial that more products be specifically designed for this market and are of good quality. In the first part of our project we test several products for their efficacy in poor rural settings. We use our testing to recommend key design elements for the lights.

There is substantial room for innovative financing and distribution models to help modern lights penetrate the rural developing country market. Prior to embarking on this segment, it is imperative to identify a community that is most likely to be an early adopter of the new technologies, which we have already done during the course of the semester. In the second part of our work, which will take place this summer (of 2007), we will conduct a market opportunity analysis that will identify the best means by which modern lights can be brought to the poor. We will assess the viability of several models that shield the user from the upfront cost many of which have already been implemented with good success in India by our partners.

Background: Our Indian Partners

While our team was aware of the problems of fuel-based lighting in poor communities in a general sense, our decision to pick this problem over so many others was dictated in large part by our enthusiastic and dedicated partners in India. All our partner organizations have already been working on this issue for some time and the aspects that we tackled fitted neatly into the overall thrust of the work done by them. Our work, which included the selection and testing of existing off-grid modern lighting products to inform the design of new ones, belonged to areas of the project best accomplished in a US-based university.

Aurore: Auroville Renewable Energy (Aurore) is a small energy services company that brings modern energy services to the rural and urban poor in India. Aurore has built up a reputation of excellence throughout India over the last few years. Aurore is especially strong at coming up with innovative financing schemes to make modern energy technologies accessible to the poor. Over the last year or so Aurore has been investigating the possibilities of bringing a basket of modern off-grid lighting products to rural and urban markets in India. Given Aurore's expertise in the development of business models for distribution they are our primary project partner.

Sahjeevan: Prior to our arrival in the project, Aurore had partnered with Sahjeevan, the energy wing of Abhiyan, an NGO based in the Kutch district of Gujarat. Sahjeevan works with transient fishing communities on the Kutch coast addressing their energy issues. Sahjeevan identified the fishing communities as an ideal early adopter of modern lights due to their high need for lighting. We will be working with them closely during field trials of the lights.

S3IDF: The Small-Scale Sustainable Infrastructure Development Fund (S3IDF) is a non-profit company working in India to facilitate the building of small-scale infrastucture for the poorest communities. When modern lighting options for the poor become more widely available, S3IDF will play a similar role to Aurore in setting up distribution models. S3IDF and Aurore have partnered on another lighting project in the past.

Some of the strongest barriers to the penetration of new technology to the poor are cost, the lack of a distribution infrastructure and an improper assessment of needs. While the latter two factors present similar barriers irrespective of the end-user, the issues surrounding cost can vary substantial from one community to another and is intimately dependent on their current cost of lighting. Hence, a community that already pays a lot for its lighting needs will be more easily enticed to switch to a newer technology because their cost savings can be substantial. With this in mind, we used the help of our partners to identify communities that would be likely early adopters due to high existing lighting expenses. After some investigation, we realized that fishing communities across India have very high lighting needs since they both fish and process their catch after dusk or before dawn. In addition a large number of fishing settlements are unelectrified thereby forcing the use of off-grid lighting. Kerosene based lighting is most common among these communities. Through our partner Aurore, we were introduced to Sahjeevan who were working closely with transient fishing communities with incredibly high lighting needs.

Background: Indian Fishing Community

This project targets a specific segment of the population in India that has a particularly high demand for illumination, yet lacks access to modern lighting. Thousands of fishing communities live in transient settlements all along India's 4500-mile coastline. In this project we address the provision of modern lighting to one such community, the "Wagher" fishing community in the Kutch District of Gujarat state in northern India. One member of our team, Josh Apte, visited several Wagher fishing settlements during April 2007.

Geographic context and settlements

Our target community resides in the Mundra region of Kutch district, and is home to roughly 800 families engaged in ocean fishing. Fishing in this region has traditionally been dominated by the Muslim Wagher community[1] for the past 200-300 years (Sahjeevan, 2007). As fishing is a seasonal occupation for this community (September – May), fishworkers reside in informal, temporary settlements for nine months each year, migrating there from inland home villages. Nine fishing settlements exist along a 72-mile stretch of coastline (Sahjeevan, 2007). Each coastal fishing settlement tends to be occupied by families from a particular set of villages, but one inland village may have its members living in several coastal settlements. Thus, the migration pattern is complex, and people may migrate as far as 70 km down the coast to their fishing settlement. As the government does not formally recognize these settlements, they lack even the most rudimentary infrastructure. Limited access to roads, sanitation and clean drinking water,

[1] 'Wagher' means "Wah! Gher" in the local Kutchi dialect, an expression applauding spectacularly skilful laying of net to trap fish, which is believed to be a skill mastered by a Wagher only.

grid electricity, and government ration cards are key concerns for the fishing community. Several fishing settlements are currently threatened by the construction of a Special Economic Zone at the port of Mundra; one settlement recently lost its only road connection after it was demolished for the construction of an airstrip (MacKinnon, 2007).

Partial map of fishing settlements, Kutch District.
Source: *Down To Earth* Magazine, March 31, 2007.

Fishing settlements are typically constructed from recycled materials such as driftwood, sticks, and burlap sacks, and are divided up into family compounds which are re-assembled each fishing season. Up to 10 adults from different generations may live within a family compound. Married sons will build their own huts within the family compound, while daughters marry into other compounds. The family appears to be the core economic unit within the settlements; one family may own one to three boats depending on how many working-age sons live within a compound. Each compound is fenced off and contains several huts – one as a family kitchen (~ 3m x 2m x 2m), one as a storeroom, and then separate huts for each married couple and their children. Additionally, some families construct a shelter (~3m x 2m x 2m) used to provide shade when doing fish sorting.

Two views of typical Wagher fishing settlements. Note the stick fences used to separate family compounds.

Economic Context

The Wagher community fishes primarily with nets set by 30-foot diesel foot powered boats. This is a relatively capital intensive mode of fishing, requiring large annual expenditures for the purchase and maintenance of fishing boats and nets, as well as for diesel fuel to operate boats. Many of these expenses are seasonal, taking place at the beginning of each season when finances are most strained. Since they fishworkers lack access to mainstream forms of credit, they take out loans from local fish middlemen, with whom they then sign exclusive contracts for the marketing of their fresh fish catch. In lieu of paying interest, fishworkers receive prices several times lower than the market value of their fish. Our partner NGO Sahjeevan estimates that this translates into implied interest rates of greater than 150% year. Given the low price of fish and high cost of doing business, many fishworking families are caught in a vicious cycle of debt bondage – saddled by high debts, they are unable to receive a fair price for their fish and are thus unable to repay their loans. As the following table provided by Sahjeevan shows, typical debt levels in may greatly exceed annual family incomes of Rs 10,000 – Rs 20,000 Rs ($100 - $250, Sahjeevan, 2007).

Amount of Debt (in Rs.)	No. of Persons (families)
< 30,000	91
> 30,000 < 60,000	86
> 60,000 < 90,000	62
> 90,000 < 120,000	69
> 120,000	66
Total	374

Data for Bavdi, Juna Bandar, Luni & Vira bandars and Bhadreshwar, Shekhdiya, Vandi villages. Source: Sahjeevan, 2007.

Fishing Livelihood

A strong division of labor exists between men and women within the fishing villages. Working age men are responsible for fishing. Fishing is typically conducted in two distinct phases during a month-long lunar cycle. During the nine brightest nights of the full moon, two fishing trips are conducted daily, each lasting roughly ten hours and corresponding with tides[2]. This is the most intense period of fishing during the month, and men practically live onboard the boats, returning only to drop off fish and collect food and water. During the remainder of the month, only one trip is conducted each day.

[2] Due to the flat nature of the Kutch coastline, boats can only reach fishing settlements at high tide.


Fishing boats being unloaded. The same process occurs at night for nine days each month.

In addition to housework, women are primarily responsible for the sorting and processing of fish. Sorting work begins immediately after the arrival of fish, in order to separate high-value fresh fish from lower-value shrimp, prawns and fish for drying. Overfishing, increasingly a problem over the past thirty years, has increased the need for fish sorting. Fishermen have sought to combat lower fish catches with more tightly woven nets, which increases the proportion of low value fish in a catch. The lowest value fish are dried and sold for use as fertilizer. The sorting of a fish catch may take 4-6 hours and is a household activity usually involving 3-4 women, as well as any children and the elderly.


Nighttime fish sorting using a Petromax-type lantern.

Fishing Community: Baseline Lighting Needs Assessment

As our team began to develop potential lighting solutions for the Kutchi fishing community, our NGO partners stressed the need to provide a "basket" of lighting products, with each product tailored to a particular need of the community. While the team identified several potential end uses of light, it quickly became clear that a thorough needs assessment was necessary. To this end, one team member, Josh Apte, spent a week working with the Sahjeevan in several fishing settlements in Kutch in order to identify baseline lighting requirements, expenditures and technologies. Sahjeevan employees conducted preliminary, informal exploratory surveys addressing baseline conditions. Impressions based on these investigations are presented below. Based on their findings, a more rigorous study will be conducted in Summer 2007 using a survey instrument approved by the UC Berkeley Committee to Protect Human Subjects (pending approval).

Lighting Requirements

Several distinct lighting needs were identified:

1. Household work, typically 1-1.5 hours a day year-round. Cooking and cleaning are the predominant uses, and are typically carried out indoors by one or two people.
2. Fish processing and sorting. 4-6 hours per night during the night-fishing portion of the month, preferably quite bright. This dominates the lighting fuel use on land. This work is conducted outdoors (although sometimes under a shelter) by 2-5 people working together.
3. Illumination while walking at night, unloading fish, et
4. Security / night light in huts while sleeping (6-8 hours / night at low level).
5. On-boat night fishing, hauling of nets, etc. Up to 10 hours/night during night fishing trips.

Existing lighting technologies: Kerosene

With the exception of on-boat use, kerosene lamps are the dominant lighting technology in fishing settlements. Three types of kerosene lantern are typically used:

1. *"Chimney"* wick kerosene lamp. This is a very large wick kerosene lamp and the most prevalent in the community. The wick is a bundle of fabric 1-1.5" across and perhaps 4-6" tall, mounted in a metal can that has a small handle brazed on. It gives a very large, dancing, and very smoky flame. We measured fuel consumption to be ~80 g / hr in somewhat windy conditions. This lamp appeared to be used more often outdoors than indoors, perhaps due to the large flame it produces. Repeated attempts to find such a lamp in local bazaars were unsuccessful, but we estimate that this lamp would sell for between Rs 80 and Rs 120. This lamp appears produces the most soot of the three lamps found in the settlement due to its large, uncontrolled flame.

2. *<u>"Hurricane-style"</u>*. This lamp design is common throughout the developing world and mass-produced in China. The lamp has a thin, wide wick (0.75"-1" wide), and is enclosed in a glass wind-protector to keep the flame steady. By adjusting the wick height, the lamp's output can be varied. This lamp is very easily carried around using its metal handle, and can conveniently be hung to cast a wider, if dimmer, light. This lamp seems to be used both indoors and out. At its lowest setting, it is commonly used as a night light. At its highest setting, the glass enclosure quickly darkens from soot production; optimal light output is actually achieved by a less-sooty flame of medium intensity. We purchased one of these lanterns for Rs 120 in the Kutch Bazaar; it was available for a similar price in the Mundra Bazaar, which is closer to the fishworker's settlements. Our team tested fuel consumption and light output for this lamp in Berkeley.
3. *<u>Petromax style</u>*. This is a pressurized Kerosene lantern that uses a mantle to give a very bright light. After preheating an element in the lamp, it provides gasified fuel to the mantle, which leads to relatively efficient combustion, low soot output, and an intense white light. Like the hurricane lantern, this lamp has a handle, making it somewhat portable, although the mantles used in the lamp are quite fragile and must be handled carefully. This lamp appears to be preferred by many families for fish sorting, but it is considerably more expensive to own and operate, and thus not used for many other tasks. The lamp costs roughly Rs 350-450; we tested light output and fuel consumption in Berkeley.

A mix of incandescent lamps and tube-style fluorescent lamps powered by an onboard diesel generator are used on fishing boats. Unlike the kerosene lighting used within the settlements, these technologies provide light at an acceptable cost to the fishworkers. Because of this, we do not address on-board lighting in this report.

(Left and Center) *Petromax lanterns, (Right) Hurricane style lantern.*

Each household tends to own several lamps, often of several types. This appears to be for several reasons. First, each lamp tends to perform best in certain applications. For example, a hurricane style lamp is desirable for indoor use, since it provides an appropriate amount of light without the high fuel consumption of the chimney and Petromax lanterns. While each lamp type has its “strong suits”, flexibility is also important – a lamp should be able to perform well at several applications. Having multiple points of light adds to flexibility as well. For example, a family may use two chimney lights and a hurricane lamp while sorting fish as a group. By having a larger number of points of light, people can come and go from this process and take light with them, adding to convenience.

Informal illumination measurements

Chimney

The “chimney” illuminates an area roughly 1m in diameter, the average light levels on the ground were 5-15 lux. Outside of this directly illuminated area, there is a broad area that is dimly lit at 1 lux or below. One’s eyes can actually adjust to these levels quite well, though, so there is a relatively large area where one can at least make out large objects (“My bowl with fish is over there…”). The light levels change constantly as the flame blows in the wind, and the light takes on a very orange glow. Light levels also depend on where the lamp is used; if it is placed on a metal pot or stand (as is sometimes done), the light will spread farther, but also be weaker. These lamps effectively provide light for one or at most two people. When used indoors, these lamps are often the sole source of light. Outdoors, several chimneys may be used to illuminate a large 2m x 3m area for fish sorting.

(Left) A "Chimney" seen indoors. 10-12 Lux were found on the brightest spot on the wall, lux levels of 2-3 lux were found towards the right edge of the rug in the center of the picture. Note that the lamp is elevated on a storage tin. (Right) Note the copious smoke produced by the Chimney.

Hurricane Style

We were unable to measure hurricane-style lanterns in use outdoors. Indoors, they are frequently used for nighttime security lighting at low flame; this provides illumination of 0.5 – 1 lux.

Petromax Lantern

Petromax lanterns tend to be the brightest kerosene lantern available in the fishing settlements. Crude lux measurements here suggest that light levels of 10 to 30 lux were available over a useful area with a 3-4 m diameter. As the photos show, one lantern is sufficient for an entire family's fish processing needs.

The above shows at least 4 people using light from one Petromax lantern. Note that it's hung from an overhead shelter.

<u>Existing Lighting Sources</u>: Non-Kerosene

During a tour of one fishing settlement, we discovered a household using a small solar powered CFL lantern (5 watt) which had been purchased for Rs 2500 in a nearby bazaar. The users praised its bright light for fish processing (we were unable to take a measurement), but complained that the battery life was far too short – only one hour. However, we noticed that the solar panel for the lamp was installed incorrectly, with the panel facing north; the users were unaware of the need to properly orient the solar panel.

(Left) Local CFL Lantern found in fishing settlement, (Right), Adjusting solar panel for improved power supply and thus light output from CFL.

<u>Kerosene Lamps: Fuel Consumption</u>

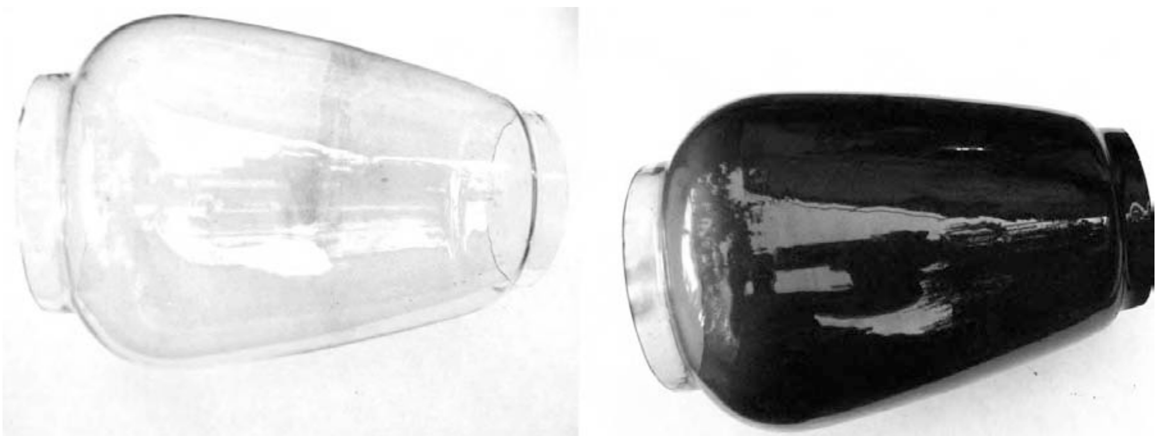
Informal conversations with several households within fishing settlements suggests monthly fuel consumption of 15-30 L of kerosene per month; or 0.5-1 L of kerosene per day. Up to 8 liters of kerosene/month are available using government ration cards at the subsidized price of Rs 9 /L, while the remainder of the fuel must be purchased illegally on the black market for approximately Rs / L. When this fuel is not available, some households substitute diesel for kerosene, at a price of approximately Rs 35 / L.

We measured fuel consumption of kerosene lanterns using a mass-balance technique, weighing a lantern before and after use, and dividing the mass of fuel consumed by the time elapsed. We assumed that wick burnup and soot deposition made negligible contributions to the overall mass balance, both reasonable assumptions for the lamps tested. Except for the Chimney, which was field tested in India, lamps were sheltered from a moderate outdoor wind, so our results represent relatively still conditions. Still conditions may underestimate fuel consumption in the windy conditions more typical of the beach environment lamps are used in by the Wagher community.

We obtained the following results:

Lamp Type	Fuel Consumption Rate (g/hr)
Hurricane Lantern (medium flame)	12
Hurricane Lantern (high flame, sooty)	20
Petromax	62
Chimney (windy)	80

We tested the Hurricane-type lantern at a typical wick height, as well as at high wick height, which represents an upper bound for fuel consumption. This mode results in very high soot production, as shown in the photograph below.



Glass housing for Hurricane type kerosene lantern, before (left) and after (right) 45 minutes of runtime at high flame. Note the large amount of soot buildup.

Fuel consumption testing of Kerosene lanterns in Berkeley, May 2007.

Existing Economics of Lighting

We used the following values for calculating the monthly levelized cost of lighting for each type of kerosene lantern. It is important to keep in mind that each family uses multiple lanterns for different uses.

Values of parameters used for lighting cost calculation

Parameter	Value	Reasons
Discount rate	150%	High levels of indebtedness in the community
Kerosene cost	Rs. 20 per liter	Subsidized kerosene is available much cheaper in India. However, these communities are forced to buy kerosene on the black market
Hours of daily lantern use	6 hours	The needs vary a lot based on the fishing season but 6 is a good average

Monthly levelized cost of each lantern

Lantern Type	Lantern cost (Rs)	Lantern life (yr)	Rate of fuel consumption (g/hr)	Monthly levelized cost (Rs/month)
Hurricane	100	1	12	70
Chimney	100	0.5	80	377
Petromax	400	1	62	338

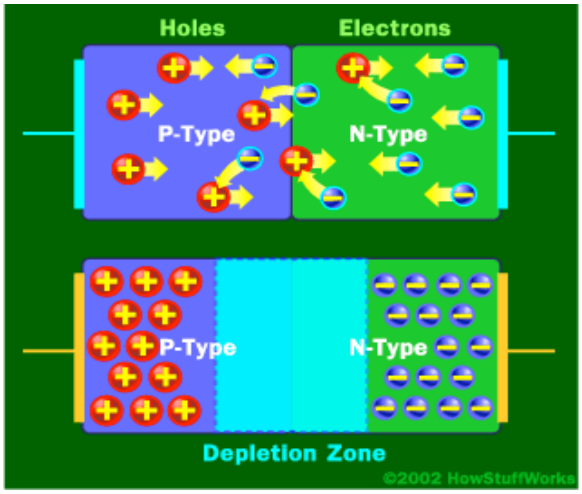
Since each family uses more than one of each type of lantern in addition to owning different types, their monthly cost of lighting is a weighted summation of the levelized cost values shown in the above table. Sahjeevan estimates that lighting related kerosene use averages **20 L/month** for each family. Using this figure we were able to calculate a monthly levelized cost of lighting for each family.

Estimated monthly levelized cost of lighting per family = Rs. 425 per month.

Given family incomes of around Rs. 2000 per month, an extraordinarily high portion of that goes toward lighting.

Background: LED Technology

A semiconductor is formed when a poorly conducting metal is doped with another material to create holes (P-type) or electrons (N-type), which can conduct electricity. P-type and N-type semiconductor material joined together form a diode. When connected to an electrical circuit, the P-type conductor to the negative terminal and the N-type conductor to the positive terminal, the electrons lose energy as they are forced to move through the P-type semiconductor and fall into the holes (orbitals of lower energy). A big energy gap will cause visible light to be emitted as the electrons fall into the orbitals of lower energy.



Source: http://electronics.howstuffworks.com/led1.htm

Energy Efficiency of LEDs

Nichia developed the first white LED in 1996, by coating a blue LED with phosphor. Solid state lighting using white LEDs are very energy efficient because the process of light emission does not involve any generation of heat, unlike in incandescent lights which rely on heating a filament to emit light.

Light Source	Typical Luminous Efficacy Range in lm/W (varies depending on wattage and lamp type)
Incandescent	10-18
Halogen incandescent	15-20
Compact fluorescent (CFL)	35-60
Linear fluorescent	50-100
Metal halide	50-90
Cool white LED 5000K	45-59*
Warm white LED 3300K	22-37*

*Current as of October 2006.

Source: http://www.netl.doe.gov/ssl/PDFs/energyEfficiency_oct25_06.pdf (accessed May 14th, 2007)
US Department of Energy

White LEDs are ideal for rural lighting purposes owing to their long life time, ruggedness and low maintenance costs associated (Mills 2002). Compact fluorescent lamps (CFLs) are also a viable option as they offer higher lumens per watt than white LEDs. Upfront costs associated with LEDs in spite of their long lifetimes make CFLs a more attractive option, but in countries such as Nepal LEDs have been employed to meet rural lighting needs with resounding success (Craine et al 2002). In a study carried out by Nieuwenhout et. al 1998, it was shown that CFLs were better suited for large-scale area lighting than LEDs. Though LEDs find wider application in task lighting. Since the fishing communities are transient, the lights must be sturdy to withstand stress making LEDs an attractive option. Moreover, white LEDs have a superior color rendering index compared to other lighting technologies under consideration (Sebitosi and Pillay 2003). Considering these facts, it can be inferred that LEDs are a better solution than CFLs for purposes of task lighting.

LED technology is improving and may eventually overtake CFL lighting in the area of energy efficiency. Researchers at Rensselear Polytechnic Institute and Crystal IS invented a new nano coating that virtually eliminates reflections, and should be available in three to five years. With this coating an LED could emit 40% more light making them a much more efficient light product (Bullis 2007).

Improved Lighting Products: Selection

Types of Lighting Products Suited to User Needs

The trip to India and observations of field conditions gave extremely useful information about the need for lighting products in the day to day lives of the fishermen. Substantial improvement can be made especially in the lives of women, as they require light to do household work such as cooking. Apart from use on boats, lighting needs also arise with most activities associated with fishing such as fish sorting and processing, which are again primarily performed by women. They also require lights for traveling at night. Hence, there is the need for a variety of lighting products in their homes. Flashlights are useful for traveling at night. For domestic use, fish processing, and fish sorting there is need for task lighting (e.g. lanterns, bulbs, and other area lighting).

Products Researched

Internet searches were conducted to find a variety of products to meet user needs. Flashlights, headlamps, lanterns, tasklights, bulbs, and floodlights/spotlights designed for the American market, international market, and for developing country markets were identified. The products were compared based on criteria such as the price, lux, life per charge (if data were available), and total life of the product. Other physical parameters such as weight of the light, size were also taken into account (since the lights are sometimes used for traveling). The product matrix was developed to assess the suitability of each product (See below). A number of promising products were purchased through the internet. In addition, several LED products and one CFL product were purchased in India and Bangladesh by team members in April 2007. A summary of purchased products and their characteristics is in Appendix B.

Products A, B, C and D are LED flashlights. Product A and Product B look similar although Product A was bought in USA and Product B in India. They also appear to be made by the same (Chinese) manufacturer. Product C is a flashlight made in the USA expressly for use in developing countries. Product D is a flashlight currently available in India in the villages close to the settlements where the fishing community lives.

Product E is another LED flashlight made in India for the purpose of bringing lighting to the rural poor. It operates in a focused mode (more lux output over a smaller area) and in a diffuse mode (widespread distribution of light across the surface), which makes the product useful for a variety of needs. Product F is a commercially available product which is designed to function as both a LED lantern and a LED flashlight. It is marketed to campers. Product G is a LED headlamp (also marketed to campers) whose application for night travel and tasks that require both hands (e.g. fish processing) made this product an option to be explored. Product H is a LED tasklight, made in India to meet lighting needs of the poor. Product I is a CFL tasklight obtained from Bangladesh, and Product J is an eight LED lantern which was procured in USA (again marketed to campers).

Products K, L and M were dynamo hand powered lights. These products were tested and compared to each other by not fully analyzed. Some believe that it is unlikely for hand powered lights to succeed in this community (Sahjeevan 2007b).

Product N is a submersible fishing light which will be discussed in the next section.

We also purchased two LED light bulbs, one from India (Edison base, 12 White LEDs, 12VDC, 1.2W) and one from the US (Edison base, 8 White LEDs, 110VAC). The former was not tested due to its power requirements and the latter was deemed to dim to be worthwhile for our application.

Charging Options

Various charging options were analyzed and a matrix was developed to compare those options (Appendix C). Energy efficiency, ease of maintenance, infrastructure (upfront) and maintenance (reoccurring) costs, and feasibility of the technology in India were some of the criteria used to evaluate each option. Many technologies were eliminated as they were not technologically or economically appropriate. In addition, observations on the ground helped us to narrow down our options to feasible possibilities. In the end, we decided the most realistic light charging/powering options are:

- Solar PV panels to recharge batteries
- Diesel dynamo to recharge batteries (using boat motors)
- Grid (local entrepreneur arranges battery charging in nearby electrified town)
- Disposable (alkaline) batteries

Battery options were also explored and compared in a matrix (Appendix D). Due to cost, the most appropriate batteries identified were:

- Rechargeable lead acid
- Rechargeable NiMH/NiCd (usually in AA or AAA form)

Products A, B, D, F, and G function only when powered by batteries. Alkaline batteries are easily available near the settlements, though battery costs are high. Product C is equipped with a solar PV panel which charges NiMH or NiCd batteries. Product E has multiple modes of charging its NiMH battery: a solar PV panel and a charging cable. Product H and I each have a rechargeable lead acid battery which is charged through a charging cable. Product J, which has NiMH batteries, can be charged through its charging cable or with a hand crank.

Products K, L and M are powered by some human action which stores the energy in a capacitor or rechargeable battery, these lights need to be charged frequently and are not suitable for task which require constant use of hands, such as fish processing and sorting.

Improved Lighting Products: Testing

To determine the suitability of the products selected for the clientele population various tests were conducted. Our goal was to quantify what the user cares most about:

- light distribution over an area
- discharge characteristics (how the light quality changes while the light is being used)
- charge time
- cost of ownership (upfront costs and reoccurring costs e.g. cost per charge)

Several other parameters that are not directly of interest to the user have not been quantified during our testing, but relevant tests would be worthwhile for a thorough analysis of each product:

- current and voltage over battery during charge and discharge (requires sophisticated and precise data-logging equipment)
- light efficiency - lumens/watt (requires use of an integrating sphere[3])
-

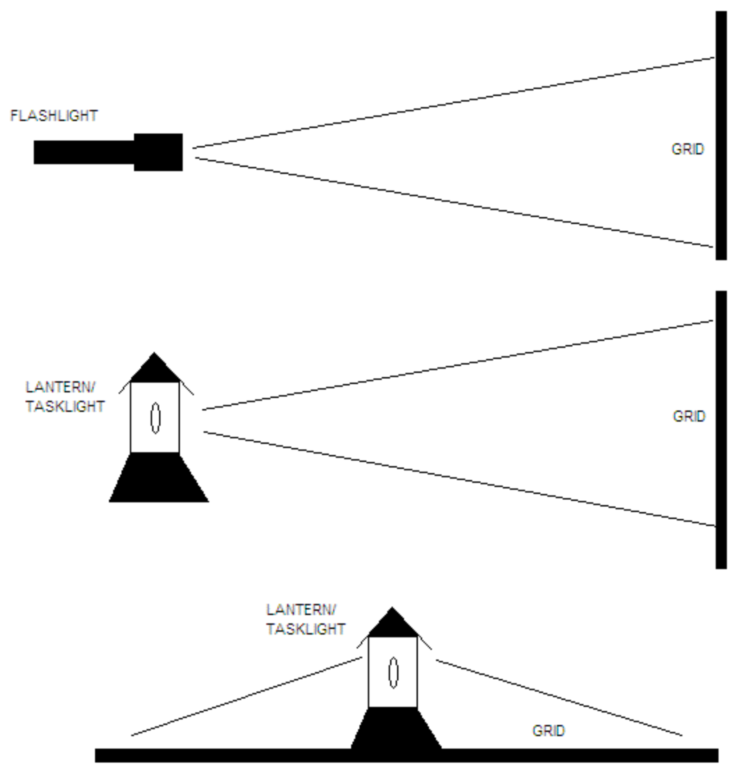
The majority of products were tested for their light distribution (with the exception of the hand powered lights, bulb, and fishing light). Based on the results of the light distribution test we selected only eight of these products for discharge testing, due to the time it takes to perform those tests. We also performed a discharge test on the most promising hand powered light. Appendix E shows which tests each light went through. Charge time was determined through manufacturer specifications and cost of ownership was calculated with the help of testing results and relevant specifications (see below).

Light Distribution Tests: Methodology, Errors, and Results

[3] Integrating over our light distribution plots, projected on a sphere could give an approximate value for lumens. Therefore, efficiency could be approximated as this value divided by average power use of the product. However, we chose not to perform this calculation due to its immense imprecision. We believe qualitative efficiency information is adequately captured through our light distribution plots and calculations for cost of ownership, which relate to power consumption.

A data-logging light meter was purchased from Extech Instruments[4] and used in all product testing. To determine light distribution over a wall, a grid was set up on the wall (comprising squares 4” x 4”). Lighting products were mounted at a known distance from the wall. We attempted to center each light on a grid node in order to capture to point of highest intensity. Lights were positioned horizontally and vertically with a carpenter’s level. The lateral angle was set by inspection, and by attempting to align the light so that the light intensity around the center node was as symmetric as possible. Then, after all other light were turned off and the product was turned on, light intensity (in lux) was measured at each node of the grid and recorded in a spreadsheet. We did not assume complete symmetry of the light and therefore took lux measurements that captured all (or at least as much as possible) of the light output, in all directions.

Each flashlight was pointed directly at the grid. In some cases flashlights were tested in multiple modes (e.g. dim, bright). Both the hurricane lantern and Petromax lantern were tested for baseline lantern comparisons. Each lantern/tasklight (kerosene, CFL, and LED) was tested for light projected on to a wall and also for light projected on top a table top.



Orientation of Lighting Products and Grid

[4] http://www.extech.com/instrument/products/400_450/401036Light.html

Measuring light output from a kerosene lantern.

Three dimensional plots were constructed in MATLAB to observe the distribution of light from each product. Using the measured distance between the product and the grid, we standardized the plots so that the lux levels would correlate to each light being set at the same distance (1m from the product's lighting element to the closest point on the grid). To do this we used the correlation that the intensity of light varies inversely proportional to the square of the distance. In each mesh plot, the x and y axes are the geometric coordinates of the point, while the z axis is the lux measurement at that point (standardized for distance as described above). This methodology gives a 'carpet plot' showing areas of high and low illuminance clearly. These plots also give a sense for how focused the beam is and how symmetric the light is. The MATLAB code used is provided in Appendix F.

Appendix G contains all of the plots created, and comments about the results.

There are several sources of error in our data. We performed tests in two spaces: a study room in Davis Hall and a team member's garage. Using a carpenter's level we noticed that the wall of the study room, upon which we hung the grid, was not perfectly vertical. In the garage, we hung the grid on the back of the garage door and that was also not perfectly vertical. We estimate that the wall/garage door were at most 3 degrees off from vertical. Another source of error stems from our alignment of the product with respect to the grid. Our attempt to position the brightest point at a node and then adjust the lateral angle such that the light output was symmetric around that node assumes that the product's optics are symmetric. Moreover, this was a difficult task and we are not fully confident we achieve the best alignment for each product tested. We estimate that the lateral angle was off at most 3 degrees from perpendicular to the wall. In sum, our lux plots are unsymmetrical in part because of these errors. Moreover, we measured the distance between the product and the grid to the nearest half inch and any inaccuracy and imprecision in that measurement is propagated in our calculations to standardize that distance to 1m. However, that alone should introduce less than a 1% error to our plotted values. In general, our plots should be used for comparison of various products, and not to quantify specific products.

Discharge Tests: Methodology, Errors, and Results

To determine how the lights discharge over time, they were first fully charged through whichever method they were designed for. Afterwards they were carefully positioned and the light meter was positioned at the point where the light output was maximum. The product was switched on and the light meter's data logger recorded the lux at fixed time intervals (30 seconds or 1 minute depending upon the expected discharge rate of the light), the data retrieved was used to construct a plot of lux output versus time. The time for which each light product lasts per charge was determined. The shape of the discharge curve can also help assess if the circuitry in the product is proper.

Appendix H presents the results of our discharge tests. Note that most lights exhibit the following characteristics: steep initial slope, a leveling out that characterizes the majority of the light's charge life and a steep final drop off.

There are several sources of error associated with these tests. We were unable to monitor the testing room at all times. Small lux spikes in the plots could be caused by someone opening the door and/or turning on the lights in the room. Moreover, on occasion when the datalogger was full of data we had to pull off the readings mid-test. Generally, the light was turned off while this was done. However, when it was turned back on it was not usually at precisely the same lux output as before. It was noted that when this was done to the CFL, it was so drained of energy that it was unable to warm up again to the point it had been at before it was turned off.

Charge Time

Many of the lights purchased use disposable batteries and therefore have no "charge time." For those that do charge, none give feedback about when they are need charging, or are done charging. Therefore, our intent had been to determine product charge time by measuring the time it takes for the light to go from 10% to 90% of its possible lux output (measured at the center of the light). Unfortunately, most lights can not be on while charging, and lux readings vary when lights are turned on and off, so this did not prove to be a sound method. Therefore, we chose to rely on manufacturer's specifications for charge time. Of course product specifications are often inaccurate (as evidenced by our discharge plots) so this assumption introduces some error in our calculations.

In the future we hope conduct charge tests at Humboldt State University which is equipped with precise data-logging voltage and current meters, allowing us to collect relevant data efficiently.

Cost of Ownership: Economic Analysis

When calculating the total cost of ownership of a product, we will not present calculations for products that are clearly unsuitable in other ways. Hence products B, F and J are eliminated due to poor light quality. Headlamp product G is eliminated due to cultural inappropriateness.

Product	Monthly levelized cost (Rs/month)
A	1130
C	75
D	225
E	293
H	75
I	66
Assumptions: All lights will last for 2 years. Charging will be done through diesel engines that run boat.	

All the products except for Product A show substantially better economics than the current monthly lighting expenses for each family of Rs. 425. Products C, H and I are cheaper than even owning individual hurricane and chimney wick lanterns. The quality of light from each of these lights is substantially better than all kerosene lanterns. The direct comparison between the area light CFL lantern I and the petromax yields interesting results. The CFL lantern is substantially cheaper but the petromax does put out a slightly better quality of light.

Product Comparison

Based on product testing, manufacturer specifications, and our economic analysis we were able to directly compare the improved lighting products to each other. Our results are summarized in the following table.

Product Pros and Cons. Products highlighted yellow were identified as promising after the first round of analysis. Reasons for eliminating products are highlighted in red.

Light Code	Type	Light distribution	Discharge	Charging	Price	Other
A	Flashlight	focused, intense	diminishing, ~5 hours	Disposible	Low upfront cost, high battery cost	
B	Flashlight	focused, poor intensity		Disposible	Low upfront cost, high battery cost	already available in India
C	Flashlight	focused, intense	steady, 8 hours	Solar	Moderate upfront cost, no reoccuring cost	rugged
D	Flashlight	focused, intense		Disposible	Low upfront cost, high battery cost	already available in India
E	Tasklight/ Flashlight	focused, intense or diffuse task lighting of good intensity	N/A	Solar, versatile	High upfront cost, no reoccuring cost	versatile use/ charging
F	Lantern/ Flashlight	focused, intense or task lighting of poor intensity	N/A	Disposible	High upfront cost, high battery cost	versatile use

G	Headlamp	focused, intense	N/A	Disposible	High upfront cost, high battery cost	Not culturally appropriate.
H	Tasklight/ Nightlight	task lighting of good intensity	steady, 2 hours	Long time to charge	Moderate upfront cost, charging cost	already available in India
I	Tasklight/ Nightlight	task lighting of good intensity	steady, 10 hours	Long time to charge	Moderate upfront cost, charging cost	already available in India
J	Lantern/ Nightlight	task lighting of poor intensity	N/A	Moderate time to charge, or hand wind	High upfront cost, charging cost	versatile charging

As it has been suggested that we identify a basket of appropriate products, each of the lights we have down-selected could play a role in the fishing community. For instance, a very simple led flashlight with disposable batteries and little circuitry could be a successful low-end product, while the more expensive task-lights could be used as the petromax is now.

Product Design Recommendations

Based on our analysis of the LED lighting market and various products as described above, we have generated a list of suggestions for the design of need lighting products for the fishing community. Each of the products we have analyzed has some of these features, but we believe that for a product to be successful in this community it would have to take in account as many of these design recommendations as possible.

1. **Versatility:** Successful lighting products must be suited to many uses. Our main concern with traditional flashlights is that they are limited in ability.
2. **Overcharge protection and charging feedback**: Most products we have analyzed are battery dependant. It is essential that the user is given feedback on charging as overcharging batteries diminishes their life span dramatically, upping user costs.
3. **Simplicity:** Simple lights that are easy to fix are preferable to high-tech, complicated camping lights designed for the American consumer.
4. **Inexpensive:** Many of the quality products that we identified are simply too expensive for the target audience. Upfront costs are incredibly important to people with such high discounting rates. Product costs must come down for LED lighting products to be successful.
5. **Use of batteries which hold large charge:** Lead acid batteries are preferable to AAA and AA batteries as they hold longer charges. As people will not necessarily be able to charge their own light it is necessary that the batteries hold sufficient charge for several days of use.
6. **Quality LEDs and circuitry:** Despite the fact that it is more costly, good quality LEDs are integral to the success of the product. Many of the LED products we tested (especially lanterns) were not even competitive with the baseline hurricane lantern. For LED lights to be competitive they must have an obvious advantage over existing lighting products.

Design of a Submersible Fishing Light

Overview

The majority of the lighting products described above would be best suited for home use, by women and children. Though not the primary focus of this project, we also explored how improved lighting products could be used by fishermen on fishing boats. In Kutch, boats already use dynamos connected to diesel powered boated engines to power electric lights and charge cell phones. In general, the boats are far better equipped with improved lighting than the homes. Some boats use fluorescent tube lights for deck lighting as well as beacons. In general, we do not believe existing LED products would be appropriate for onboard deck lighting since LEDs are not efficient in that capacity; however, LED headlamps (if deemed culturally appropriate) could be useful to fishermen who need hands-free task-lighting for tying knots etc.

During the field trip it was observed, that the fishermen spend long hours (16+ hour/day) at sea trying to maximize their catch, this time could be reduced if they were to use a submersible fishing light to attract fish to their boats. Submersed lights are known to attract fish as evidenced by several patents for the creation of several fishing lights.[5] These lights are commonly used by fishermen, especially bass fishermen, in the US. Fishermen in Africa commonly hold kerosene lanterns close to the surface of the water to attract fish to their boat (Mills, 2006). Use of a fishing light would enable Kutch fishermen to utilize their time at sea more productively, generating extra time for them to get involved in other activities which can augment their income.

It is also important to recognize any potential problems associated with the introduction of a fishing light, specifically overfishing. Unfortunately, the fishermen may not use the fishing light to decrease time spent fishing, but instead use it to increase their catch in order to attempt to pay off middlemen to whom they are heavily indebted. Though most of the overfishing in the area is due to large fishing trawlers, it would be important to ensure that local Kutch fishermen do not adding significantly to the problem. The introduction of a fishing light should be accompanied by an educational campaign related to the dangers of overfishing.

[5]Some of the many fishing light patents:

Hurt, B. (1978). “Fishing Light.”
http://www.google.com/patents?hl=en&lr=&vid=USPAT4190976&id=ktgtAAAAEBAJ&oi=fnd&dq=fish+attracted+light

Crum, D. (1987). “Portable Light.”
http://www.google.com/patents?hl=en&lr=&vid=USPAT4827389&id=LPkrAAAAEBAJ&oi=fnd&dq=fish+attracted+light

Fishing Light Products

Fishing lights were researched and it was found that most existing fishing lights are generally high priced ($200+). These lights generally use high powered green LEDs, since short wavelength light (violet, blue, green) can penetrate water further than other colors.[6] One low priced fishing light (~$25) was found and purchased for analysis. The light has 6 high power green LEDs and a ridged reflecting strip, which the LEDs are pointed at. Therefore, instead of sending light out in beams the device aims to disperse light over the length of the device, causing it to 'glow.' We found the product to be poorly designed. It is hard it is to operate primarily because the batteries are submersed along with the light making it necessary to open and close the waterproof pressure housing in order to change the batteries. Also, there is no switch on the light (a difficult feature to implement in an inexpensive waterproof product), which necessitates opening and closing the housing every time the light is turned on or off. This is bad for the O-Ring seal. When brought the fishing light to Lake Anza (Berkeley, CA) to be tested we found that two of the green LEDs had already failed. The product had only been used approximately five times before testing. We submersed the light into the water (approximately 2 feet deep) and were unable to see a green glow (from the 4 working LEDs), though the water was murky. No fish were seen approaching the light.

As a result of our cursory glance at the fishing light market and our experiences with the inexpensive fishing light product we believe there is a niche in the market for a good quality, low priced fishing light.

FlishLight - The Ultimate in Efficient-SEA: Design of a Submersible Fishing Light

Based on what we learned from the inexpensive fishing light, we brainstormed several different fishing light designs through an iterative sketching process. Our goal was to develop a proof of concept fishing light that would be cheaper and easier to use than the light purchased.

In the end the simplest design was selected and built. This design features a permanently sealed LED light housing (made from clear plastic/glass salt and pepper shakers). No o-ring seal is necessary as the user is never meant to open the housing. The housing is sealed with superglue and waterproof silicon sealant (designed for bathroom use). Power is sent down to the housing through an approximately six foot long tether (which penetrates the housing through a small hole, sealed with the silicon sealant), consisting of a hot wire and ground wire taped together with electrical tape. Twine is tied to the tether with cable ties and used to relieve tension on the wires. Twine is also used to suspend a ballast weight (heavy carabineer) since the housing and submersed components are positively buoyant. The ballast weight serves to make the fishing light slightly negatively

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[6] "Light Transmission in the Ocean." The Ocean Encyclopedia. http://www.waterencyclopedia.com/La-Mi/Light-Transmission-in-the-Ocean.html

buoyant. The batteries are kept in battery cases, soldered to the end of the tether, on board the boat.

We built two fishing lights of this design to compare the performance of six standard 5mm green LEDs (connected in series) to a 1W white LED purchased from Luxeon Star LEDs (www.luxeonstar.com), one of the leading manufacturers of high power LEDs. Note that it would have been more appropriate to use a 1W green LED as that would be more efficient, in terms of power used relating to light penetration. The standard green LEDs are powered by two 9V batteries. No resistor is needed due to the resistance inherent in the 6 foot long tether. The 1W white LED requires is powered by two AA batteries, with power conditioned by a driver circuit (80% efficient). Again no resistor is needed. Specifications for the LEDs and driver circuit are in Appendix I. Note that each standard 5mm LED emits less than 7000 times less light than the 1W LED.

Costs

One of the goals of this aspect of the project was to build a fishing light that is less expensive than the off-the-shelf light we purchased ($24.99). A summary of fishing light expenses is listed below.

Fishing light expenses. The costs listed only contribute to upfront product costs and do not take into account battery/charging costs.

	6 green LED	**1 white LED**
housing	$1.99	$1.49
super glue		
silicon sealant		
twine		
electrical tape	~$1.00	~$1.00
wires		
cable ties		
solder		
LED(s)	$3.87	$6.19
driver circuit	n/a	$9.95
battery clips	$1.04	$1.49
ballast weight	$5.99	$5.99
total	***$13.89***	***$26.11***

Note that the 6 green LED fishing light is significantly cheaper than the purchased light, while the 1W LED light is slightly more expensive (due primarily to the driver circuit). One way to reduce costs would be to find a less expensive ballast weight such as lead fishing weights (note that the purchased light did not come with ballast weight—

fishermen are expected to add their own fishing weights). Unfortunately, it is not fair to directly compare our 6 green LED fishing light to the purchased light because our LEDs were of lower luminous output (this is based on observation – we do not have the actual specifications for the LEDs used in the purchased light). Based on an internet search (ebay and www.ledsupply.com) we estimate that the LED cost would go up two to four fold (depending upon the characteristics of the LED) to substitute high powered green LEDs for the standard bulbs. Still the components of this fishing light would be less expensive than the purchased light. Another option would be to use a 1W green LED as described above but that would necessitate use of a driver. However, with bulk purchasing, manufacturing scale-up, etc. we expect that the costs above (especially for LEDs and drivers) would come down significantly.[7] Therefore, we believe it is possible to build a good quality submersible fishing light for less than the current cost of such lights.

Baseline Testing

A second goal of this aspect of the project was to demonstrate that our lights function better than existing products. Therefore, we tested our two lights along with the purchased fishing light. All tests were qualitative as we were unable to locate facilities to perform accurate underwater product testing.

After building the lights we tested them to ensure that they were waterproof by submersing them in a bucket for several minutes. Though the 6 green LED light did fine, there was a leak in the 1W white LED light and so we had to take it apart and reseal it.

We tested light penetration through water by submersing our fishing lights in Lake Anza (Berkeley, CA) along side the purchased fishing light as described above. Despite the fact that our green LEDs were much lower power than the green LEDs used in the purchased fishing light, we were able to see light emitted by our fishlight at a depth of more than 2 feet (note that the water was also green tinted from algae and incredibly murky). However, we noticed that the green LEDs we used to build our fishing lights were quite directional (20 degree spread) and so emitted light could only be seen when one was looking straight at it.

The 1W white LED fishing light was also quite visible at more than 2 feet depth, and we believe that we could have seen this light at much greater depth if we had been able to submerse it further. The light was not nearly as directional as the green LED light (the white LED features a lambertian spread) and when submerged appeared to have a greenish tint (mostly probably due to the color of the lake as opposed to the fact that green light is better able to penetrate water than warmer colors).

In both cases we did not see any fish approach the lights. Based on our qualitative comparison it seemed as though both of our fishing lights projected light further than the

[7] One Chinese company we approached (Tyreida Industrial Co Ltd) sells 61 LED tasklights (using 36 white LED and 25 red LED) for only about $15.00 each, indicating that inexpensive LEDs are available on the international market.

purchased fishing light which is designed to reflect light over its area. In the future, quantitative measurements are necessary to confirm our observations and more thoroughly compare the products.

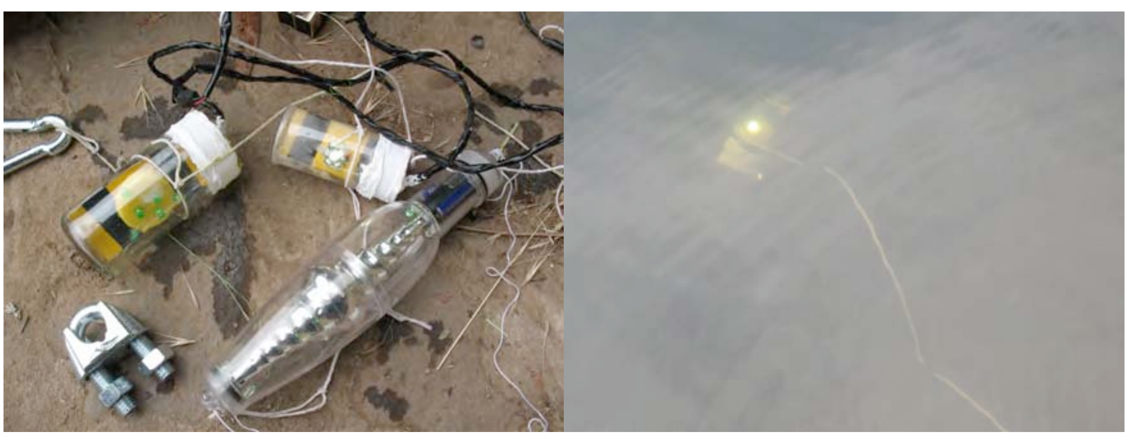
Recommendations for Future Improvements

We have many design recommendations for future improvements to the fishing light:

- The housing should be a completely sealable, spherical container in order to minimize leaking and maximize ability to cope with pressure.
- The wires should penetrate the housing through a secure, waterproof connector. We suspect the leak in the 1W white LED fishing light was due to this seal.
- Silicon sealant should be replaced with durable potting material as the sealant is not designed for prolonged underwater use.
- The housing should be heavier or containing some ballast so that we do not have to add excessive amounts of external ballast.
- It is necessary to experiment with different kinds of high power green LEDs.
- Disposable batteries should be replaced by rechargeable batteries such as lead acid batteries which could be charged by the on board dynamo.

It is also important that we answer several questions before proceeding with this aspect of the project:

- In attracting fish, is it better to have a directional beam of light, or to light up an object?
- What is the concentration of suspended particles in the waters surrounding Kutch? How far does natural light penetrate into the sea in this area?
- What kind of fish are caught in Kutch? Are they attracted to light?
- Are Kutch fishermen interested in this innovation? Do they feel like they catch enough fish already?



Left: Two Flishlight prototypes, above. Right: WLED Flishlight in underwater test.

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Sahjeevan 2007b. Personal communication with Dhairya Dholakia, Sahjeevan, April 2007.

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The Dungeon (and the room next door), Davis Hall

Appendix A. Some LED/LED Lighting Manufacturers and Suppliers

Don’s Green Store:
www.shop.donsgreenstore.com/splashPage.hg
Lighting Science Group:
store.lsgc.com
Super Bright LED’s Incorporated:
www.superbrightleds.com/cgi-bin/store/commerce.cgi?product=MR16
The LED light:
www.theledlight.com/
LED Neon:
www.ledneonflex.com/
Edmund Optics:
www.edmundoptics.com/US/onlinecatalog/displayproduct.cfm?productID=2819
Phocos – Solar Energy System Components
www.phocos.com
Solar Illuminations:
www.solarilluminations.com/
The Lightup Company:
www.thelightupco.com/THE_LIGHTUP_CO/The_Lightup_Cx.html
Lux USA Tasklight:
www.luxous.com/
Permlight LED Estimator:
www.ledestimator.com/
CREE:
www.cree.com/
Advance:
www.advancetransformer.com/products/led.jsp
LED Supply:
www.ledsupply.com/
LED Dynamics:
www.leddynamics.com
Light World:
www.lightworld.com
List of LED manufacturers (found on scrolling down):
www.electronics-manufacturers.com/Lighting_products/LED_lamps/
Kingbright Corporation:
www.us.kingbright.com
Dialight Lumidrives:
www.lumidrives.com
Nichia:
www.nichia.com
Colour Kinetics:
www.colorkinetics.com
Luxeon Star LEDs:

www.luxeonstar.com
Radioshack:
www.radioshack.com
Phillips LumiLeds LED Lighting:
www.lumileds.com
Petzl:
en.petzl.com
Princeton Tec:
www.princetontech.com
BoGo Light:
www.bogolight.com
Thrive Light:
www.thrive.in
Cosmos Ignite Innovations:
www.cosmosignite.com
Freeplay Energy:
www.freeplayenergy.com
d.light design
www.dlightdesign.com
Lucky Marine 4 Foot LED Fishing Light:
www.bluemarlinchronicles.com/hotspot_fishing_lights.htm
BassPro:
www.basspro.com
Hydro Glow Fish and Dock Lights:
www.luresonline.com/shopping/hydro_glow.html

Appendix B. Products Purchased

Light Code	Country of Purchase	Bulb	Type	Battery	Charging	Charge Time	Price
A	USA	9 LED	Flashlight	3 alkaline AAA	N/A	N/A	$7.95
B	India	9 LED	Flashlight	3 alkaline AAA	N/A	N/A	
C	USA	6 LED	Flashlight	3 NiCd/NiMH AA (rechargeable)	Solar	8 hours	$12.50
D	India	1 LED	Flashlight	3 alkaline AA	N/A	N/A	
E	India	1 LED	Tasklight/Flashlight	1 NiMH (rechargeable)	Charge cable/ Solar	"a full day"	$50.00
F	USA	1 LED	Lantern/Flashlight	3 alkaline AAA	N/A	N/A	$20.00
G	USA	1 LED	Headlamp	3 alkaline AAA	N/A	N/A	$49.95
H	India	15 LED	Tasklight/Nightlight	Lead Acid (rechargeable)	Charge cable	16-24 hours	$12.00
I	Bangladesh	1 CFL	Tasklight/Nightlight	Lead Acid (rechargeable)	Charge cable	16-24 hours	$7.21
J	USA	8 LED	Lantern/Nightlight	NiMH (rechargeable)	Charge cable/ Hand	15 hours, 60 second wind = 5 minutes	$39.95

K	USA	2 LED	Flashlight	Dynamo	Hand	Unknown	$6.95
Light Code	**Country of Purchase**	**Bulb**	**Type**	**Battery**	**Charging**	**Charge Time**	**Price**
L	USA	1 LED	Flashlight	Dynamo	Hand	1 minute pump = 30 minutes	$12.95
M	USA	# LED	Flashlight	Dynamo	Hand	1 minute crank = 20-25 minutes	$5.95
N	USA	6 green LED	FishingLight	3 alkaline AAA	N/A	N/A	$24.99

Appendix C. Charging Options Matrix

The most promising charging options are highlighted yellow.

	Scale	Infrastructure cost	Recurring costs	Energy efficiency	Main infrastructure	Life Span	Maintenance
Solar - PV	Large or Small scale	High	None	Poor	PV cells	Long	Low maintenance
Solar - Concentrator	Large scale	Very High	None	Moderate	Mirrors, Thermal element	Long	Low maintenance, skilled operators needed
Grid	Large Scale	Very High	Maintenance	Moderate	Distribution network and power plant	Long	High maintenance costs
Small-scale hydro	Small Scale	Very High	Maintenance	Dependent on water source	Pelton wheels, turbines	Long	High maintenance costs
Wind turbine	Small Scale	High	None	Moderate	Shafts, gear boxes, anemometers, rotor, tower, wind vanes	Long (~20 years)	Low maintenance costs
Generator - Diesel	Small and centralized	Mid	Fuel	Moderate	Generator	Mid	Low
Generator - Propane	Small and centralized	Mid	Fuel	Moderate	Generator	Mid	Low
Generator - Biofuel	Small and centralized	Mid	Fuel	Dependent on fuel source	Generator	Mid	Low
Dynamo	Very Small scale	Very Low	None		Dynamo	Short	None
Pedal Generator	Small Scale	Very Low	Maintenance		Bicycle generator	Short	Routine maintenance
Linear generator	Very Small Scale	Very Low	None		Magnet, coil	Short	None

Appendix D . Battery Comparison Matrix

The most promising battery options are highlighted in yellow.

	Upfront Cost	Life span
NiMH/NiCd	Affordable	2 years
Li-ion	Expensive	24 - 36 months
Lead Acid batteries	Affordable	6 months
Capacitors	Varying costs	Long
Alkaline	Affordable	Short (Not rechargeable)

Appendix E. Light Testing Performed

Light Code	Distribution Plot?	Run Down?
A	y	y
B	y	y
C	y	y
D	y	y
E	y	n
F	y	n
G	y	n
H	y	y
I	y	y
J	y	n
K	n	y
L	n	n
M	n	n
N	n	n

Appendix F. Sample MATLAB Code

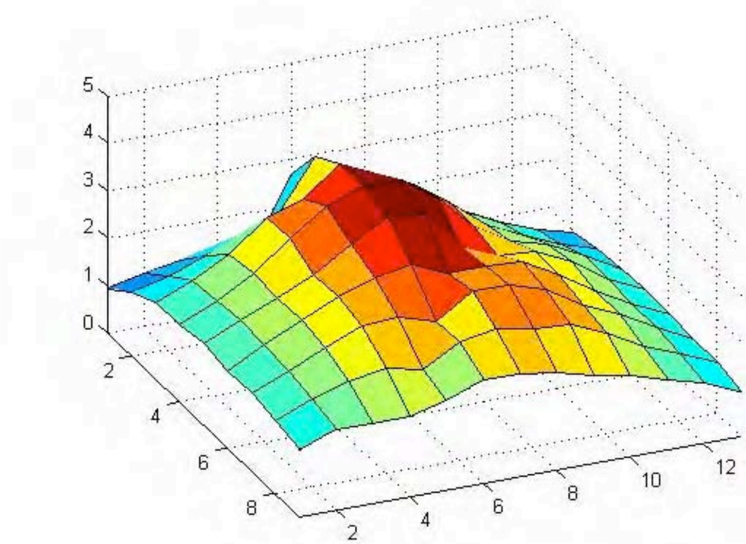
This MATLAB code was used for creating the mesh plots in the following appendix. A different program was written for each type of product (flashlight, lantern, etc.) and each orientation (pointed at wall, on table, etc.). We have only included our code used to plot flashlight lux measurements since the code is quite repetive.

```
function plotflashlight(col)

%distance of gridlines in meters
gridli=4/39.37;

%import the data from excel spreadsheet
spread=xlsread('plotdata');
x=spread((4:120),col);
centerdistance=spread(128,col);
[center,I]=max(x);

%assign the points to the grid (note that the grid was numbered 1 to
117)
d(1,:)=x(1:9);
d(2,:)=x(10:18);
d(3,:)=x(19:27);
d(4,:)=x(28:36);
d(5,:)=x(37:45);
d(6,:)=x(46:54);
d(7,:)=x(55:63);
d(8,:)=x(64:72);
d(9,:)=x(73:81);
d(10,:)=x(82:90);
d(11,:)=x(91:99);
d(12,:)=x(100:108);
d(13,:)=x(109:117);

%calculate distances
x=floor(I/9)
y=mod(I,9)

for n=1:13
    for m=1:9
        distance(n,m)=sqrt(((x-n)*gridli)^2+((y-
m)*gridli)^2+centerdistance^2);
        theta(n,m)=acos(centerdistance/distance(n,m));
        newdistance(n,m)=1/cos(theta(n,m));
        newd(n,m)=distance(n,m)^2*d(n,m)/newdistance(n,m)^2;
        newd1m(n,m)=distance(n,m)^2*d(n,m);
    end
end


%generate the mesh plot
[X,Y] = meshgrid(1:1:9, 1:1:13);
surf(X,Y,newd)
axis([1 9 1 13 0 50])
```

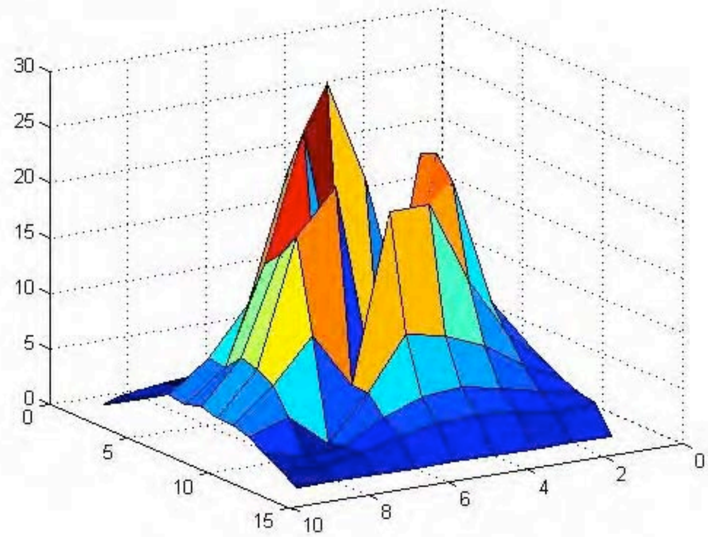
Appendix G. Light Distribution Plots

Please note that most of the plots are not on the same scale. This was done to preserve light distribution characteristics. Each unit on the x and y axes is equal to 4 inches. The z axis is measured in lux.

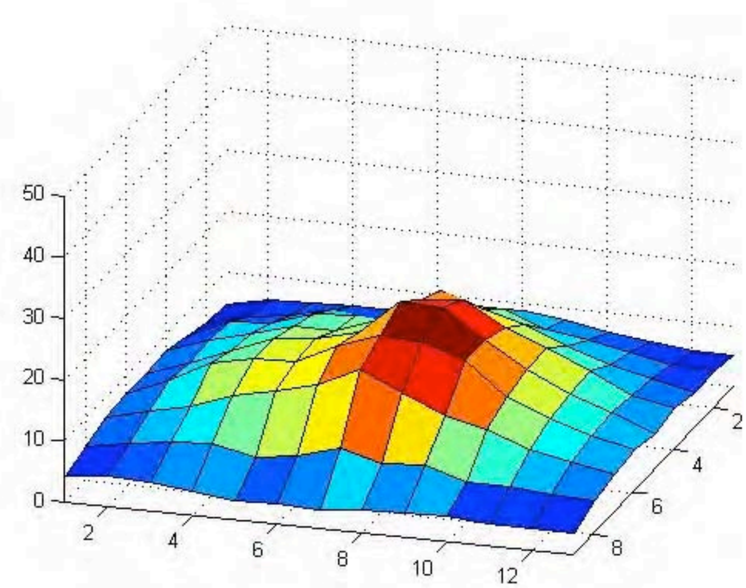
Hurricane (Kerosene) Lantern – (pointed at wall, 1m away)
Note the two distinct humps. This is due to the orientation of the lantern wick.



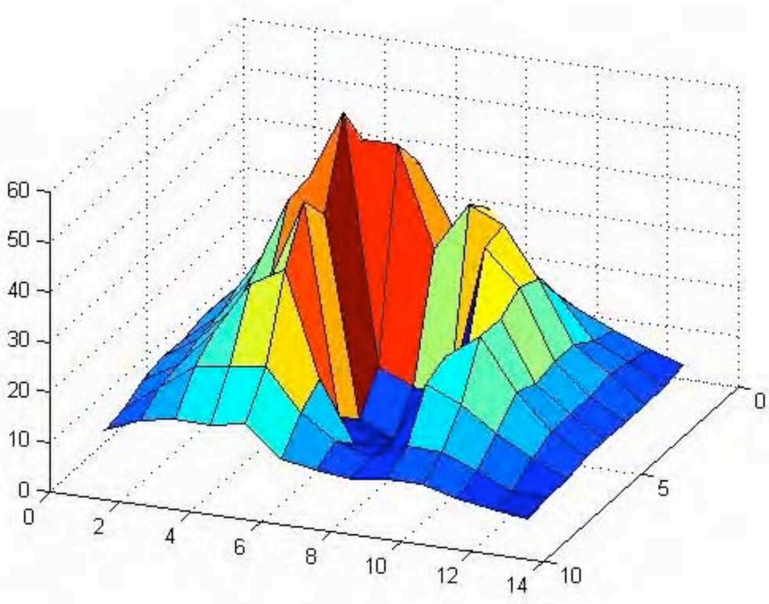
Hurricane (Kerosene) Lantern – (on table)
The lantern sat at the center of the plot. The spikes are due to our method of measurement (measurement taken at rectangular grid nodes despite that fact that the light is approximately radial symmetric. Note the line of low lux levels. This is due to the physical structure of the lantern, which has two rods that hold the glass and block light.


30
25
20
15
10
5
0
0
5
10
15
10
8
6
4
2
0

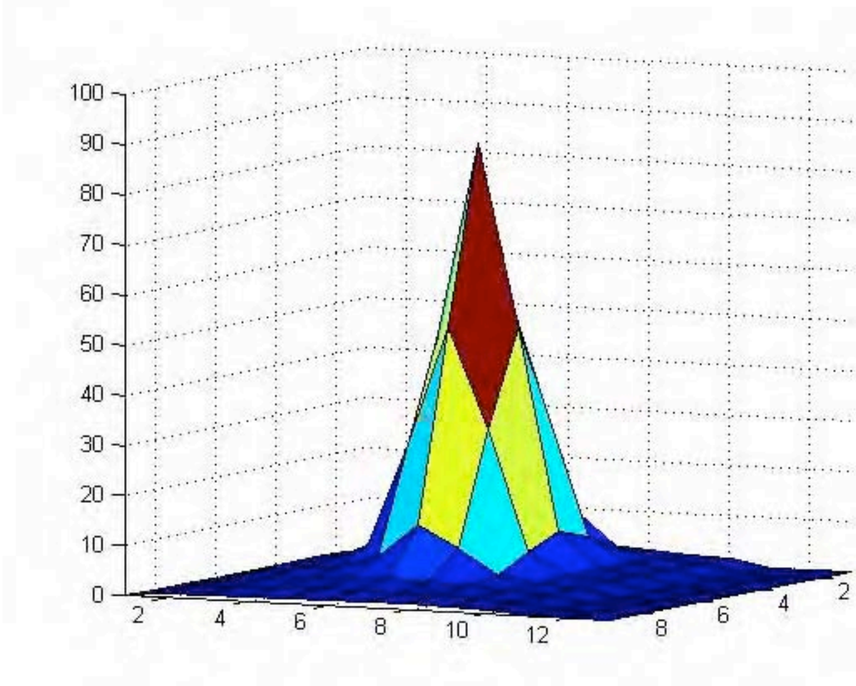
Petromax (Kerosene) Lantern – (pointed at wall, 1m away)
Note the scale. The Petromax puts out significantly more light than the hurricane lantern.



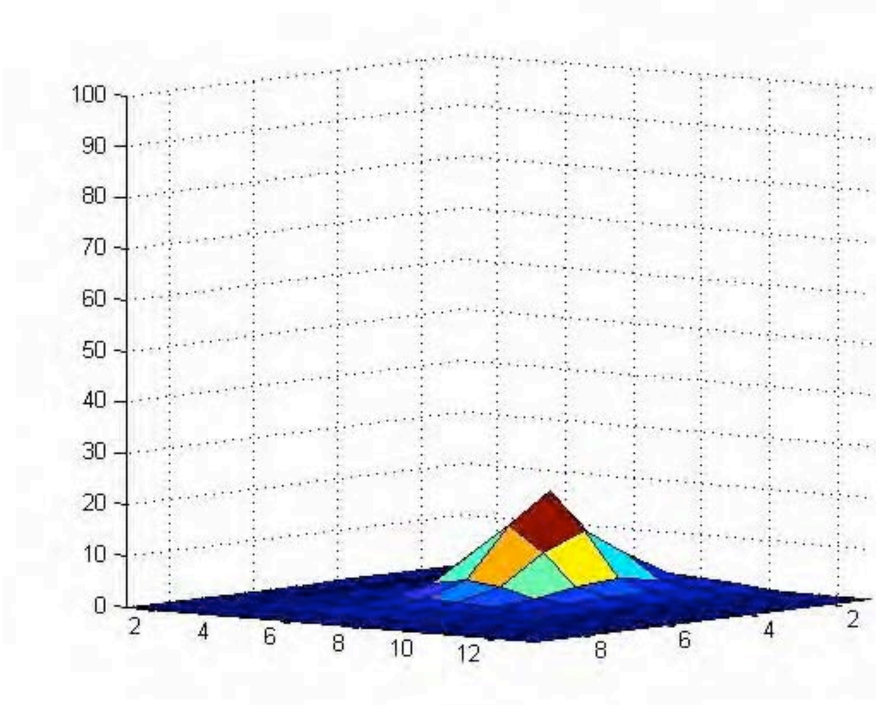
Petromax (Kerosene) Lantern – (on table)
The lantern sat at the center of the plot. Notice that one side of the lantern put out significantly less light than the other. This is primarily due to an excessive amount of soot buildup on that side of the lantern during testing.



Flashlight A

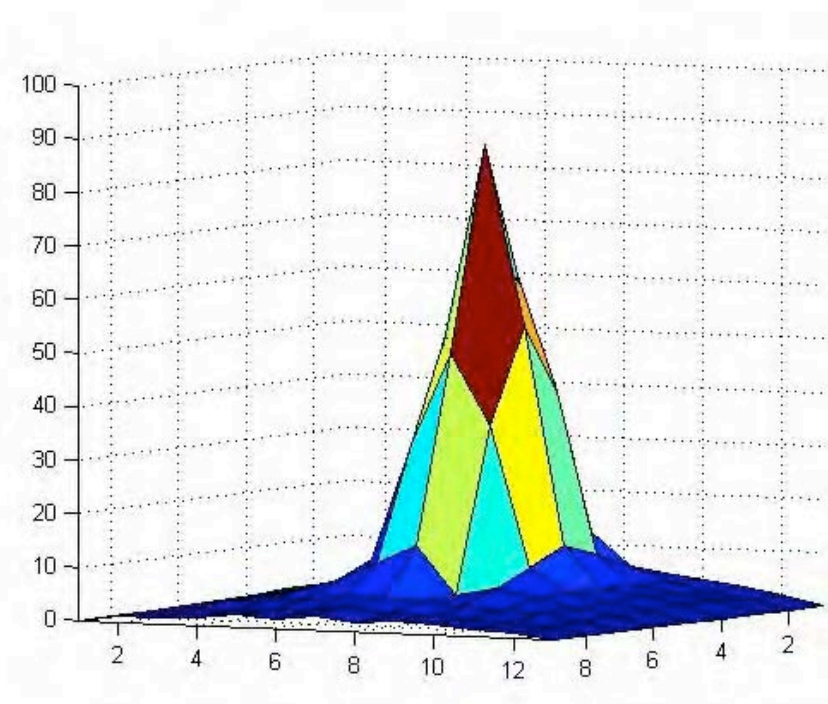


Flashlight B

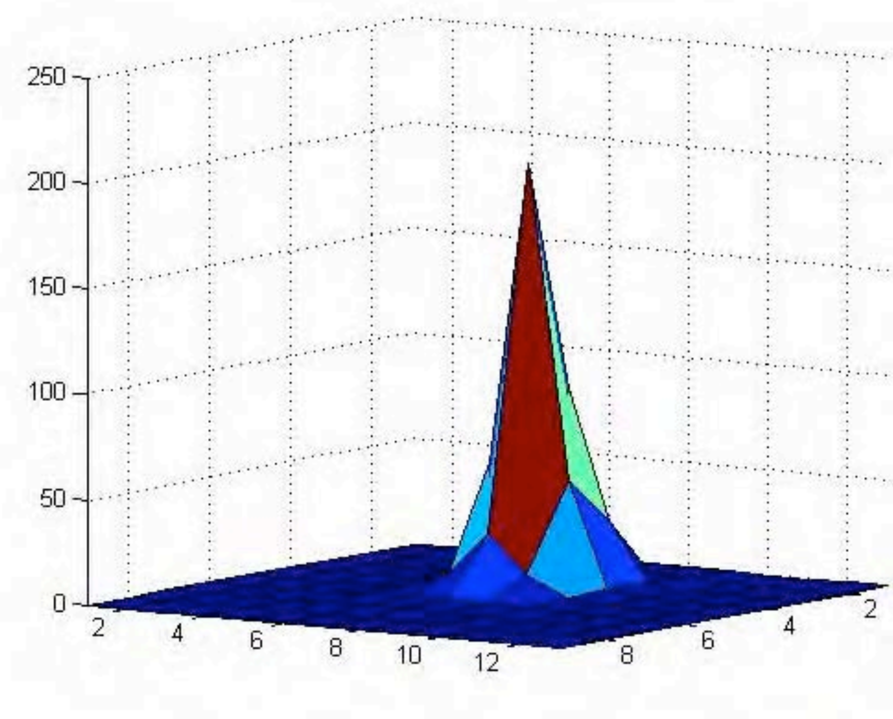


Flashlight A and B were plotted on the same scale to demonstrate the enormous difference in light output between the two lights that are physically indistinguishable (besides color). Note that Flashlight A was purchased in the USA and Flashlight B was purchased in India.

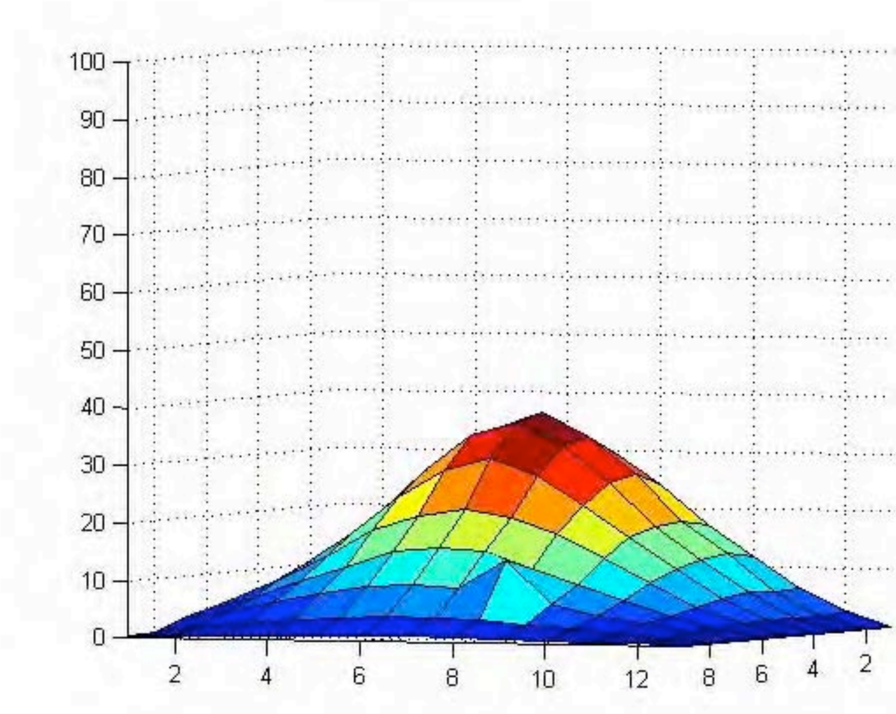
Flashlight C



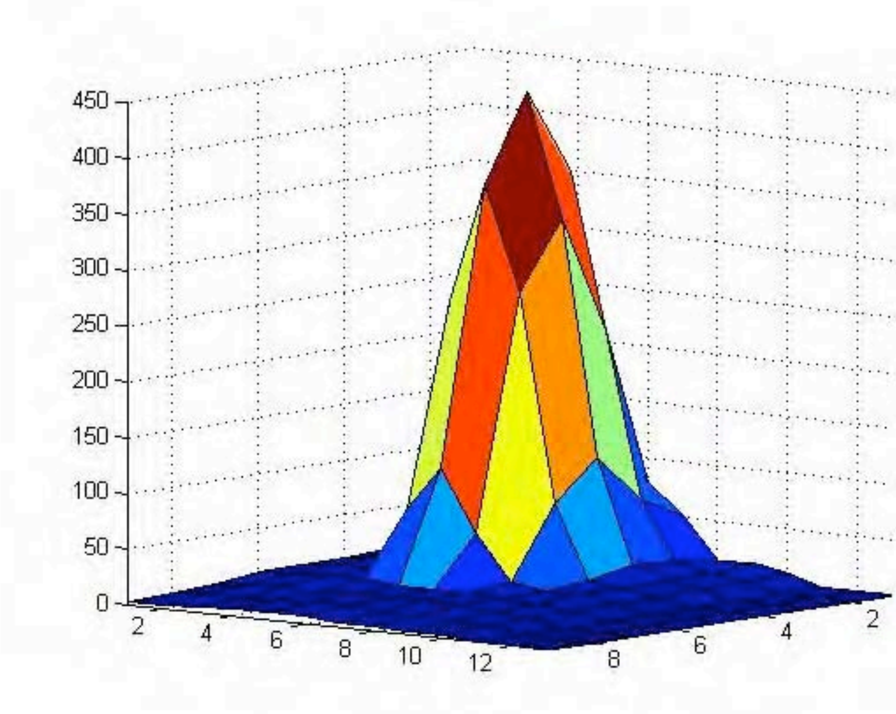
Flashlight D
Note the scale. This flashlight is much brighter than Flashlights A, B, and C.



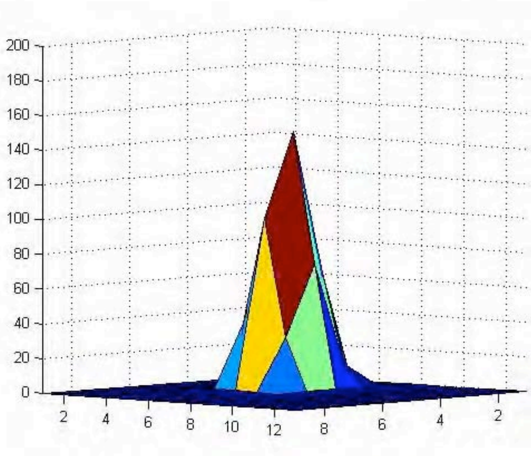
Flashlight E – Diffuse Setting
This flashlight features an optional diffuser.



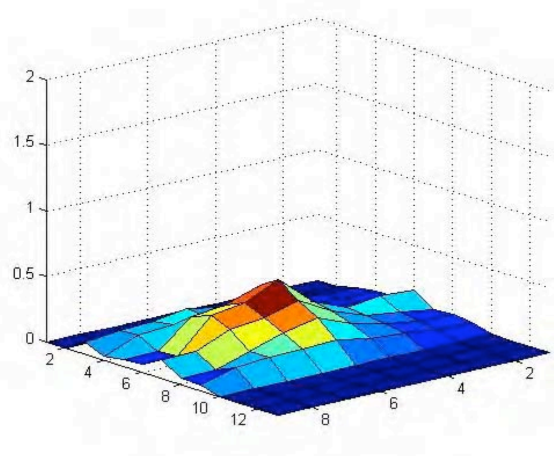
Flashlight E – Focused Setting
The same flashlight as above without the diffuser. Note how the beam is not as focused as that of the Flashlights A-D. Moreover, it is much stronger.



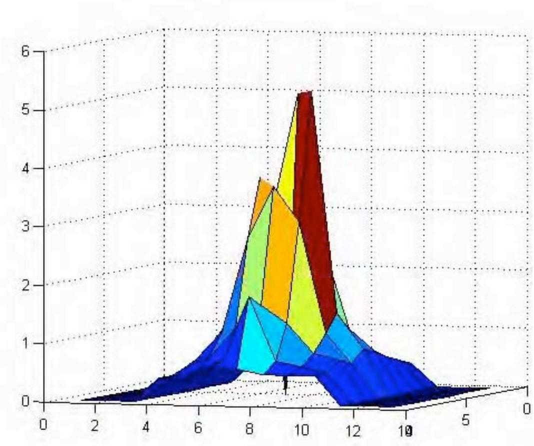
Light F – Flashlight Setting
This light has two modes: flashlight and lantern. The flashlight is quite strong.



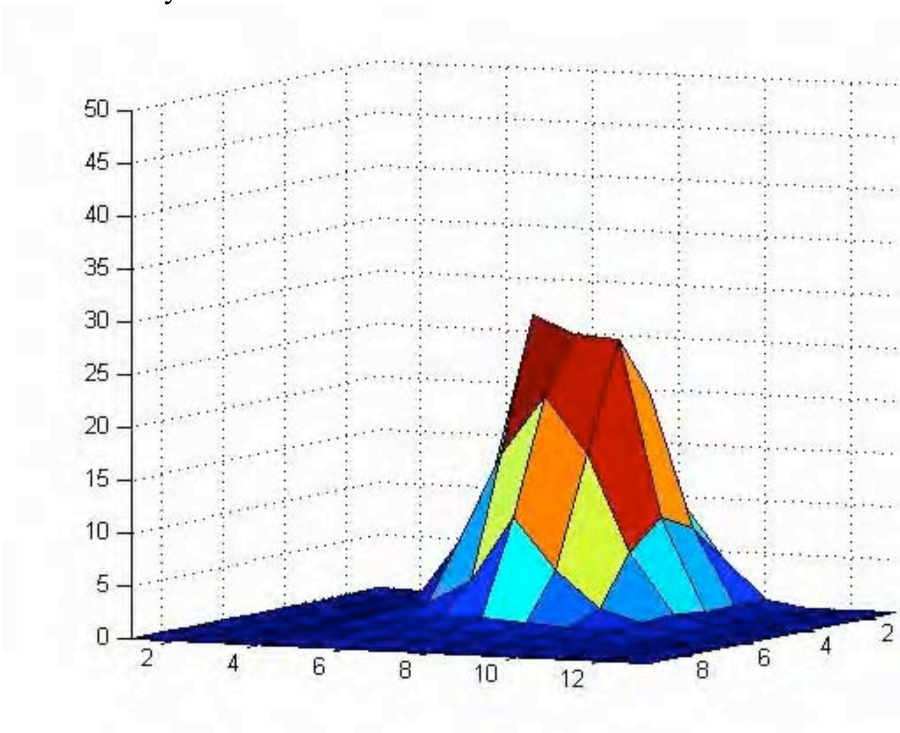
Light F – Lantern Setting (pointed at wall, 1m away)
Note the vertical scale. This lantern puts out less light than the hurricane lantern.



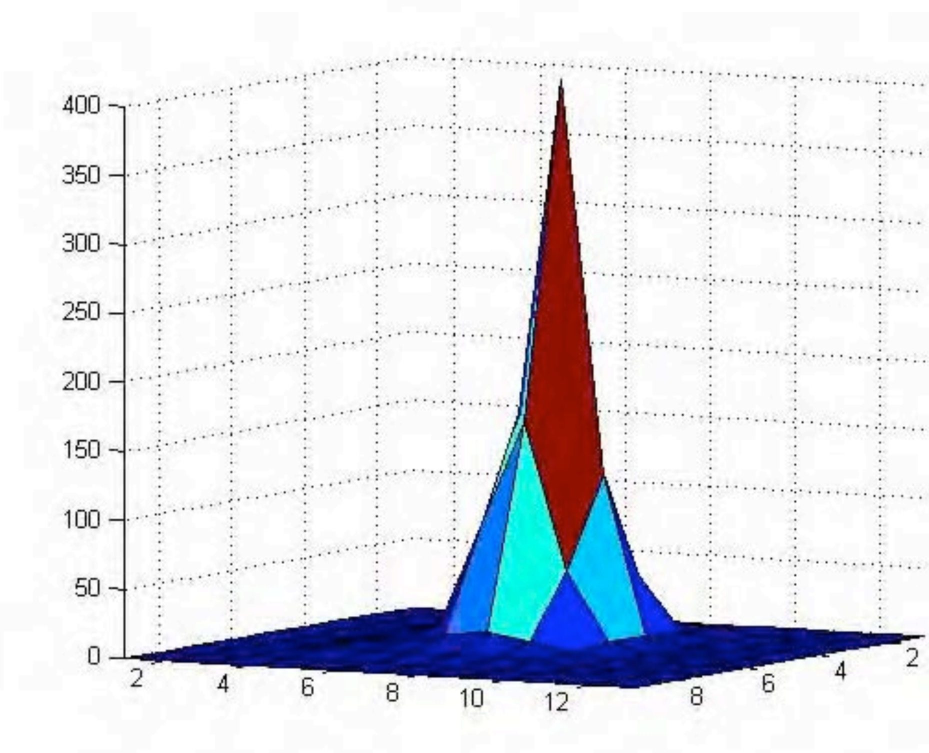
Light F – Lantern Setting (on table)
Again note the vertical scale.



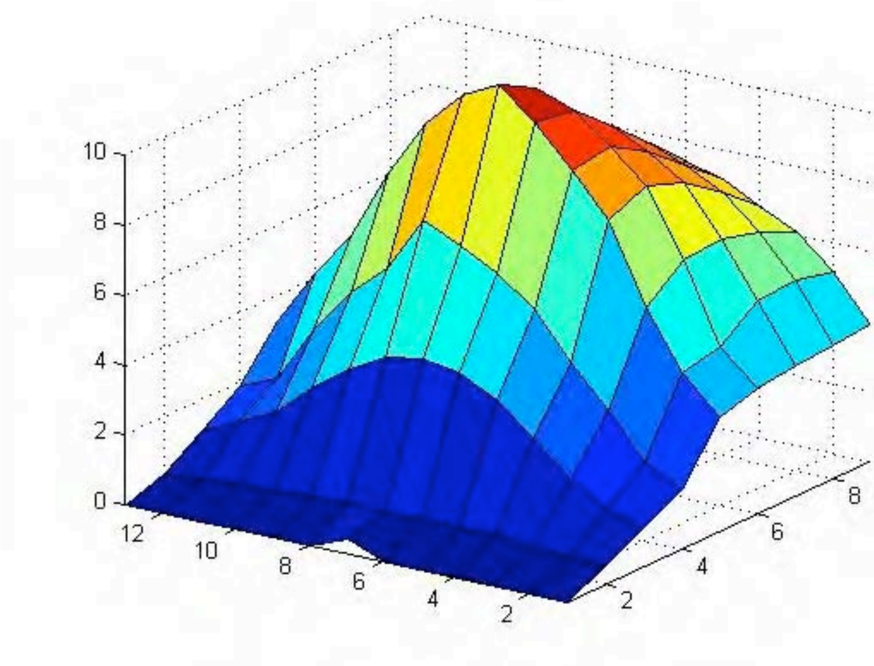
Headlamp G – Diffuse Setting
The headlamp features several settings including a diffuse setting. Note how the beam is still relatively focused.



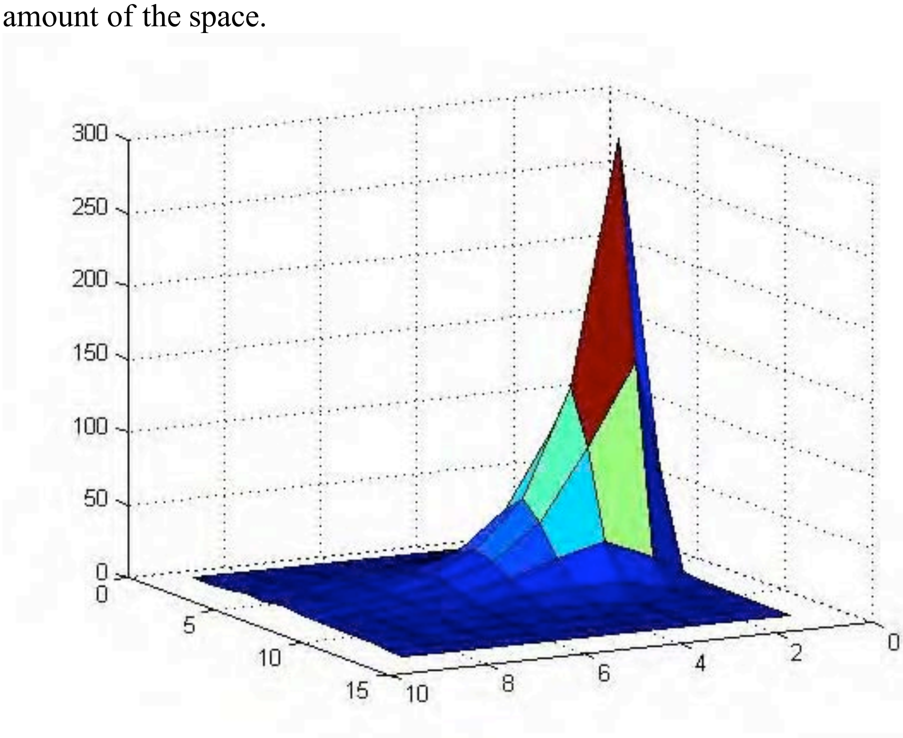
Headlamp G – Focused Setting
The focused headlamp is very strong.



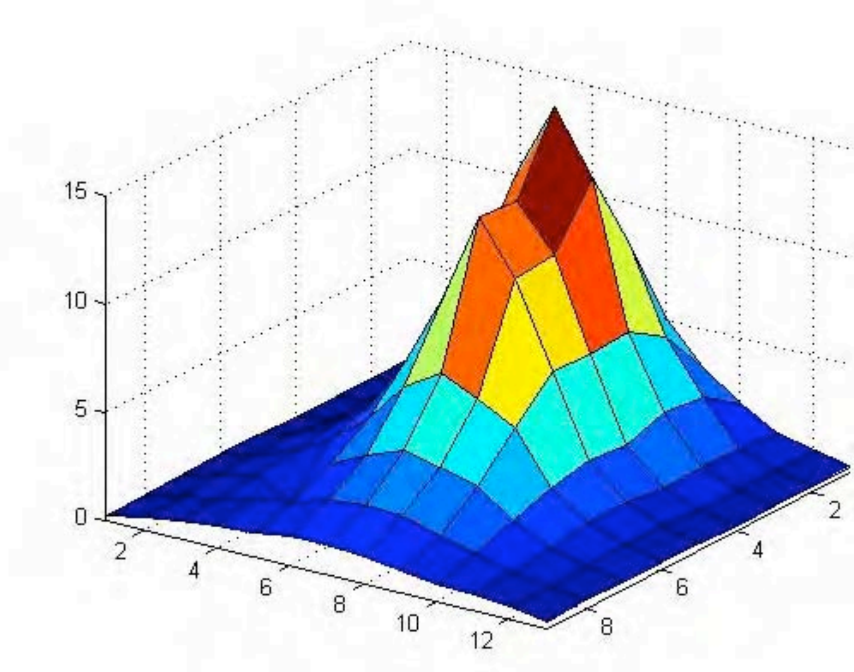
Tasklight H – (pointed at table, 1 m away)
This LED tasklight puts out diffuse light if hung 1m from the table (note that it is made to point down so we did not measure lux when pointed at the wall). The scale is small; however, this light is not really designed to be this far away from the surface it lights up.



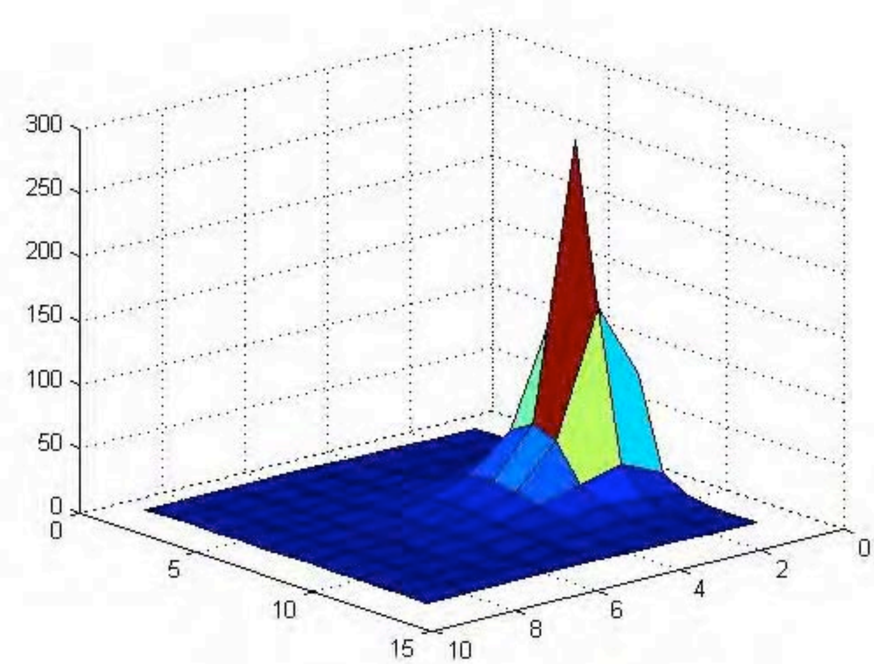
Tasklight H – (on table)
When placed directly on the table this light project most of its light onto a very small amount of the space.



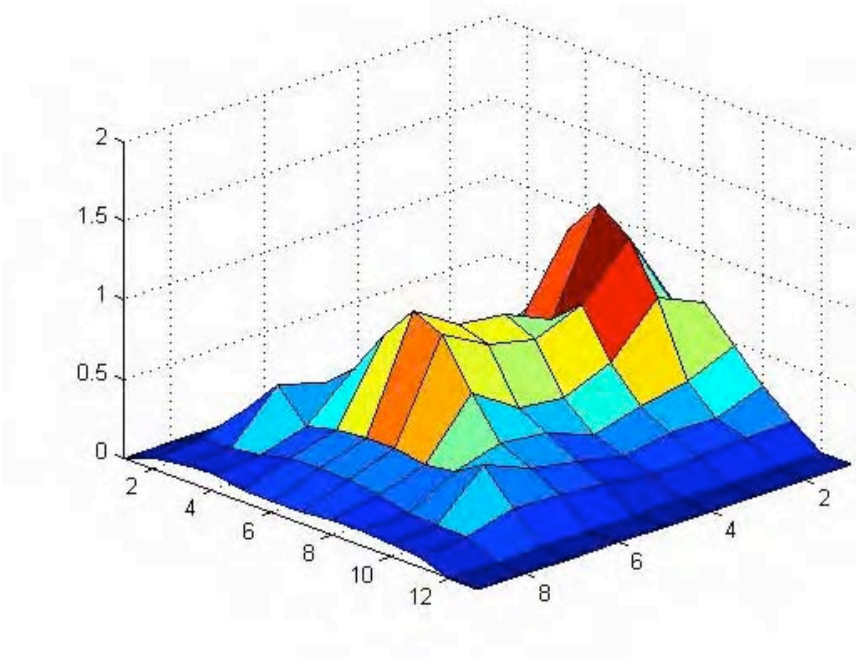
Tasklight I – (pointed at wall, 1m away)
This CFL tasklight is a great improvement over the hurricane lantern, but still not as strong as the petromax. Note the two distinct humps caused by the bulb.



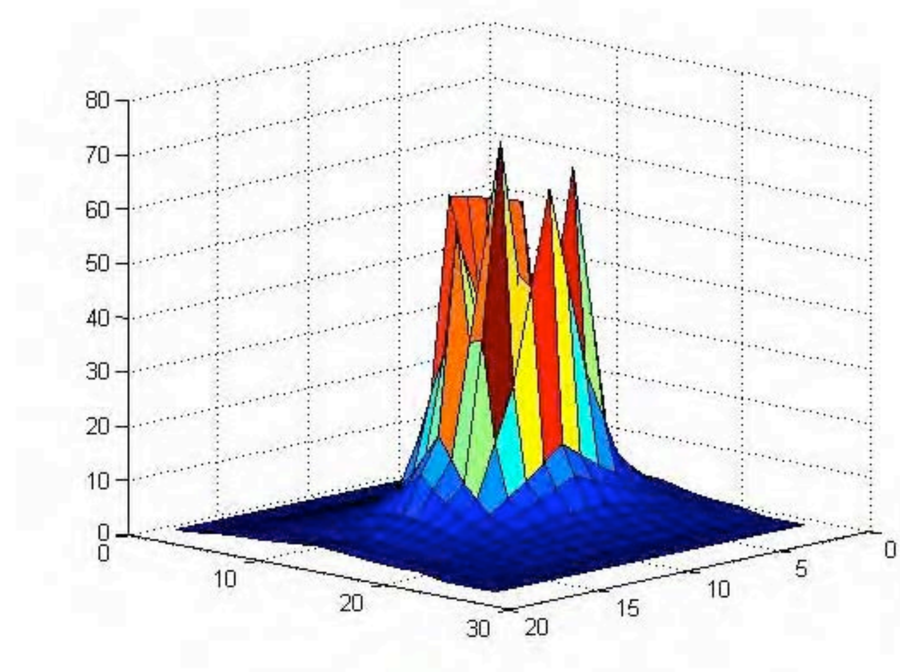
Tasklight I – (on table)
Like tasklight H when placed directly on the table this light project most of its light onto a very small amount of the space.



Lantern J – (pointed at wall, 1m away)
This LED lantern is quite weak. Note the light output trends caused by the optics.

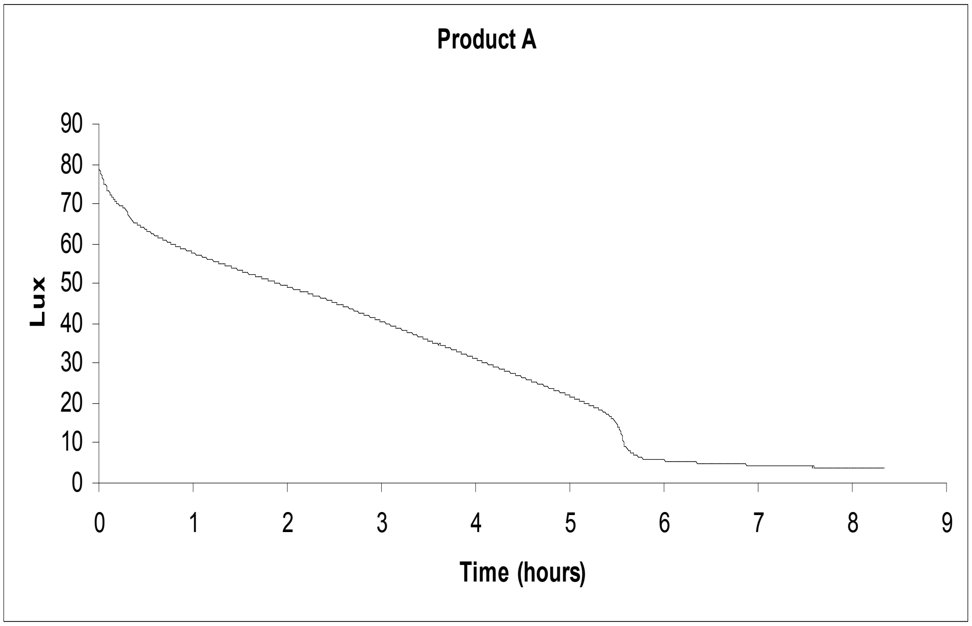


Lantern J – (on table)
The lantern sat at the center of the plot. Note that we took more data points for this light to better capture the radial symmetry of light output; however, our measurement method (collecting measurements at rectangular grid nodes) continues to be a problem, causing a spiky plot. Notice how the light does not go much further than the radius of the product.



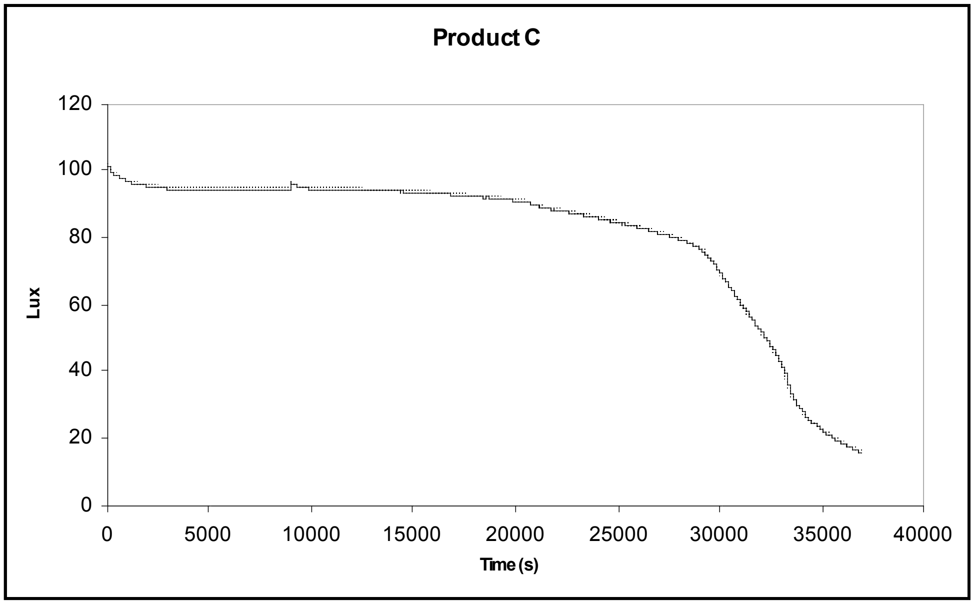
Appendix H. Discharge Plots

Flashlight A
Note how this flashlight discharges steadily over time. Clearly it does not use circuitry to control light output.



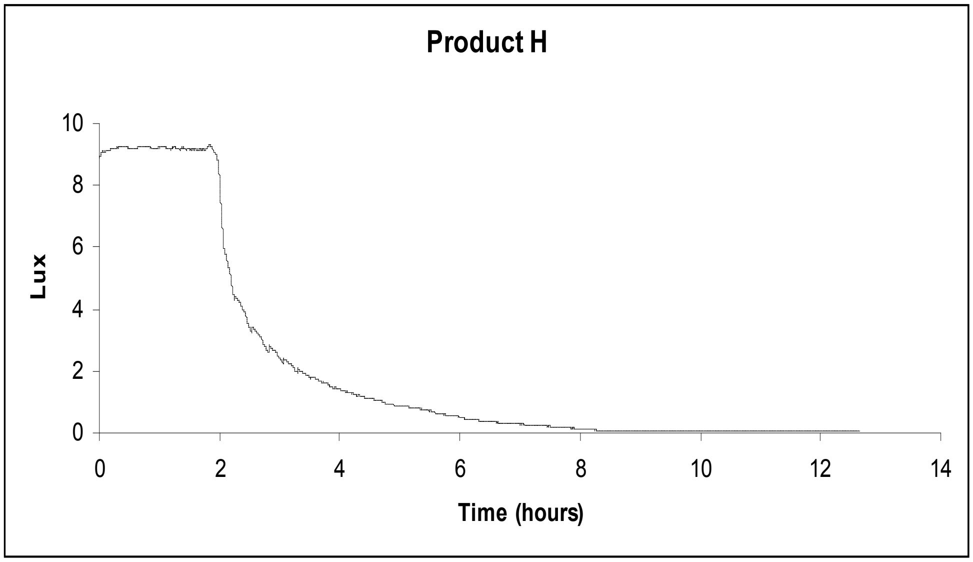
Flashlight B
Unavailable due to technical difficulties with datalogger.

Flashlight C
This flashlight, rated to five hours of use, clearly uses appropriate circuitry, giving it a much longer life at near full charge.

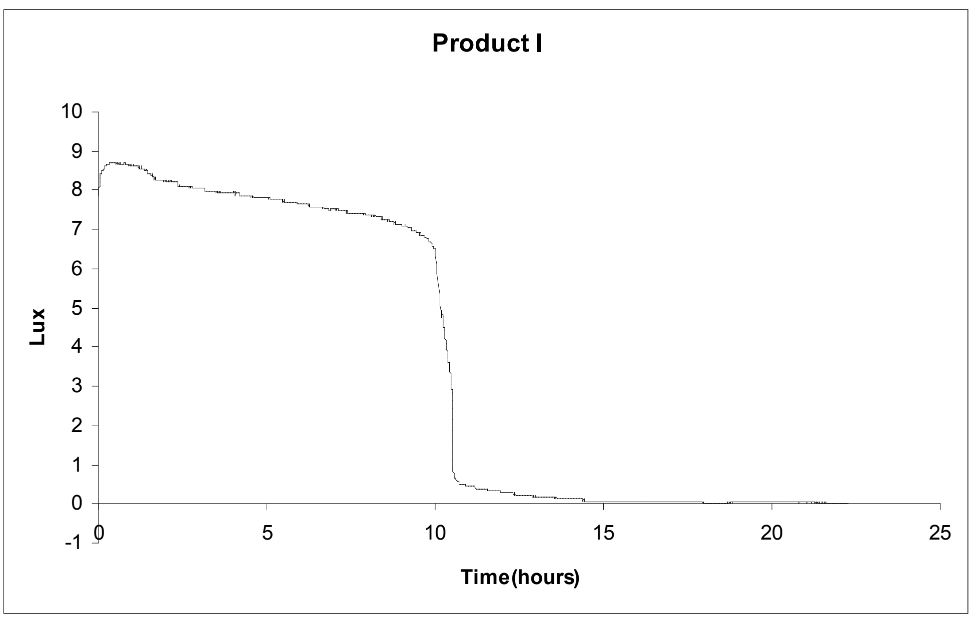


Flashlight D
Unavailable due to technical difficulties with datalogger.

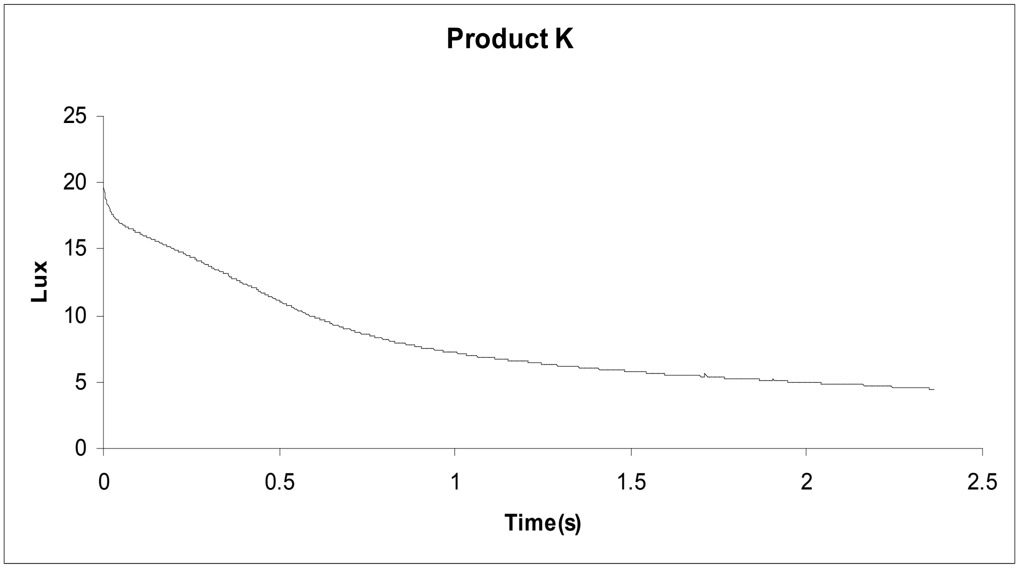
Tasklight H
This product is rated to 75 hours of use but only lasted about 2 hours in our test.



Tasklight I
This product is rated to 5 hours of use and lasted about 10 hours.



Light K
This product is hand powered.



Appendix I: Fishing Light LED Specifications and LED Driver Specifications

Various LEDs

The fishing lights were built with 5mm green LEDs and a 1W White LED. A better option would be to use a 1W Green LED or higher illuminance 5mm green LEDs. For comparison, a typical white LED's specifications are also given.

	5mm Green (typical)	1W Green (Luxeon star)	5mm White (typical)	1W White (Luxeon star)
Wavelength	565nm	530nm	various	5500k (dominant)
Viewing Angle	30 degrees	Lambertian	~180 degrees	Lambertian
Max Current	10mA	350mA	20mA	350mA
Typical Voltage	2.2V	3.42	3.6V	3.42
Illuminance	0.0063 lumens	53 lumens	1 lumen	45 lumens
Cost	$0.65	$5.69	$5.29	$6.19

LED Driver

LED drivers can be used to condition battery voltage and current, facilitating the powering of high power LEDs or strings of LEDs with out the need for more batteries in series. These specifications are given as an example of driver specs.

Input Voltage	3V
Output Current	350mA
Max Output Voltage	8V
Max Output Power	1.5W
Efficiency	80%
Cost	$9.95

Appendix J - Companies/NGOs making lights for the poor

Thrive, India (http://www.thrive.in)

Thrive is an NGO that addresses rural health, education and technology. They have created a spinoff company called Thrive Energy Technologies Pvt Ltd. Thrive won the World Bank's Development Marketplace award to design an energy efficient off-grid lighting product. Their product, a lantern, is the most popular LED off-grid light in use by the poor in India. The lantern uses a lead-acid battery that is charged off the grid.

Andslite, India (http://www.andslite.com/)

Andslite is a New Delhi based company that sells LED flashlights in India. All their lights use replaceable batteries. There is a significant cost difference between disposable and rechargeable batteries in the Indian market. Andslite has a wide range of products and most are very affordable.

Cosmos Ignite, India (http://www.cosmosignite.com/)

Cosmos Ignite is a spinoff company from a group of Stanford students who designed an LED light for off-grid use by the poor. It is based in New Delhi and makes just one product called the MightyLight. The product is extremely expensive at this point. It comes with a solar panel for charging.

Sunnight Solar, USA (http://www.bogolight.com)

The Bogo light designed by Sunnight solar is targetted specifically at the global poor who do not have access to the grid. It is an LED light that can be charged in 2 ways: through an integrated solar panel on the side of the light or by directly charging the 3 AA batteries in a separate battery charger.

Sollatek (UK) Ltd, UK (http://www.glowstar.net)

Sollatek sells the Glowstar CFL lantern which was designed by the Intermediate Technology Development Group (ITDG). The light was sepcifically designed for African communities without grid access. However, it appears as though the price is exorbitantly high (81 GBP). The lantern is also functions as a universal charger.

Freeplay Energy Plc, UK (http://www.freeplayenergy.com)

Started by UK entrepreneurs with the goal of providing modern lighting and communication services to all. Their primary product for this market is an LED lantern that can be charged through the grid power or by a hand crank.

Appendix K - Contacts

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