The Blind Leading the Blind: What's Wrong with White LEDs

A Technical Analysis of White LEDs and Why They Suck for Caving, At Least For Now
By C. Taylor

The marketing hype surrounding white LEDs just does not hold up to scrutiny. While white LEDs may suit the miserably small caves that we have in abundance in New England, if you want to avoid groping in the dark and going around in circles, not to mention falling down poorly lit drops, forget about white LED lamps. Go out and buy a real headlamp that can produce 50 lumens of light such as a Petzl Duo with an FR500 halogen bulb. And if you insist on using **ANY** lamp that takes four or fewer AA cells, use only Energizer e2 or similar lithium / iron sulfide batteries, which can handle the load, not conventional alkaline AAs, which fare poorly in most headlamps of adequate brightness for caving.

I first knew something was amiss with white LEDs in July of 2004, when James Keary, Adam Dobson, Manos Pothos and I spent a long weekend caving in big passages in West Virginia. Everyone used a white LED headlamp except for me. I used an old Justrite electric headlamp, and unlike my buddies, I could actually see where I was going. James was even using the latest Nova white LED headlamp from Speleo Technics, which seemed to make no difference whatsoever.

We came down from an upper level passage in Buckeye Creek and walked a few feet around some breakdown in the main stream passage. I think it was James that said, "Look, there is ***another*** upper level passage. Let's check it out!" This was the exact same passage that we had just come down from. I was the only person that could see it clearly enough to recognize it.

The Evolution of Cave Lamps

Okay, this is not a comprehensive history, and some of you may take issue with exact dates and details, but here is a brief history of cave lighting leading up to the present sorry state of affairs with cavers going around in blind circles in caves of any size.

5,000 BC or earlier. The Lord said "Let there be light," and there was, and it was good. However, it did not illuminate caves very well, except for caves in Eastern Massachusetts, which even back then were not very deep or long. Even in places with big deep caves, Man limited his caving mostly to cave entrances where he built fires to stay warm.

4,999 BC – 1,500 AD. Man used cane torches for illumination in caves. I have seen remnants of cane torches in the Flint-Mammoth system. Presumably a few hours of light required carrying a huge bundle of cane and a leather cave pouch containing at least threes sets of flints.

Note: According to some archeologists, man used primitive oil-based wick lamps made out of clay around 18,000 BC, but creationists disagree.

1600s – 1915. Miners in the U.S and Europe adapted the tallow candle, the handheld coal oil lamp and later the kerosene lamp for mining and caving. One of the most popular lamps, the Wolf Safety Lamp, used naphtha as its fuel, and a wire screen to reduce the probability of igniting flammable mine gases. The brightest of these lamps produced about 0.9 to 1.0 candlepower of illumination. Saltpeter miners around the time of the Civil War used burning bundles of lighter wood commonly called faggots for illumination in Sinnett, Trout, New Trout, and Cave Mountain caves, West Virginia.

Early 1900s – 1940s. James Morehead and Thomas Wilson developed an economical way to make calcium carbide in 1892 (see http://www.ray-vin.com/cat/smoker/carbide.htm). Carbide reacts with water to produce acetylene gas. By 1892, several companies had developed carbide lamps of various types for use on carriages and bicycles. The first known use of carbide for underground illumination occurred in 1897 in the Millgrove Mining Region of New South Wales. The U.S. Government granted the first patents on carbide lamps to F E Baldwin and the John Simmons Company in 1900.

The carbide lamp quickly displaced oil lamps and candles in mines, although the safety lamp was still preferred in coalmines known to have high concentrations of methane gas. Furnished with a reflector, a carbide lamp has an effective candlepower between 4.2 to 6.2. The founders of the NSS used carbide cap lamps for caving at least as early as the late 1920s and early 1930s.

Early carbide lamp makers included Springfield Lamp Co., Shanklin Mfg. Co., Wolf, Elkhorn, Buddy, and Grier Brothers. At the height of the carbide lamp's popularity, more than a dozen manufacturers made them, including Hansen, Drylite, Force Feed, Maple City, Ever Ready, Snell, Schneiders, Oshkosh, Maumee, Scoby, Arnolds, Koehler, Guy Dropper, Autolite, Premier and Justrite. The finest of the carbide lamps resembled technological works of art and sported machined cooling fins, multiple chambers and fine adjustment screws.

1940s – Present, electric filament lamps: By the 1940s, most miners had adopted electric headlamps. A few enterprising individuals used these for caving. One of the most popular of the mine-approved lamps was the Wheat lamp, which used a dual-filament bulb and a very sturdy cord connected from the cap lamp to a lead acid battery worn on the belt. The dual filament bulb had two settings, bright and normal, and a three position on / off brightness selector switch. The Wheat lamps gave off about six candlepower and could last 12 hours when fully charged.

1960s. The electric Justrite. While somewhat cheesy in construction, with a half amp three-watt bulb, these produced several candlepower of light. Best of all, the 4D cell battery pack could provide illumination for 10 hours. However, Electric Justrite cavers faced derision from carbide cavers, who regarded the Electric Justrite as cheap and unreliable compared to the Cadillac boat anchor Wheat Lamp.

Early 1970s. The plastic Justrite. Around this time, in an effort to stem rising costs and a declining market, Justrite switched from making brass carbide lamps to making plastic lamps. The gas jets of these tended to clog easily, especially after a carbide change, and some cavers reported that by turning the flame up they could induce a lamp to melt. While very entertaining, melting lamps did not prove particularly effective for cave exploration.

To many cavers, the plastic Justrite marked the end of the carbide era. Certainly, it marked the end of highly regarded brass Justrite. Soon after, Justrite ceased production of even the plastic carbide lamps. Premier halted production in 1974, but then restarted production briefly from about 1980 to 1985.

Sometime around the time of the demise of Premier and Justrite, Petzl came out with a modern version of the belt-mounted carbide lamp. The Petzl "ceiling burner," which uses a high-capacity carbide chamber connected to a helmet-mounted gas jet and reflector by a PVC hose, became popular among European cavers.

1990s to 2004: The fluorescent cap lamp. Fluorescent lamps have electric efficiencies up to five times that of filament bulbs, but require big bulky gas filled tubes and high voltage ballast transformers. Reasoning that a fluorescent cap lamp for caving should have very low battery draw, Nevin Davis, engineer and inventor of the motorized ascent device (MAD), set to work. His finished product, the Nevtek Lamp, uses solid state circuits to convert DC battery voltage to the higher voltages required to drive a fluorescent tube. The Nevtek lamp uses a very small diameter fluorescent tube shaped into a square, mounted behind a protective clear plastic cover on the helmet.

The Nevtek lamp produces about four times the illumination of a conventional filament bulb with about three times the efficiency compared to headlamps using tungsten-halogen bulbs. With the push of a button, the caver can reduce the brightness to match the typical electric headlamp for extended battery life.

The maxim "He who has the brightest cave lamp leads the way" was demonstrated to me a few years ago when a group of us visited one of the larger caves in Greenbrier County, WV. Kevin Harris had a Nevtek lamp, which made our white LEDs and even our conventional electric lamps look pitifully dim. Kevin's lamp helped us to avoid going down the wrong passage several times, and generally improved the illumination and our speed of progress. The only problem we had was that in smaller passages we could not see well with our own lamps alone because our eyes adapted to Kevin's brighter lamp. This was especially troublesome when Kevin faced in our direction and *beamed* us.

The Nevtek, which went out of production in 2004, sold for about $350. The white LED marketing machine may not have killed off the fluorescent cap lamp, but it surely contributed to its demise.

Late 1990's to Present: This brings us to the LEDs in general and white LEDs in particular.

LEDs

A light emitting diode (LED) is essentially a semiconductor that consists of two materials that form a p-n junction that emits light of a single color when voltage is applied in what is called the forward bias direction. If voltage is applied in the opposite direction, the LED essentially passes as much current as it can, overheats and self destructs. See the sidebar for more about semiconductors and how LEDs work.

A typical LED consists of a tiny chip of semiconductor material that contains the *p-n* junction, a substrate or mount to which the chip is attached, and tiny wires that attach the chip to larger wires, all encapsulated in epoxy for strength and protection.

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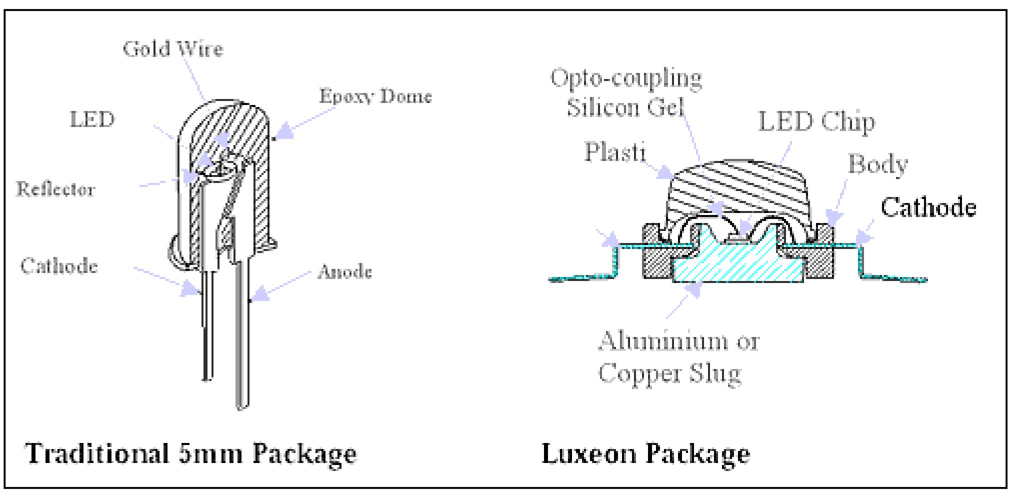
Figure 1. Construction of LEDs *(source: Lumileds)*



A Short History of the LED

Scientists observed emission of light from semiconductive materials such as silicon carbide and zinc sulphide as early as 1907. The challenges of making these materials into practical devices and a lack of understanding of the phenomenon prevented anyone from making practical electric lighting sources from these materials.

In the early 1960s, British scientists experimenting with the semiconductor gallium arsenide (GaAs) developed the first crude light emitting diodes. These devices could only operate in a bath of liquid nitrogen at 77 degrees above absolute zero, and they emitted light in the infrared, which the human eye discerned as a very feeble red glow.

The first challenge to making LEDs operate at room temperature was to improve the quality of the semiconductor crystals. The first successful commercial LEDs used a process in which high temperature liquid GaAs (about 850 degrees centigrade) was slowly cooled to allow it to form high quality crystals. The developers of the LPE process (liquid phase epitaxy) figured out a way to add a second zone of melted material on top of the first so that the crystallizing melt would contain a *p-n* junction.

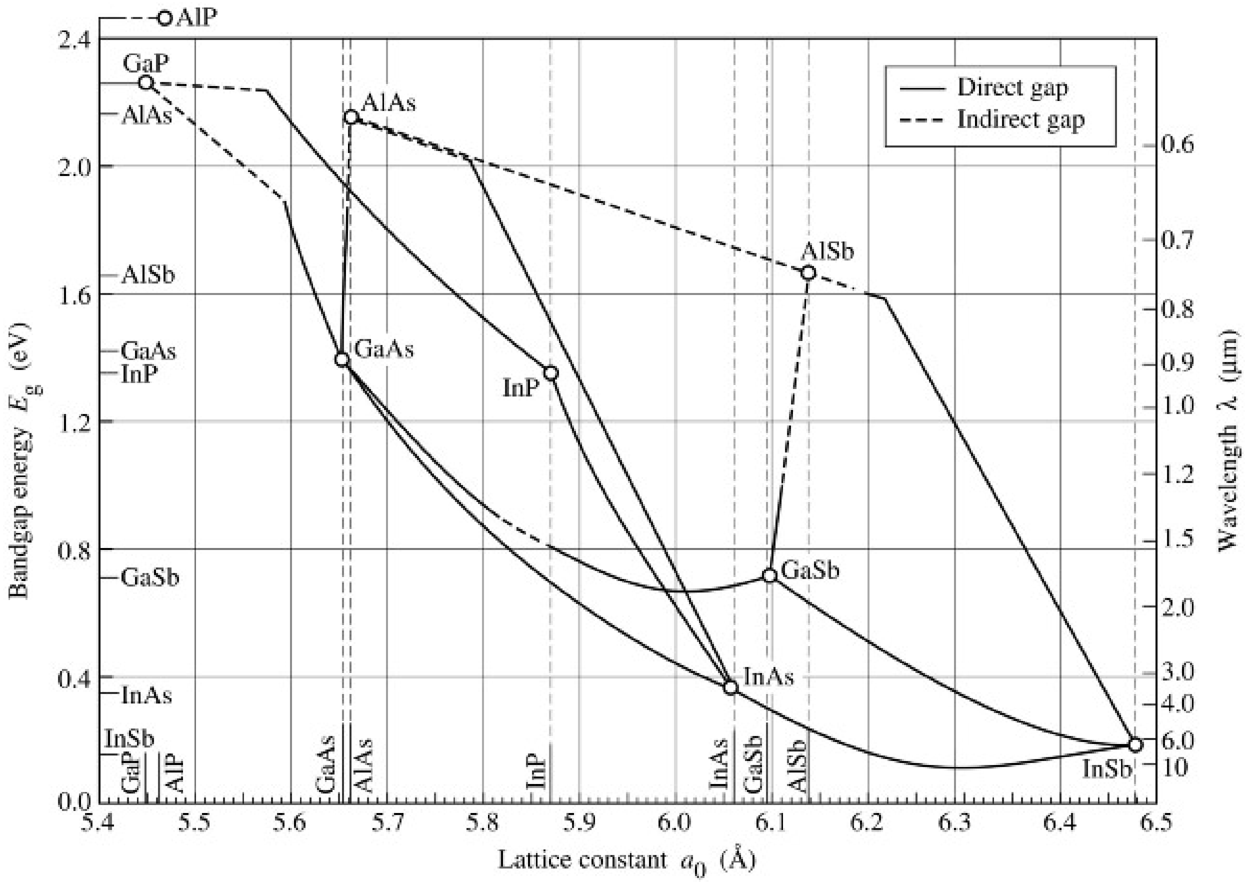
Scientists soon devised a second commercial growth process called vapor phase epitaxy (VPE), which, as the name suggests, uses vapor gallium and arsenic instead of liquid in the crystal growth process. VPE simplifies the process of forming the *p-n* junction somewhat by allowing the introduction of different elements and impurity vapors to the growth chamber as the material cools. Both the LPE an VPE processes require a crystalline substrate or "seed" of GaAs on which the liquid or vaporized atoms of gallium and arsenic can attach themselves, or nucleate, to grow more crystalline material.

Although LPE and VPE require expensive equipment and hours for the growth of a small amount of material, even a 2-inch diameter wafer with *p-* and *n-* layers forming a junction can produce several thousand LED chips when sliced up.

New colors – shorter and shorter wavelengths. GaAs belongs to a family of possible semiconductors consisting of elements from Group III and Group V of the periodic table. By selecting from among the elements in these groups, scientists can change the bandgap and hence the color of the light emitted by the *p-n* junction. This raises a new challenge, however. Different compounds have different lattice constants, or distances between atoms, as shown in Figure 2. As scientists attempted to develop LEDs with new colors, this meant that they could no longer count on using gallium arsenide as the seed or substrate material.

By the late 1960s, the first commercial GaAsP LEDs reached the market. By adding just the fight amount of phosphorus in substitution for arsenic, scientists had hit on a material that emitted light well into the visible **red** part of the spectrum but could still be grown on GaAs at low cost.

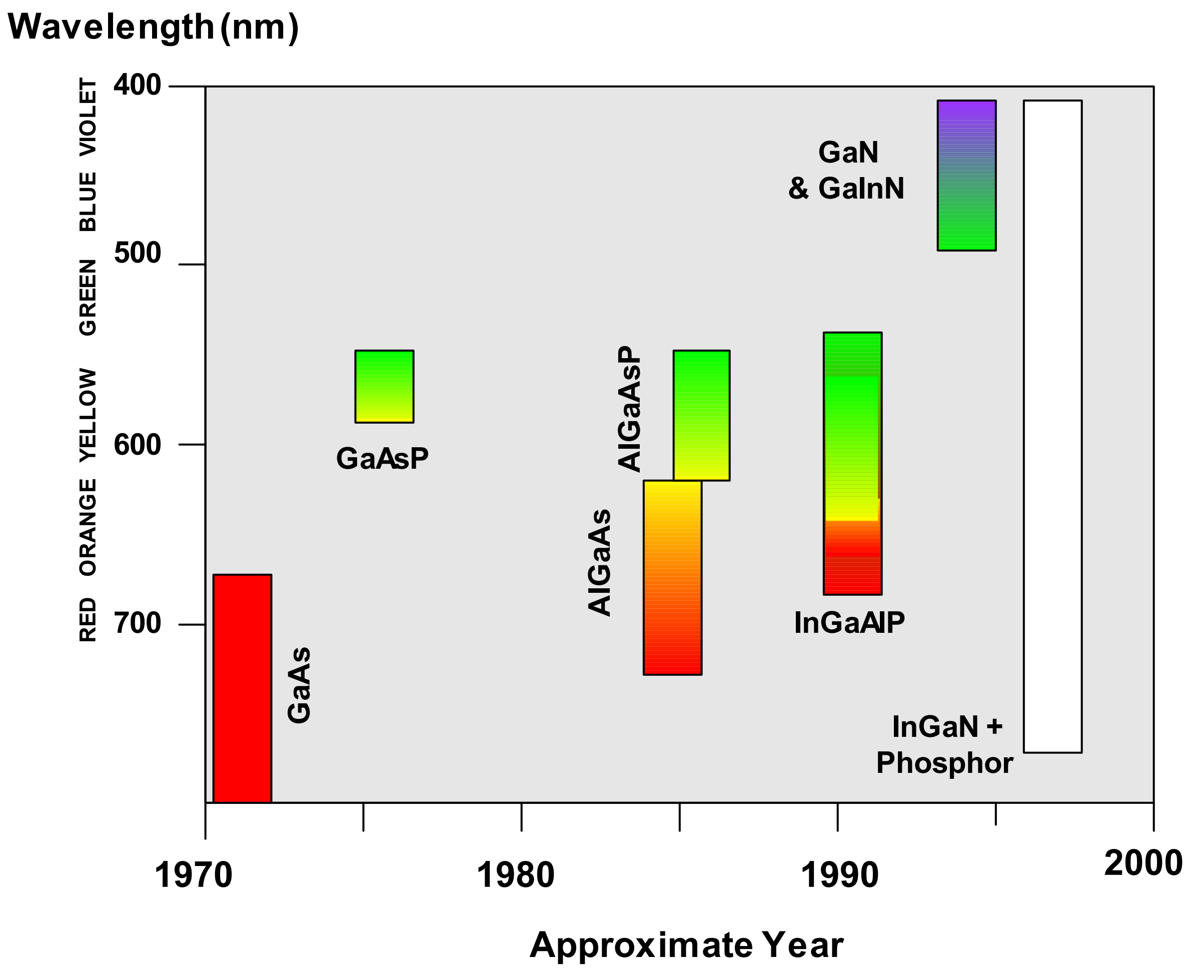
Figure 2. Compound Semiconductor Materials & Lattice Constants *(Source: France Telecom -- CNET)*



A few years later, scientists had devised a way to produce GaP (gallium phosphide) substrates. Growing GaAsP on these substrates reduced the mismatch between the p-n junction and the substrate, which reduced crystal dislocations and improved the efficiency and reliability of the LEDs. Freed from the limits of using GaAs substrates, scientists and engineers soon developed commercial orange LEDs based on GaAsP. By the mid-1970s, green LEDs based on GaP as the emitter had reached the market.

In the early to mid-1980s, another crystal growth technique reached the mainstream for commercial production of LEDs. The OMVPE technique uses hydride materials as precursors for growth, for example phosphine (PH_3), gallane (GaH_3) and arsine (AsH_3). These materials break down at high temperatures into non-reactive hydrogen and the desired elements needed for crystal growth. In comparison, VPE uses chlorides, and reactive chlorine gas produced as a byproduct of the precursor breakdown can interfere with crystal growth. OMVPE proved to be an economical method for growing a wider variety of compound semiconductors than were available using VPE.

Figure 3. Rapid Evolution of LEDs



With OMVPE, commercial fabs could grow GaAlAsP, which allows offsetting the lattice changes brought about by phosphorus with aluminum. The result of this was very high efficiency super bright LEDs in red, yellow and eventually green. By the early 1990s, even brighter LEDs based on InGaAlP (indium gallium aluminum phosphide) had reached commercial production.

The first blue LEDs, based on silicon carbide, appeared in the early 1990s. Soon after, ultrabright blue LEDs based on gallium nitride (GaN) and gallium indium nitride (GaInN) appeared on the market. These materials have a very small lattice constant that does not match most available substrates, but eventually scientists succeeded in growing good crystals using sapphire (aluminum oxide) as the substrate material. See Figure 3 for a summary of the recent history of LED development.

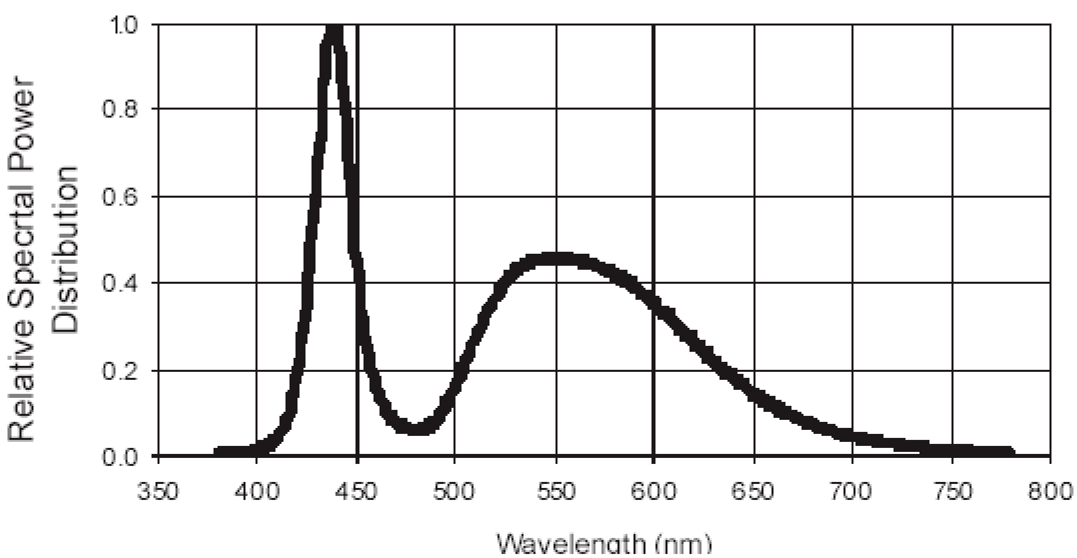
White LEDs. Simple LEDs produce light of one color. White light consists of light of all colors. While it is possible to build a white light lamp using blue, green, and red LEDs, collimating the light to produce a single white beam is a geometric and optical nightmare. The result is a big, expensive assembly that produces colored shadows.

To get something approaching white light in appearance, one can get away with mixing just two different complimentary colors, for example blue and yellow. This is the approach used in white LEDs, most of which use blue emitting InGaN diodes coated with a phosphor that converts some of the blue light into yellow light. We perceive the mixture of light produced by these devices as white. Many people in the semiconductor industry use the term phosphor converted LED (PCLED) for the white LED.

Most white LEDs use YAG:Ce as the phosphor. This stands for yttrium aluminum oxide garnet doped with cerium. This material absorbs blue light, and in the process the energy of the blue light pushes electrons up to higher orbits in the cerium atoms. The electron orbits quickly decay to lower orbits, and in the process the cerium emits yellow light.

Scientists are searching for new phosphor materials that produce a more natural light with higher efficiency when stimulated by blue light. Meanwhile, the semiconductor crystal scientists continue to work on new materials, substrates, and growth techniques in an attempt to push LEDs to even shorter wavelengths into the ultra-violet. A very wide variety of phosphorescent materials that emit under ultra-violet light is already available.

Figure 4. Spectrum of a White LED *(source: Lumileds)*



One problem with white LEDs is the phosphors vary in thickness across the device, which causes very visible color inconsistency at different viewing angles. You may notice that the illumination from a white LED appears yellow at the edges and blue in the center.

So, What's So Great About White LEDs?

According to the marketing hype, white LEDs are much more efficient than conventional bulbs. For example, the Inner Mountain Outfitters on-line catalog says that "[the white LED headlamp] uses about 10 times less current and therefore will run 10 times longer with the same battery, which is very comforting underground." **This may be true, but if so, the lamp produces one tenth or less the light. Comforting, my butt!**

The white LEDs now on the market are **not** significantly more efficient at producing light than filament bulbs. Table 1 compares white LEDs to several other sources of light commonly used in caving, including headlamps that use incandescent bulbs, tungsten-halogen bulbs, and fluorescent tubes. Only the new 5-watt Luxeon Star, available in the Speleo Technics Nova, beats tungsten-halogen, and then only by a very slim margin when the headlamp is new and the LED has not aged under use.

Table 1. Typical Lamps for Caving

Type	Example Bulb / Headlamp	Power (Watts)	Efficacy (Lm/W)	Light Output (lumens)	Bulb Lifetime (hrs)	Price
White LED (small)	Single T3 lamp	0.09	5	0.45	20,000 – 100,000	$3.50
Standard Incandescent Flashlight	502 bulb / Easter Seal	1.2	9.9	12	~ 30	$0.50
	425 bulb / Electric Justrite	3.0	11.6	35	15	$0.75
Carbide Lamp	Premier or Justrite cap lamp	NA	NA	35 - 100	NA	NA
Tungsten Halogen	FR0025 / Petzl Mega Belt	2.4	15	35	~ 100	$6.75
	FR500 / Petzl Duo	3.0	17	50	~ 100	$6.50
White LED (Medium)	Princeton Tech EOS	1.2	20	24	10,000	$15
White LED (large)	Luxeon Star / Nova & Petzl Myo XP	5	20	100	10,000*	$40
Miniature Fluorescent	Nevtek	4	50	200	20,000	$4
Short Arc Metal Halide	HID Diving Lights	10 – 24	45	450 - 1100	100 – 300	$80 - $120

*10,000 hours at rated current to 70 percent output.

So far, the claim for the vastly superior efficiency of white LEDs is true under only one circumstance. If you run an incandescent or halogen bulb below its rated power, the light output and efficiency drop. In comparison, as your batteries slowly run out of juice, your white LED continues to burn with no loss efficiency, even as it grows dim.

The reason that filament bulbs lose efficiency when dimmed is that they are what physicists call black body radiators. As you lower the temperature of the filament, much of the radiation shifts into the infrared. Therefore, you can no longer see anything with your dimmed bulb unless you are wearing near infrared night vision goggles while caving.

A related claim to the above is that LEDs draw very little power and do not waste energy as heat. LEDs ***do*** waste energy as heat, both in and around the *p-n* junction in the form of phonons (lattice vibrations), and in the fluorescent phosphor material in the form of Stokes conversion losses. It is true that virtually none of the light from a white LED is emitted as infrared (radiated heat), however, this does not mean that the white LED does not waste energy as heat. In fact, the new Lumileds 1 watt and 5 watt Luxeon

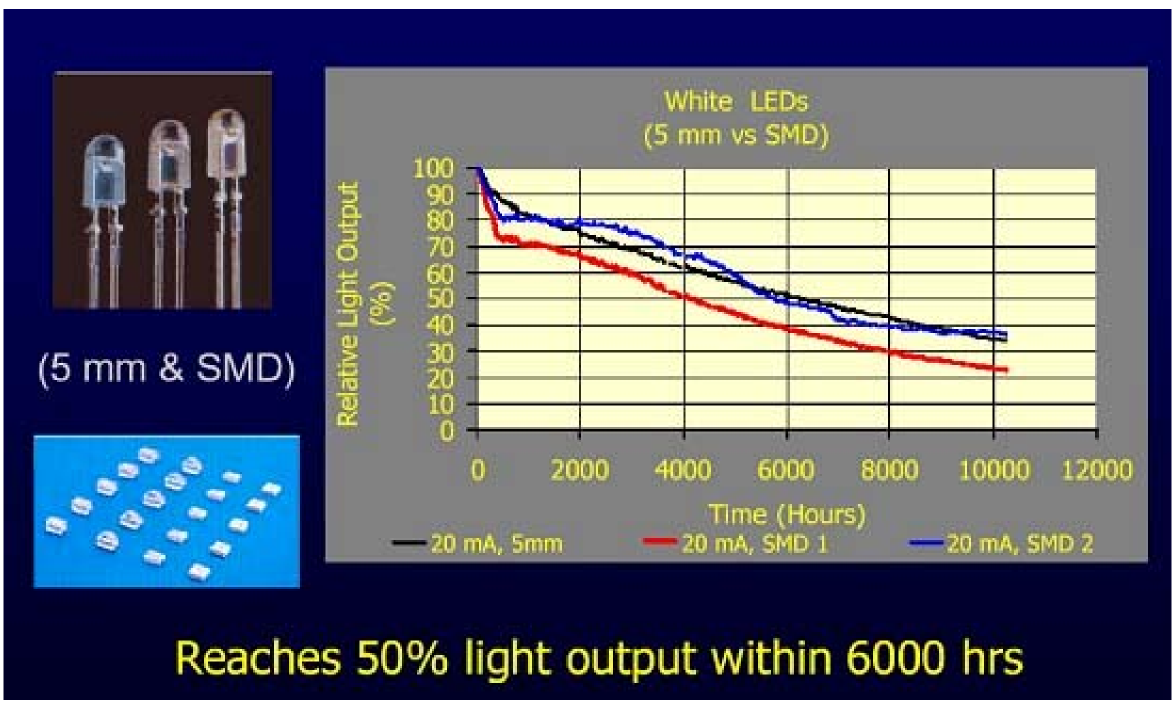
Star LEDs require heat sinks. The heat comes out through the base of the LED. An insignificant amount of it is emitted in the direction of the white light.

In reality, white LEDs ***do*** have some advantages over filament bulbs:

- More rugged than tungsten filament bulbs – no filament to break
- Lifetime of as much as 100,000 hours
- Dimmable without loss of efficiency.

White LED Lifetime. Makers of LEDs claim that the life is 50,000 hours, but of course it depends on how you define "life." LEDs, in general, do not burn out, they simply get dim as imperfections in the crystalline material grow under the influence of operating heat and the electric fields within the LED. Manufacturers typically specify the number of hours of operation at which the lamp, running at rated current but no more than rated current, will lose 30 percent of its brightness from aging. For example, Lumileds rates its Luxeon I white LED at 50,000 hours to decline to 70 percent brightness when running at 350 mA. This is equivalent to 2100 days or 6 years of continuos operation. Similarly, they rate their Luxeon III at 20,000 hours to get to 50 percent at 1 A, equivalent to 833 days or 2.3 years of continuous operation. According to Lumileds, 70 percent of original brightness is just noticeable as a diminution in brightness to most users.

Figure 5. Example of White LED Aging *(source: Rennselear Polytech)*



Dimming and Efficiency – Driver Circuits. LEDs are quantum devices, and very finicky about voltage and current. The InGaN light emitting diode inside a white LED has a natural forward voltage drop of about 3.7 volts typically when running at its optimum 20 mA of current. If you try to hook the white LED up to a higher voltage battery, let's say a 6 volt battery, the white LED will attempt to maintain a voltage drop of about 3.7 volts, and to do this it will draw a huge current from the battery, perhaps amperes. This will quickly burn out the LED. On the other hand, if you attempt to drive a white LED with less than about 3.5 volts, it will simply not light.

In most inexpensive white LED headlamps, the manufacturer uses an inexpensive dropping resistor between the battery and the white LED to take up the slack between the actual battery voltage and the desired voltage to the white LED. You can estimate the value of the dropping resistor using Ohm's Law, V = I x R. For example, in a six-volt system, a 115 ohm resistor will drop the supply voltage from 6 volts down to 3.7 volts while passing 20 mA, just what the white LED needs to reach full brightness.

The drawback to this approach is that the dropping resistor wastes power. In the example above, the resistor dissipates 2.3 volts x 20 mA of power, or 46 mW. In comparison, the white LED dissipates 74 mW. Therefore, by adding the dropping resistor, you have decreased the efficiency of the white LED in terms of lumens per watt by almost 40 percent.

The solution to controlling a white LED to keep the current from going too high is to use a driver circuit to deliver just the right current. Most of these circuits have the added advantage of allowing you to control the brightness of your white LED. Linear Technologies, Analog Devices, National Semiconductor, Fairchild Semiconductor, Maxim and many other companies make inexpensive integrated circuits priced at a few bucks for driving LEDs. To one of these integrated circuits must be added a few additional components, usually inexpensive capacitors, resistors, and inductors. Properly designed, one of these simple circuits will maintain the proper current to the white LED even as the battery voltage sags. According to the manufacturers of these integrated circuits, the efficiency penalty is only about 10 percent, far better than using a dropping resistor. As you dim the white LED with one of these integrated circuits, the efficiency of the white LED remains constant, so you can cut way back on light and conserve batteries without a big penalty.

In contrast, consider a very crude, early example of a dimmer circuit for conventional bulbs, a transistorized chopper circuit. I have one of these built into my old electric Justrite, in which I use a halogen bulb. The circuit, which appeared in the NSS News in the early 1970s, does not actually regulate the voltage or current to the bulb. Instead, it allows you to vary the "on" duration of a rapidly pulsing transistorized on-off switch with a twist of a knob. Although the circuit allows me to run a filament bulb at lower brightness levels than full blast, if I choose, to conserve my batteries, the bulb produces more heat than light at the lowest settings. Replacing the bulb with white LEDs of equivalent brightness and a suitable driver circuit for white LEDs would extend battery life considerably at the dim settings compared to the rig I have now.

So What is the Perfect Cave Lamp?

The answer to this depends on several factors, for example, how much light does the lamp produce, how long until you have to replace it, and how much it costs to replace. For now let's assume that all cave lamps can use the same batteries. We will deal with batteries later.

The first part of this question is, **"how much light do you need to see in a cave?"**

The light emitted by a bulb can be measured in lumens. The lumen is a measure of the light emitted by a standard candle. By definition, a standard candle emits one lumen per steradian of solid angle. If you put a standard candle inside a sphere and collect all the light it emitted, you have 12.57 lumens.

The lumen is a photopic unit of measurement, which means that it is based on the response of the human eye in bright light conditions. In such conditions, corresponding to the light of at least three standard candles falling on a one square meter surface one meter from the candles, the eye sees in color using the cone-shaped cells of the retina.

In comparing illumination from lights with different color temperatures or hues, the lumen value has to be corrected for the sensitivity of the eye to different colors. The bluish-yellow light from a white LED can only have the same lumen output as the yellowish-orange light from a filament bulb if the human eye perceives them as equally bright – at least that is the way the lumen is supposed to be used.

In very dim light conditions, the human eye uses the rod-shaped cells of the retina, which pick up light but do not provide for color perception. The rods are most sensitive to blue-green light, while cones are most sensitive to yellow-green light. In dim light conditions, the illumination from a bluish light source may appear brighter compared to the apparent illumination from a yellowish light source. However, rods are concentrated away from the center of the human eye, and you may have noticed that you cannot see worth a damn in very dim light if you look directly at something. The distribution of the rods negates any slight advantage in apparent brightness that you might get from using a pathetically dim bluish white LED.

The table below lists some relative illuminance values (or illumination) of surfaces under various lighting conditions.

Table 2. Surface Illuminance (lumens per square meter)

Bright direct sun	130,000
Overcast daylight	1,000
Very dark day	100
Twilight	10
Moonlight (full moon)	0.1
Starlight	0.001

Source: RCA Electro-Optics Handbook, 1968,

The answer to the question "how much light do you need to see in a cave?" depends a lot on your eyesight, but from looking at the table, 100 to 1,000 lumens per square meter would seem to be the minimum. Architects recommend an illuminance of about 1,000 lm/m^2 on reading and work surfaces in the home, and perhaps a tenth of this for ambient lighting.

In reality, as shown in the previous table, cavers typically get by with less than 50 lumens, and this is spread across several square meters of cave, depending upon the distance the caver is standing from the walls and floor and the beam pattern of the lamp. This explains why cavers have no idea where they are going half the time. This also explains the fondness that some cavers have for the carbide lamp. Carbide lamps are cantankerous and smelly, but they can produce a lot of lumens, even though the lumens are not always directed where you want them.

So let's settle on 50 lumens as the benchmark. This is about equal to the light given off by the brighter of the two bulbs in a Petzl Duo, and it is about equal to the light given off from a carbide lamp with the flame maybe one third to on half inch long. The sort of illuminance you would like to have in a cave, from Table 1, requires more than 100 of the small white LEDs, or one honking big Luxeon Star operating at about half power.

The second part of the question "So What is the Perfect Cave Lamp?" is **“What does the headlamp (including bulb and batteries) cost per hour of caving?"** I have based the following analysis on work by Joel Dry of OptoLum, but modified his figures for caving lamps.

Referring to Table 1, we can estimate the amount of light produced per dollar spent on various bulbs. For example, incandescent bulbs costs about $0.75 and produce as much as 35 lumens, so let’s use the figure 47 lm/$. The Nevtek fluorescent lamp produces 200 lumens at a cost of roughly $4 for just the bulb, or 50 lm/$, about the same as incandescent bulbs. The halogen bulbs in the table produce up to 50 lumens and costs $6.50, so the figure is 7.7 lm/$. A 10-watt HID diving lamp produces 450 lumens at about $80 per bulb, so the figure is $5.6 lm/$. A 5 watt Luxeon Star white LED lamp used in the Speleo Technics Nova produces 100 lumens at a cost of $40 or 2.5 lm/$. At this point it is starting to look pretty good for ordinary light bulbs and not very good for white LEDs, but this is not the end of the story.

To arrive at a figure for total cost over time, we have to take the initial cost of the bulb and add the cost of the batteries used and the cost to change bulbs over time. To make the comparison more meaningful, we should do the comparison for systems producing 50 lumens, our benchmark, even if this requires multiple or even fractional bulbs.

The cost of electricity will depend to some extent on the batteries used, but I will simplify by assuming that a 7800 mA-hour C cell 1.5 volt battery costs $1.25. This is equivalent to 10.6 cents per watt-hour. I will also assume that a caver’s time is worth $10 per hour and that he or she can change six bulbs per hour, so the cost of changing a bulb is $1.67 in labor.

Table 3. Total Cost of Caving with Various Lamps*

	Incandescent (#425 bulb)	**Halogen (FR500)**	**Fluorescent (Nevtek)**	**HID (10 W)**	**White LED (5 W)**
# of Lamps for 50 Lumens	1.43	1.00	0.25	0.11	0.5
Initial Cost of Lamps	$1.07	$6.50	$1.00	$8.88	$20.00
Replacement Cost per 100 Hours Underground	$7.15	$6.50	$0.005	$8.88	$0.20
Battery Cost per 100 Hours Underground	$45.43	$31.80	$10.60	$11.77	$26.50
Maintenance Cost per 100 Hours	$15.92	$1.67	$0.008	$1.67	$0.017
Total (100 hrs)	$71.00	$46.47	$11.61	$31.20	$46.72

*Does not include the cost of headpiece and battery charger, if required.

Table 3 compares the cost of caving lights that produce 50 lumens. I have ignored the initial up-front cost of the durable parts of the cave lighting system, the headpiece, control electronics, cable and recharger, if required. In the case of white LEDs and HIDs, the cost of the system can be quite significant, $350 and above. If the caver takes good care of these, they should last many hundreds of hours, making the cost per hour of use negligible compared to consumables like batteries and bulbs.

Based on this analysis, fluorescent beats everything else easily. The newest, most expensive white LED systems are now competitive with incandescent and halogen in long-term cost per hour of use, but these still have a long ways to go to match fluorescent. However, unless you like tinkering with electronics and want to build it yourself, you will have a difficult time finding a fluorescent cap lamp suitable for caving. Nevin Davis recently stopped producing the Nevtek.

Now that I have talked you out of white LEDs in favor of conventional headlamps like the Petzl Duo using filament bulbs, preferably halogen, I should add that white LEDs will get better, although slowly. Researchers have reportedly demonstrated white LEDs in the laboratory with efficiencies better than 50 lumens per watt, comparable to fluorescent bulbs. If these improved white LEDs make it to the market at reasonable prices and with good reliability, then we may see some really great caving lamps.

Batteries and Battery Life – What the Packaging and Ads Don't Tell You

If you cannot win by purchasing a white LED headlamp, then what about spending your hard-earned cave equipment budget on exotic batteries? This would seem like a promising way to get away with running your system with a brighter bulb without the nuisance of more battery changes. Have you ever wondered just how long a given brand of battery is actually supposed to last? The packaging and the ads talk about "long lasting," "heavy duty," and "keeps going and going" but never provide any specifications.

Well, like just about everything electrical and electronic, batteries have specifications. The table below lists the specifications of the most common consumer battery sizes available from Duracell, one of the leading battery brands. Other brands of alkaline batteries have very similar specifications.

The rated capacity in milliampere-hours is the product of the current that the battery can provide multiplied by the time it can provide the current under low-load conditions. As you would expect, D cells have the highest capacity of common over-the-counter batteries, followed by the smaller C and AA cells, as shown in the table below. All of the batteries in the table are alkaline batteries, the most commonly available type in the U.S and most countries.

<u>Alkaline Batteries & The Peukert Effect</u>

Using the rated capacity of your chosen battery, you can estimate how long a bulb that draws a known current will stay lit using that battery. For example, you would expect a 1.5 volt bulb that draws 500 milliamperes (mA) to last 30 hours, when hooked up to a single D cell (= 15,000 mA-hours divided by 500 mA). I doubt that you will find such a lamp. A better example is to hook up a 6-volt 500 mA lamp to 4 D-cells in series (4 x 1.5 volts = 6 volts). Because the same current flows through all 4 batteries, you get the same answer, 30 hours.

As shown in the table, you do not really get what the rated capacity would lead you to believe for battery life. The battery makers are not lying. Well, not exactly. The rated capacity of a battery is only accurate at very low current. At higher current, the capacity of a battery drops as a result of internal resistance and other loss mechanisms. This is called the Peukert Effect, or as some cavers call it, the "pukey batteries effect."

As a consequence of the Peukert Effect, using small batteries for a bright lamp is a recipe for having to carry way too many batteries. For example, a typical 6-volt caving headlamp such as an Easter Seal or SafeSport, if used with four AA cells and a 500 mA bulb, will give you something just shy of 2 hours of light, not the nearly 6 hours that you would expect. Those little AA cells get slaughtered in these lamps. Hence, most 6 volt lamps either use larger batteries or lower rated bulbs, for example 502 (180 mA @ 5 volts) or PR-35 (around 350 mA @ 6 volts).

If you want reasonable battery life, you should use only D and C cells or equivalent or greater capacity rechargeable batteries, making sure that the batteries can handle the current necessary to generate 50 lumens using filament-halogen or the new Luxeon Star / Nova.

Figure 6. Discharge Characteristics of Typical Alkaline Batteries *(Source: Duracell)*

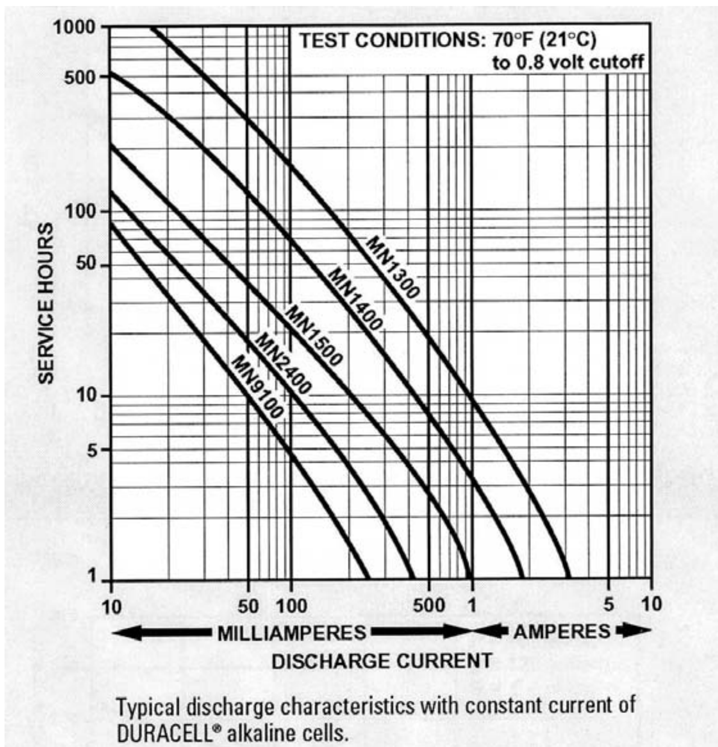


Table 4.   Consumer (Alkaline) Batteries *(Source: Duracell)*

Duracell Product Number	Size	Rated Capacity* (mA-hours)	Rated Load (ohms)	Initial Current (mA)	Initial Power (watts) in a 6-volt, 4-cell system	Energy Density, (watt-hours per pound)
MN1300	D	15,000	10	150	0.9	59.2
MN1400	C	7,800	20	75	0.45	65.6
MN1500	AA	2,850	43	35	0.21	65.8
MN2400	AAA	1,150	75	20	0.12	57.5

Table 5. Real VS. Rated Alkaline Battery Life With a 3-Watt Cave Headlamp

Size	Battery Life in a 6-volt System with 500 mA bulb (3 watts)	
	At Rated Capacity (hours)	Actual Useful Life* (hours)
D	30.0	11
C	15.6	4.5
AA	5.7	1.8
AAA	2.3	Forget it!

*Time to uselessness as a caving light, based on my own experience. Your eyesight and mileage may vary.

Other types of batteries

Alkaline batteries have one thing going for them: You can find them just about anywhere, even at gas stations in the middle of nowhere. If you have the patience and money to go for some of the less commonly available high-tech batteries with higher energy density than alkalines, you can come up with a lighter cave lighting system. Alternatives to alkaline generally have voltages other than 1.5 volts per cell, which means that you may have to select a different bulb for your headlamp. Some of the more exotic batteries also cost quite a bit more than alkalines and you will need to make sure you have a good supply before a caving trip.

Battery types other than alkaline that you can buy at speicalty shops, electronics stores and on the internet include lead-acid / lead-acid gel, nickel-cadmium, nickel-metal hydride, lithium, lithium-ion, and lithium polymer. Some of these are rechargeable.

Lead-acid batteries (rechargeable) have been around for more than 100 years, and have proven reliable and durable. The main drawback is weight. These have much lower energy density than alkalines. Another drawback is that lead acid batteries do not tolerate deep discharge well. A couple of cave trips that take a lead acid battery all the way to “empty” will generally render it about as useful as a lead brick.

Nickel-cadmium (rechargeable) batteries handle high current discharge well and have better energy density than lead acid, although still lower density than alkalines. NiCads have about 15 percent share of the market for small rechargeable batteries, and are used mostly for power tools and emergency lighting. The biggest drawback of NiCads is the so-called "memory effect" which occurs when you partially discharge the battery several times in a row, as a result of which, the battery loses capacity upon recharge.

Lithium batteries have about double the energy density of alkalines, typically 105 W-hour/Lb. Compared to 56 W-hour/Lb for alkalines, but they are very expensive and can be quite hard to find. These non-rechargeable batteries have a shelf life of up to 10 years, which makes them popular for military and industrial applications. These are not rechargeable.

Lithium batteries come in four common chemistries, Li / MnO_2, Li / $SOCl_2$ (thionyl chloride), Li / SO_2Cl_2 (sulfur dioxide or sulfuryl chloride), and Li / FeS_2 (iron disulphide). These batteries generally produce odd voltages, for example 3.0 volts – 3.7 volts, making them unsuitable for consumer applications without some tinkering. ***The Energizer e2 Lithium L91 is probably the best choice for caving***

among the lithium batteries. As shown in the table, the Energizer e2 Lithium L91 is an AA battery that produces 1.7 volts based on lithium / iron disulphide chemistry. Available from Radio Shack, the Energizer e2 lithium L91 provides a little more capacity than an AA alkaline with about two thirds the weight, making it a good choice for caving if you can stomach the price. The specific energy density of these cells is around 95 watt-hours per pound, almost double that of alkalines.

On a recent trip, Morrie Gasser outfitted a group of cavers with four Energizer e2 AA lithium cells per headlamp with 425 bulbs (one half amp 6 volts). He claims that the headlamps ran over 5 hours with no loss of brightness until complete battery death. In comparison, count yourself lucky if you get 2 hours from alkaline AA cells with the same 425 bulbs thanks to the Peukert effect.

If you find a source of 3-volt industrial lithium batteries, such as those made by SAFT, and you have a cave lamp that takes four alkaline cells hooked up in series to produce 6 volts, you can use two lithium cells rated at 3 volts each and short out the two empty battery slots with wire or dummy cells. Beware of the sulfur dioxide varieties such as the SAFT LO 26 SX, though. These have only about half the rated capacity at discharge currents above 100 mA.

Nickel-metal hydride batteries (NiMH, rechargeable) provide up to twice the energy density and up to three times the capacity of NiCad batteries of the same size, but less capacity than similar size alkaline batteries. NiMH batteries cost quite a bit of money, but you can get up to 1,000 uses from a set of batteries by recharging. NMH batteries exhibit a memory effect to some extent, but this is not as much of a problem as it is with NiCads.

Consumer NiMH batteries in C and D cell sizes produce 1.2 volts. A homemade cave lighting system using rechargeable NiMH batteries would have to have a different number of batteries if used with a conventional bulb or white LED headlamp designed for alkaline batteries. For example, a 6-volt C-cell system would have to have **FIVE** NiMH C cells. Battery life would be less than with alkaline batteries, but after a few recharges you would come ahead in terms of out of pocket expense.

Lithium-ion batteries (rechargeable) are light in weight and very high in energy density, making them popular in cellphones and notebook computers. They can support high discharge rates, exhibit no memory effect and have a service life up to 1,000 recharging cycles. These typically cost more than NiCad and NiMH batteries, and they require careful charging using chargers specifically designed for them. The most popular type of small rechargeable battery, lithium-ion batteries have about 70 percent share of the market.

Lithium-ion polymer batteries (rechargeable) use the same chemistry as lithium-ion batteries, but the batteries are constructed with laminated layers of conductive polymers. This allows the manufacturers to make the batteries in a variety of shapes and sizes for hand-held portable devices, and they have started to replace lithium-ion in many applications, for example in cellphones. Lithium-ion polymer batteries have high energy density, about 95 W-hour / Lb. (210 W-hour / kg), about 50 percent higher than alkalines.

Zinc-air batteries have a negative zinc electrode and positive "air-breathing" carbon electrode. Zinc-air batteries are available as button cells for hearing aids, pagers, and medical equipment. Typical cell voltage is 1.3 volts. Manufacturers claim battery capacities in the range of 125 to 200 watt-hours/Lb, several times that of comparable lithium-ion batteries. One disadvantage is that the batteries must be sealed from air prior to use to prevent premature discharge. Large capacity Zn-air batteries suitable for caving are not generally available, to my knowledge.

Silver oxide batteries have a cell voltage of 1.6 volts typically. These have a capacity of about 60 watt-hour/Lb. Silver oxide batteries are readily available only as small button cells to my knowledge.

Table 6. Specialty Batteries Suitable for Caving (Examples)

Battery	Type	Size	Recharge Cycles	Voltage (volts)	Rated Capacity (mAH)	Price Each
Tag Lite III Battery	Gel-lead acid	BIG!	Thousands, but shallow discharge only	6.0	7200	$55.00
Duracell MN-1203	Alkaline	Odd	No	4.5	2200	$6.40
Powerizer CR-123	Li / MnO_2	16 mm x 32 mm	No	3.0	1100	$3.00
Panasonic UltraLife U220H	Li / MnO_2	C	No	3.0	4500	$67.00
Energizer e2 Li L91	Li / FeS_2	AA	No	1.7	3000	$2.50
SAFT LO 26 SX	Li / SO_2Cl_2		No	3.7	2700	Military
AccuPower AAA	NiMH	AAA	1,000	1.2	800	$2.00
AccuPower AA	NiMH	AA	1,000	1.2	2400	$7.00
AccuPower C	NiMH	C	1,000	1.2	4500	$7.00
Powerizer C	NiMH	C	1,000	1.2	5000	$3.25
AccuPower D	NiMH	D	1,000	1.2	8500	$10.00
Powerizer D	NiMH	D	1,000	1.2	10000	$6.00
ProLite II "Red"	NiMH	--	1,000	6.0	3700	$100.00
Speleo Technics Nova / CX3	NiMH	--	1,000	4.8	4500	$90.00
Panasonic CGA103450A (Pentax D-LI7) *prismatic shape*	Li-ion	--	> 500	3.7	1950	$17.00
Speleo Technics FX-Ion	Li-ion	--	1,000	3.7	2200	$155.00
SAFT MP 1706065	Li-ion (Li / Co_3O_4)	60 mm x 65 mm x 19 mm	500	3.7	6800	$55.00

Note: I have highlighted my personal choice in yellow. If I could get these batteries as C cells, I would use these over AA cells for the additional capacity.

A leading-edge electric cave lighting system in terms of light output per pound of batteries would use lithium / iron disulphide, or rechargeable Li-ion or Li-ion polymer batteries. The rechargeable lithium batteries produce an awkward 3.7 volts per cell, which makes them incompatible with most systems originally designed for alkaline cells. You have to use these batteries with a system designed to use them, and in most cases, you cannot substitute alkalines (1.5 volts) for the rechargeable lithiums (3.7 volts). This means that you need plenty of spare rechargeable batteries. For example, to use the Speleo Technics Nova white LED headlamp on a long weekend with back-to-back 8 hour caving trips, you would probably need to spend $465 on three CX3 batteries, two batteries to take into the cave, and one to sit in the charger ready to go.

Conclusion

White LEDs suck. They have gotten better, but they still suck. Using expensive lithium batteries helps lighten the load, but even with these, why not use a quartz halogen bulb that lets you see where you are going, ***or an even brighter*** and more efficient fluorescent cap lamp, if you are lucky enough to find one?

The ultimate cave lighting system if built today would consist of a fluorescent cap lamp such as the Nevtek and Li-ion batteries. Such a system would produce more than twice the light of a white LED headlamp using the latest 5-watt Luxeon Star, the batteries would last twice as long, and it would cost about one quarter as much per 100 hours of caving if each were set to the same brightness level.

Post Mortem

In April 2005, Lumileds announced an improved "Luxeon I" that they claim can produce 30 lumens per watt of electric power, compared with 18 to 20 lumens per watt for the best white LEDs available in mid-2005 as I drafted this piece. Toshiba also announced a new white LED that they claim has an efficiency around 30 lumens per watt. Nichia claims to have demonstrated a high intensity white headlamp that produces 50 lumens using an efficient blue semiconductor laser to replace the blue LED.

Not to be left behind, OSRAM Sylvania claims to have developed the OSTAR white LED, which can produce 200 lumens. The OSTAR draws 700 mA and has an efficiency of 40 lumens per watt. The OSTAR will start shipping in small quantities by the end of 2005.

These new more efficient and brighter White LEDs (& white lasers) will not be available in headlamps for at least another year. Then maybe we will have white LEDs that begin to live up to the hype. I bet they will not be inexpensive. Until then, I am sticking with my halogen bulbs, alkaline C cells and lithium AA cells.

What is a semiconductor?

A semiconductor is a material, or an electronic device made from materials that behave as either conductors of electricity or as electric insulators, depending on minute amounts of impurities in the materials. Semiconductive materials generally reside near silicon on the periodic table of the elements. Silicon has just the right number of electrons in its atoms – neither too many, nor too few – so that it cannot quite decide whether to behave as a metal or an electrically inert insulator.

To make useful electronic devices out of semiconductive materials, the atoms of the materials generally have to be formed into periodic rows and columns, as they are in crystals. In semiconductor crystals, free electrons, necessary to conduct electricity, can only have certain allowed energies. The reason for this has to do with quantum mechanics, but you can think of it as if the electrons are cars driving over a washboard road surface. At certain speeds, the car's suspension resonates with the undulations in the road, making driving almost impossible. At faster or slower speeds, the driving goes more easily. Applying a voltage across a crystalline semiconductor material speeds up the electrons, giving many of them enough kinetic energy to make it through the material from one terminal of a battery to the other. The difference between the energy of electrons bound to the atoms and electrons free to move about and conduct electricity above the disallowed energies is called the bandgap of the material.

Introducing a few parts per million of impurities such as boron, arsenic, and phosphorus, can tie up free electrons, or provide additional free electrons. If the impurity donates electrons, the semiconductor material is termed *"n-type."* If the impurity atoms grab up electrons, it is called *"p-type."*

When putting an *n*-type semiconductor in contact with a p-type, the allowed energies of the electrons in the two materials generally do not line up exactly. An electron crossing the gap in the forward bias direction will have extra energy when it gets to the other side. Again, the explanation delves into quantum mechanics, but this extra energy has to go some place, either into vibrations of the crystal lattice or into some other manifestation. With the proper selection of the semiconductor materials, this extra energy is converted into light, the color of which depends on the differences in allowed energies between the two materials.

Figure 7 LED Cross-section Showing *p-n* Junction. Right: Luxeon Star *(source: Lumileds)*