The Art and Practicalities of Cave Lighting

In memory of Zsolt Borka, my friend

1. Introduction

Surprisingly or otherwise, nothing in particular has motivated me to draft this paper.

In my previous life I worked extensively designing equipment, in particular lighting systems to help protect the often unseen and unknown underground world of caves. During this period I was particularly fortunate and grateful to be able to work with and shared ideas with István Szenthe, as to how best to configure cave protection equipment and then later to similarly design and implement suitable lighting equipment systems for a variety of caves with Pál Berczik, the best and most experienced expert in this field. Indeed, it is he who should be writing this handbook, had he persuaded himself to do so.

Initially I was naive enough to think that over the course of time and as technologies developed all the appropriate rules for operating lighting efficiently and effectively in caves would have been understood and established, and all the relevant tricks and practical solutions applied in the most appropriate ways to suit the individual circumstances in caves throughout the world. Having visited many caves, I soon realised however this is not the case. Neither the designers, contractors nor cave managers apply those principles which to me were so obvious, be they evident or trite. Shockingly this was particularly the case in Central Europe, where I found the lack of sympathetic cave lighting configurations a most worrying issue.

Whilst recent cave lighting systems have frequently used the most modern technologies, regrettably their aesthetic and safety standards are invariably poor. Rather than helping in principle to enhance the environment and experience of the cave, they have led to a deterioration of their quality. It is for this reason, I thought it appropriate to reflect on my experiences and publish the knowledge I have accumulated over many decades, before I lose my ability to write it down or desire to do so. Thus the reason for drafting this paper is the hope that it can be used to your advantage and that of the caves, along perhaps with the desire to satisfy the vanity of an ageing man.

The principles in this document are however not dogmas, nor a set of authoritative principles which are incontrovertibly true, but a series of suggested rules worth considering and observing. What is more important however, is to understand the reasons and justification for these principles and those methods that make it possible to apply them successfully. This paper and its recommendations are therefore aimed primarily at those responsible for the management of caves, since experience shows me that planning engineers are unlikely to read them, as they regard learning as something beneath their dignity. However, if some contractors follow these principles, I would be touched and believe that my efforts have not been in vain.

2. So why light caves?

To most, the answer to this question is so banal it is hardly worth asking! Obviously when anyone goes into a cave he or she wants to see not only what is around them but also more specifically to see what they want or what someone would like to show to others. Therefore the principal aim of seeing, is to obtain information and then to create those conditions which make it possible to move around safely, i.e. not to fall on one's face, hurt yourself or damage the natural formations in the cave.

In daylight or in a well-lit room, we don't even think about these two separate functions, but this difference becomes very obvious when comparing street lighting to floodlight in a city. This differentiation is absolutely essential however in cave lighting for a variety of practical and safety reasons, simply because caves are used or utilised for a number of different purposes. The most common reason is accessibility for tourism but also for speleotherapy, the organisation of cultural events, such as concerts, exhibitions and even wedding ceremonies. As a consequence it should be immediately obvious that a single generic multi-purpose cave lighting system is unlikely to exist. The configuration and manner in which the most appropriate lighting equipment is installed therefore depends on either the primary purpose being to provide access to *visit* the cave, or the potential or anticipated new or future reasons for using it. This paper focuses on the former, i.e. the most appropriate form of lighting for th*e tourism-oriented* use *of show caves*.

3. So, how should caves be lit?

Eyesight is the master and guiding force for suitable cave lighting. The human eye is a very sensitive, sophisticated and flexible instrument. Because it is not only an obvious light receptor, connected to the brain, it functions as a highly effective and intelligent signal processing apparatus. The pupillary movements, i.e. the eye's narrowing and widening, act like the blinds or "iris" of the camera. The eye's unique physiological (biochemical) adaptation properties also allow us to perceive objects under different lighting conditions. Strong illumination results in a greater richness of colour and detail. Biochemical adaptation likewise means that in darkness, the concentration of the so-called visual pigment (rhodopsin) increases, making the photoreceptors more sensitive. In these circumstances incoming photons of light more effectively react with the rhodopsin molecules to generate a nerve impulse to and in the brain. Unless the levels of this pigment concentration are sufficient, for instance when there is not enough incoming "light" information, the visual image or picture the eye sees, will be "underexposed", dark and therefore not detailed enough, as happens for instance when one enters a dark cellar. In bright light the opposite occurs and the majority of rhodopsin automatically breaks down. If this didn't happen, then a phenomenon similar to an overexposed image "burning" into photographic film would occur, i.e. too much information aggregating to create "noise". In daily life this often happens when one suddenly steps out into bright sunlight from a dark room.

Adaptation is not however ensured simply by just pupillary movements and biochemical processes. When light is of low intensity, the so-called rods in the retina of our eyes become active. As these light levels increase, the cones in the eye become increasingly activated. This anatomical capability is the outcome of an evolutionary process which has resulted in the eye becoming a light receptor that works effectively either in a day or a night mode. As the cones in our eyes trigger colour vision, this is why we only see the world in black and white in the half-darkness … a situation which exists equally in the figurative sense, to the unconditionally loyal activists of political parties!

Interestingly pupil contraction/dilation is an amazingly quick physical process, whilst the physiological/biochemical reaction in the eye is much slower. It is for this reason that dark adaptation is a much slower process than light adaptation. Depending on one's condition, the former might take between 20-30 minutes, the time believed necessary to produce the optimum levels of rhodopsin. In the opposite direction this result is triggered and multiplied up to 1-10 billion times faster, that means a 9-10 order of magnitude higher light sensitivity. Because it is important to see and differentiate colours effectively in caves, light levels need to be high enough to exceed a critical “black and white” illumination threshold. To do this the adaptation time of the cone cells must be taken into consideration. In certain circumstances this can take as long as 10 minutes! (This means “only” a 6-7 order of magnitude of change). The opposite process as previously mentioned is much much quicker, with the dark-adapted eyesight diminishing in less than 5 minutes, because the retrograde adaption of cone cells only takes up to two minutes. It is therefore clear that any slowly achieved state of illumination can be impaired very quickly. This scientific logic therefore tells us and points to the fact that a phased period of dark adaptation should be incorporated into the design of any cave lighting systems, particularly in the initial entrance areas.

We also know the human eye consistently adjusts and adapts to the highest level of available light. Consequently, if light levels vary, for instance where there are different pools of light of different brightness, the poorly lit spots will be simply too dark for the human eye to perceive and detect any detail. It is also obvious that most people instinctively shade their eyes from light sources which are too bright. If you’ve ever noticed this behaviour with your visitors, you can be sure your lighting regime has defects and is not well adapted to the darkness of those immediate surroundings. The pupils, flexible as they are, can however only respond effectively to this adaptation process to a limited extent (approximately one order of magnitude, i.e. 10 times in the difference of brightness). Instinctively they “do not like” being exercised to this degree, because, as mentioned, the nature of the eye’s sophisticated biological adaptation mechanism requires several minutes to take place, particularly when functioning towards the dark end of the light spectrum. This explains why the existence and exposure of the eye to a single very bright source of light for some minutes, can rob an individual of the opportunity to enjoy the details of a cave. This reaction also significantly tires the brain and again explains the reason without realising it, why we feel discomfort.

The most important principle and operational rule of thumb in cave illumination, is therefore to use the highest possible light level (within local limitations) in an even and consistent manner. The lighting regimes used by photo or film studios are good examples to follow. Brighter lighting gives more defined contours and details, colours become more vivid and humans, as diurnal beings, feel more comfortable. However, it must be remembered there will always be an upper limit to the application of levels of light intensity.

Probably the most important consideration is energy consumption. Higher light levels require more and stronger sources of light. Supplying electricity in an underground situation likewise poses its own challenges and physical limits, not the least the need for very thick or multiple cabling, or alternatively the introduction and use of higher electric potential tension systems than the normal 0.4 kV, as is the case in the Postojna caves or those in the USA. The installation of electric transformers within the caves themselves create similar challenges. All these options require space and when equipped with an oil cooling system, such systems can at best be an environmental risk and at worst a specific and dangerous hazard!

Secondly, more light means more energy and consequently more money to pay for higher electricity bills. High power and/or large number of floodlights including spotlights, are also more expensive to purchase. In addition, this equipment will not last indefinitely and will need replacing periodically, yet another expense.

The third and probably the most important limitation which all cave managers should take into consideration, is the requirement to properly protect the natural integrity of the cave environment. Light sources produce heat. Even the most efficient light systems convert only one third of the energy they use into light, the rest is emitted as heat. (Contrary to the common belief, LED light sources also produce heat, even though it is acknowledged that the direction of light and heat emission is different.) It is a known fact that conventional incandescent lights produce so much heat they can significantly increase the warmth of even quite large underground spaces. In the Ballroom of the Wieliczka Salt Mine for instance, chandeliers are deliberately used because the heat from them creates a pleasant and acceptable ambient temperature in that space. In smaller caves, this effect can cause major changes, ice caves being the most obvious, but not the only casualty. When these circumstances exist, a very serious issue can develop, causing a specific nature conservation problem; the growth of lamp flora. A whole chapter of this paper is dedicated to this topic, therefore only the key issues are discussed here.

Lamp flora is undoubtedly one of the most common issues in show caves and despite some very rare examples in a number of ice caves, but not all, it is a major challenge to cave managers all over the world. Several studies and experiments have attempted to prevent this problem. Some novel types of light source have even been presumed to perform better in this respect than traditional incandescent light bulbs. Maintaining this belief has in my view been distorted by background commercial or business interests, but this is more the consequence of the uninformed nature of decision makers, be they politicians, businessmen or the general public.

There is however some rational behind this notion. Whilst incandescent and halogen lights emit so-called black-body radiation and are similar to the Sun (also a black-body), they therefore produce “natural” white light of similar spectral properties to the Sun. To the contrary, other artificial lighting from different sources always lacks some specific wavelength radiation. This correctly led to the presumption that these sources of light do not favour plant growth, since plants require specific wavelength of light for photosynthesis to function effectively. Experience and experimentation have however not proven this assumption to be correct. Fluorescent, halogen and sadly LED lights have very quickly proven themselves to be just as efficient flora producers as the good old fashioned incandescent lamps. As I will demonstrate later, there is a scientific explanation for this conclusion. So beware, don’t be misled! If someone tells you this or that light source will reduce lamp flora, you can be sure their claims are nothing more than a commercial hoax, no matter how cleverly it is marketed!

Lamp flora cannot be reduced simply by the replacement of the light sources, but it can be minimized by the sensible reorganisation and refurbishment of the whole lighting system. Once again some “light will be cast on this” later. For now, it is sufficient simply to note, the better the colour rendering index (CRI, see below) of a light source, the closer its spectral properties will be to that of a black-body, such as an incandescent light or the Sun. This goal should therefore be the objective of any light sources, since this will automatically enhance the aesthetic experience. Of course, plants will also benefit, since they too have adapted to the same sunlight sources throughout evolution, as we have. However, producing white light that lacks some wavelength intervals does not prevent lamp flora and will certainly ruin the aesthetic experience and distort the reality of any cave feature. Similarly, the use of coloured or single colour (e.g. green or yellow) light prevents us from being able to recognise and therefore see the full colour range of an image.

From all of this we can therefore confidently conclude the light preferences and hence tastes of plants and humans are pretty much the same. In other words, if a light source doesn't cause lamp flora growth, it is not suitable for effective cave lighting. Opting for such light source is really a management non-starter.

So what is panacea? The management recipe and answer is actually quite simple. Use less light by balancing its density and duration.

The fundamental principle for modern cave lighting:

Use as little energy and light as possible, whilst providing the most possible information to suit the experience. Cave lighting should minimise lighting and maximise the effect. Achieving this balance is clearly a specialised task.

Even though, a good cave lighting system is always likely to be a compromise whatever the eventual solution, it must be based on the correct information, well-defined conditions, clear priorities and most of all, informed decisions. The provision of effective cave lighting systems therefore demands the following three priorities of sustainable use:

- **First**: Minimize environmental risks (recognising that the absolute exclusion of all hazards is not possible).
- **Second**: Ensure the safety of visitors is the utmost priority in every respect.
- **Third**: Pleasure stems from good information transfer so that enjoyment links aesthetics to learning.

Finally the demand to save energy and the need to prevent the growth of lamp flora should lead to the shortest possible periods of lighting and the lowest possible light intensities. This is the only way to balance these two opposing demands. However just saying this is too simplistic given the range of light sources comparable in energy efficiency, but significantly different in terms of their technical specifications and spectral range. This choice therefore means the selection of the proper light source is crucial.

Although sodium lights are the most energy efficient producers of monochrome yellow light, their light is not acceptable from aesthetic point of view (irrespective of the difficulties associated with time lag for them to reach their optimum efficiency). These two reasons make sodium lights totally unsuitable for use in cave lighting systems. Similarly, whilst the energy efficiency and colour spectrum of modern lighting tubes are comparable to LED light sources, again their size and the technical characteristics of their light, means the direction of light emission from them are totally different.

3.1 General principles for good lighting

From the outset, it is important to remember that humans are earthly creatures and our eyes and vision have evolved and adapted to daylight in all its different forms. The Sun characteristically radiates black cells which consist of a wide ranging spectrum of different frequencies of light. The human eye is however only sensitive to and stimulated by wavelengths of a specific band width within this spectrum. That being the case, what we need to consider is the issue of luminance rather than simply the concept of the spectrum.

The Sun is a light source which inherently has a very high luminance. As we all know, looking directly at the Sun is not only dazzling but dangerous, as doing so can damage the retina of the eye and lead to permanent blindness. Humans have however adapted to different intensities of light and in the process have learnt it is possible to look at the Sun through appropriate dark filters to block out certain harmful wavelengths of light. In this way we are able to view intense but interesting sources of light, such sun-spots or solar eclipses. We also know that sunlight is reflected off almost every type of surface or object and therefore exists nearly everywhere at different intensities, even though in many instances the Sun itself can't be seen. For example, light is continually transmitted into the buildings through the glass in windows. Similarly, if light intensities are strong, we consciously protect our eyes in different ways, for instance by using a visor on a cap or by lowering the sun blind on a car's windscreen, to block the light. The other obvious method is to wear sunglasses with various densities of filters to shade strong sunlight.

The easiest solution when lighting spaces, is to place high intensity light sources at the highest possible point. Light from these sources disturbs us less because we have the tendency to look forwards rather than upwards. Similarly elevated light emitting sources reflect light onto and from walls and objects and will therefore disperse more generally, if it doesn't fall onto a surface which is highly reflective. This diffuse form of light is therefore less noticeable and hence less disturbing to us, as it neither dazzles nor blinds us. It is worth noting however that throughout the Earth's atmosphere the majority of the Sun's light is diffused or scattered and therefore the entire sky effectively becomes and acts as a light source. This is obviously not the case however in a cave or underground space where artificial lighting is the only alternative to darkness. It is also the case the larger the surface area of any light emitting source, the less its intensity and therefore the less likely it is to cause a serious dazzling effect to our vision or harmful blinding of our eyes. It seems common sense therefore this form of lighting would be the obvious choice to adopt in caves, as it would be much more natural and far less harmful to the human eye.

Having said this, it is recognised this is not usually possible, so the alternative might be a number of high intensity, specific light sources throwing light in different directions, for instance an unshaded light bulb or a light enclosed in a glass lamp shade. Initial forms of cave lighting, such as the acetylene gas lights often applied these principles. This explains why they were common place before the introduction of electrification of cave lighting. Large halls, such as ballrooms, theatres and concert halls are usually lit by a huge central chandelier, complemented by a series of wall hung side lights, producing additional and complementary soft lighting. Such solutions exist in many caves, as is the case in one of the huge caverns in the Postojna cave system. To be honest though, these feel more like novelties to me rather than the basis of an effective and functional lighting system.

Original forms of street lighting were also based on the same acetylene gas light principle, with a naked or partially shaded light located on top of evenly spaced head high, free standing lamp post. When these are appropriately designed and sensitively located, this form of street lighting can be both pleasing and provide adequate light for the safe movement of people and traffic.

Such strings of 24V light bulbs are often used as a light source when installing cave equipment because they provide a pleasant source of lighting in the cave. However, such equipment cannot be hidden, thus give an aesthetically intriguing interpretation of the view. In addition lamp flora grows on them very quickly, making this type of lighting disadvantageous from a nature conservation point of view. That’s why we use point sources of light in the majority of caves, so as to give the feature they illuminate a very different look and feel, unlike diffused lights which are similar to natural sunlight. As we will see however, it is often difficult to use only one such form of lighting. There are often circumstances in caves where large surfaces and wide angles in narrow or two way passages, have to be lit and therefore targeted light sources are required.

3.2 **What is dazzle? What causes it? And what is light blindness?**

Excessively high or intense light contrast causes dazzle. When extreme light is introduced in normal lighting conditions, individual detail stands out and can also appear dazzling and overpowering. This makes the clarity and recognition of the detail around them almost impossible. This relative difference in luminance is known as contrast. Dazzling occurs when there is significant difference between the intensity of the light reflected from two different surfaces or objects. This creates the effect of brilliance, or to be more specific, small detail seems extremely bright compared to the appearance of other features around it when viewed in normal light. So instead of considering the illumination of an entire space, the brilliance of light relates to the amount of light focused on one specific aspect of an object’s surface which is then transmitted to the human eye. (Luminance of an object is measured as its “lux” i.e. an object’s candela/square meter).

Whilst luminance depends on the average lighting of an object, it is significantly affected by the roughness of its surface and hence how much this surface disperses any light which falls on it. It also depends on the object’s colour as this dictates how much light the object absorbs or reflects and finally the distance from which an object is viewed. Surprisingly distance is less significant than one might expect, as the pupil in the human eye whilst being circular is also adjustable and capable of varying its size. This provides the eye with the unique ability to vary and regulate the amount of light passing into and through it, so the amount of light falling on the retina remains constant or sufficient no matter what the distance is from the object being viewed. A simple but striking example which demonstrates my point perfectly, is the versatility of any individual’s everyday vision under very different light conditions. The difference between lighting and luminance is also illustrated by a photographer’s light exposure meter. Illumination is measured by placing the sensor of the device opposite the light source and a diffuser, such as an opaque glass of milk, in front of the sensor. To measure luminance, one would simply remove the diffuser and just direct the device’s sensor at the target object.

All photographic devices are therefore designed in such a way that show these two different methods with almost the same configurational outcome (namely the relationship between the light sensitivity of the film, the camera’s shutter speed and the size of the aperture which allows the light to pass through it and onto the film). The first technique gives a specific localised value, whilst the second provides the relevant average value. When an entire area is intensely lit, only bright surfaces or the light source itself create a dazzling effect. However if some surfaces are intensely lit and others much less so, then this creates a more noticeable and subconsciously unpleasant dazzling effect.

The Sun always dazzles because the eye finds it impossible to adapt to the intensity of the luminance being emitted from its surface. Technically however this effect is probably better described as light blindness. Likewise we define blinding as the condition when the field of view of the eye aligns directly within the outer limits of the light source. This results in rays of intense light falling directly on the eye, a situation which it is impossible for the pupils to adapt to or counteract.

Contrast dazzling occurs when a small surface which is brighter than its surroundings, lies within the field of view of our eyes. A good example of this difference is illustrated when the headlights of a car point directly into a person’s eyes and immediately cause that individual to go blind. However when we see these same headlights on the car’s low beam setting, only the so called waste-light from the headlights affects our eyes. This we then describe as dazzle. Having said that, there is no definitive point which marks the boundary between the two phenomena. Either way, the general point is that the different ways in which light enters our eyes affects our ability to see.

Dazzle can also occur when subconsciously we don’t realise light is entering our eye from the side. This additional light source interrupts light entering the eyes from other directions, sufficient to disrupt the object or scene we were originally looking at. In caves, the existence of an intense source of light shining into but from outside a person’s normal field of view or from behind, is particularly disturbing for those who wear glasses. If we however use our hands as a shade or in the case of a car its sun shield to block the light from a side window, our sight immediately returns. This explains why in sites having unbalanced illumination, we only see darker surfaces when we expose only brighter areas or don’t look at them directly. The pupils in our eyes and our line of vision are continually adapting to the prevailing and ever changing intensities of ambient daylight entering them, as does our colour vision. In darkness, our eyes see principally blue tones, while in brighter light, red tones prevail. Because the brain always wants to see true colours in a realistic way, it is continually reconfiguring its white balance reference points to provide a true colour impression of an object. Not surprisingly this tires the eyes and can result in visitors feeling uncomfortable without knowing or understanding why. Older people are more susceptible to this condition, because the speed and reflex time for their eyes to adapt to different light intensities, deteriorates with age. The physiological consequences of being dazzled are also particularly unpleasant, as coloured spots appear before our eyes, as a result of concentrations of rhodopsin in the eye increasing to sufficiently high levels to disrupt the clarity of our sight. In some cases this can last for a few minutes.

The lesson once again from these experiences is therefore to remember the less the intensity or brightness of a light, the better! Having said that however, on the other hand absolutely uniform lighting can create a rather dull setting and subdued feeling. This is comparable to imagining everyone wearing the same clothes, equally beautiful, wealthy and feminine. Contrasts, intense brightness on small surfaces make life beautiful and pleasant. Life is like an evening gown and should therefore be adorned with the sequins. The same applies to lighting caves, finding a happy medium, a golden balance in a world of acceptable contrasts.

3.3 Sub categories of cave lighting systems

In our homes, usually when there is sufficient daylight, we don't normally need additional lights to move around safely, to enjoy a meal or read comfortably. The same applies to the interior of buildings. However in larger community spaces, safety or emergency lighting is necessary, whilst in the case of museums or galleries, extra lighting is used to showcase specific items and a further form of lighting is needed to assist the routine movement of people. In some older cave lighting systems, there is often only one type of lighting, the so called "decorative" lighting. This was designed and installed to provide sufficient surplus light to illuminate the surface of passages, as would be the case with hidden lights in the interior of a building. A cave however doesn't just have one specific surface which has to be lit, but many which can operate and may be used as a means of reflecting light towards other areas, in the same way as a mirror. To do this, it is necessary to light these surfaces and possibly other formations more directly and intensely. This dispersed surplus light is however not easy to direct and means a visitor's head is usually bathed in light rather than it being in the dark.

Under these conditions the pupils in a person's eyes do not dilate enough to enable them to see properly or equally and all the walls and formations in the cave appear to be over illuminated. Thankfully however this does not necessarily create a dazzling or blinding effect. Whilst such lighting can be aesthetically pleasing, when it is excessive it soon encourages the rapid growth of lamp flora and the prospects of a cave rapidly turning green becomes a reality. As explained below, the solution to this problem is the creation of an independent lighting arrangement for passageways.

3.3.1 What should be lit in caves? Planning for general decorative lighting and passage lights

So, if we think beyond simply lighting large empty spaces, we next have to consider not only what, how and the amount of light needed throughout our entire cave but also a means of directing this light to best showcase those features which people want to see. Above all, we want to target the light onto those features of interest, rather than those we don't necessary want to see.

Walls, formations, water surfaces especially those upon which lighting creates spectacular reflections, such as flows of dripping water, streams or waves lapping against a cave wall, are all important features and must be considered, as these create the variety and appeal of a cave to the visiting public. In particular, lighting which best presents the cave's geology, such as its rock strata, fossils and in those caves fortunate enough to possess them, cave drawings, needs to be thought about and carefully designed. In this context, it is most important not to forget that in certain areas some features should be left in (semi) darkness, so it is possible to imagine and visualise them in the normal natural dark conditions of the cave.

In the case of caves used as a concert hall, the levels of lighting have to be appropriate to enable an orchestra or for actors to perform, and indeed for the audience to find their seats! In addition, access walkways need to be properly lit, with a special attention being given to lighting staircases and side stairs (in particular their first and last steps). The same principle applies to any barrier that might be damaged or may potentially hurt a visitor. In tourist caves, helmets are specifically not provided to visitors not only because of hygiene reasons, but also to avoid damage to any cave formations which might be knocked or bumped by the range of temporarily enlarged heads. In mining museums the situation is quite different and helmets are obligatory because Mine Authority safety regulations require them to be worn and of course because they also look funny.

As has been mentioned previously, the primary aims in cave lighting are twofold. To provide adequate illumination in ways which use the minimum amount of energy, whilst giving priority to protecting any features of nature conservation interest, in particular by minimising the likelihood of encouraging the unnecessary growth of lamp flora. This at first sight may appear to be quite a paradox. To resolve this dilemma however, the cardinal rule for cave lighting is always:

Keep the visitor's head in darkness!

This means not only preventing light shining directly into a visitor's eye, but also avoiding any unnecessary light which will affect the normal and efficient functioning of their pupils, as because we know too much light entering the eye automatically reduces rhodopsin concentration in the retina.

Excessive light also means not only a poorer standard of lighting in the cave as a whole, but also its features will effectively appear darker. In this situation the inclination to light certain features even more brightly will then effectively only result in benefits to and an acceleration of the growth of lamp flora. The crucial principle and my message is therefore; lower levels of dispersed light around the visitor's head. This means avoiding light passing above a visitor's head but instead placing any directional light and reflectors between the visitor and the detail being showcased. This prevents the creation of distracting shadows and discourages visitors from turning round and accidently looking directly into the offending light source. This principle however assumes that visitors are not that curious that they need to keep looking at each other! Even if they are, they should rely principally on their sense of touch rather than their visual senses. In summary, twilight is far more beneficial than other more intense and intrusive forms of illumination.

When lighting transparent formations, it is important to place the light source behind the formation, although this is very rarely required. When lighting pathways and access routes, preference should be given to downward facing lights, located at the standard and so called "barrier height" of about 70-100cm above the surface of the pathway. If they are placed any higher, too much dispersed light spills upward to head height. Equally, if the light is placed too low, more lights are needed and once again too much excess light will spread upwards. Having said this, it is important to remember to customise lights to meet the needs of children, shorter people and those requiring wheelchair access. Too much light whenever it is produced will be unpleasant when viewed from a distance, because it tends to appear as a series of unexpected horizontal bands. Even though this preferred height issue is important, it is often either ignored or overlooked and many places exist where lights on pathway are located just 20 cm above the path's surface or in other instances where lights are placed directly overhead.

Other options to light passages have also been tried, including incorporating lights into or underneath handrails, or using lengths of appropriately configured transparent lighting hose. This is clearly a better solution than positioning this type of lighting string along the walls of a corridor and creating an unnecessary dazzling effect, which does little more than distract from the views of the cave itself. The use of LEDs enable the correct setting of the optimum luminance levels to be ensured. Where there are physical constraints, for example in the case of low and tight two way passages, special measures are needed. Under these circumstances in a German cave, separate lighting was provided in such a passage by suspending small tube shaped lamps from stones hanging from the roof of the passage. Rather than solving the problem, this arrangement increased the dazzling effect and resulted in neither the ground nor the stones being visible. The inevitable outcome; an increase in the number of head injuries!

Similar challenges also exist in other caves. Larger caverns can be linked by two way, low passages. In such cases, the traditional method of lighting has still proven to be the most suitable, i.e. using general lights with low emission level illumination, capable of covering a wide angle (approximately 120 degree) surface area. This not only avoids illuminating the immediate surroundings of the light but also prevents the rapid growth of lamp flora. In these circumstances, lights at waist height are the optimum solution, as both the passage and the ceiling can be seen equally well and at the same time. If a corridor is at least 2 meters high, shoulder height lighting should be considered (which is also the industry standard for positioning lighting in mines and cellars). In these circumstances the lights are positioned in the junction of the vertical wall and the ceiling arch. If LEDs are used in these situations, they must be masked behind a matt glass cover, although a ship's lamp with or without a matt glass covering is much cheaper. The reason why matt glass is important and better is that it significantly reduces the luminance intensity of the light.

The effectiveness and issues associated with the use of strip lighting are almost identical to those of the better types of LED's. If the advantages of the LED are not the main factor in the decision to use them, it is advisable not to do so, even though they may be considered more modern or fashionable! Producing a generic and uniform form of lighting using strip lighting is better, cheaper and more practical, because its colour spectrum is the same as, or in some instances even better than LEDs. In addition, the colour range of strip lighting can be chosen more selectively. That is why strip lighting is used in buildings, even though the marketing literature from the manufacturers of LEDs tries incorrectly to convince us to use LEDs instead of strip lighting. The use of strip lighting in caves is questionable only because there are not many makes of this type of lighting which are sufficiently well sealed to be totally water and corrosion proof. If these can be found or manufactured, then they would much cheaper to buy and no more expensive to use than LEDs. Although it is a fact that the lifespan of a LED is longer than a strip light, they do not last forever and when they fail, the whole light fitting needs to be replaced. In the case of a strip light, the only maintenance cost involved is that relatively small price of replacing its individual lighting tube when it fails.

The most important principle when using a strip light is to position the fitting at least 10 cm away from a wall and inside some form of practical housing which has an internal reflector surface, to ensure its light is projected outwards and not in towards the wall. If your chosen installer cannot provide this type of configuration for the strip light, then the only solution is to either find another installer or an alternative light manufacturer!

The challenge in lighting the Buda Castle Cave was solved by only using this style of strip lighting. But in using them, was the cardinal rule of cave lighting ignored? The answer is no, as this type of strip lighting was used only as a specific exception to the general principles mentioned above and not as the norm. The Castle Cave is in fact by definition a cellar like labyrinth and not a cave. Its upper strata are mostly rock surfaces without any other recognisable formations, except for the occasional straw shaped dripstones which originated on and from a number of the concrete foundations.

It is particularly important that any decorative lighting and the light fixtures used in passageways are aesthetically sympathetic to that cave's environment. The illumination of the passage only needs to be minimal when decorative lighting is adequate, optimal and safe to meet visitor needs. As the lighting of passageways (especially non-sectioned security lighting system) results in a kind of continuous light pollution, minimising the brightness of lighting in these areas is very important. With the addition of light from any other elegant decorative lighting, it should be possible to create light with a 0.5-1 lux. This should be sufficiently bright to illuminate passageways. That said however, care needs to be taken to ensure the overall brightness is no greater than 10 lux in the immediate surrounding of the light fixture! Under such lighting conditions different colours are not easily distinguishable and also these levels of light are not necessary. The only possible bonus in these situations is that any lamp flora which appears on the walls of corridors is much easier to remove than from the surfaces of any drip-stones!

Where or when no separate safety backup lighting system is activated following a power failure, the alternative fail safe is to ensure that any passage lighting reactivates itself automatically. That being the case this lighting cannot be controlled manually using a switch. In many places, such as the Baradla Cave, a dual electricity supply exists within the cave system. This means the cave's electricity supply comes from cables configured so they have dual independent circuits. If the power on one of these circuits fails, the system automatically switches to the other. This transfer takes less than one to two seconds, unlike any manually controlled system which cannot be simply or automatically switched on. This is exactly why safety lighting must not be manually controlled or installed in individual sections which can fail.

3.3.2 Lighting an exit and emergency lighting

So far, we have considered two different types of lighting which are both necessary in caves, namely, general decorative lighting used to showcase the cave and safety lighting or its Aggtelek name, "passage lighting" used to ensure safe movement and reliable access. The latter is usually combined with a third variation, i.e. emergency lighting, to ensure the safe evacuation of the cave in the event of a power failure.

In order for an entire passage lighting system or at least some of it to operate effectively, it depends on having an emergency power supply. This comprises of an inverter (a component which converts a direct current into an alternating current) linked to an array of storage batteries. This is similar to the UPS devices used in a computer. As this arrangement depends on a series of independent batteries, it must be designed with a capacity sufficient to power the system for a minimum period of time. In most cases this period would be twice the length of time it takes for the largest conceivable number of people to evacuate the cave safely from its most distant point. (E.g. there used to be events in the concert hall of the Baradla Cave with audiences of up to 1000 people!) For the emergency lighting it is therefore advisable to use a light source with a low energy requirement, i.e. either an 11W strip light or more recently LEDs, in particular ones with a very low energy requirement of 1-15W. Although the light intensity of LEDs is proportionally lower, they can be more effectively directed. Because the energy rating of both strip lights and LEDs are the same, (i.e. 80-100 lumen/Watts) this means both have the same exothermic value, so effectively a LED heats the cave to the same extent as the fluorescent tube in a strip light.

In many caves the storage batteries used to power emergency lighting systems are the same as those designed to operate emergency lighting in buildings and factories. Although these lighting systems are connected to this energy supply and are therefore continually "on charge", they are only activated and their energy made available, when the primary power source supplying the emergency lighting fails, or falls below a specific threshold. The shortcoming of this arrangement is the disturbingly horrible need for and appearance of banks of ugly batteries, many of which have pairs of large spot lights mounted on their upper surfaces. In addition, these batteries require regular checking and maintenance and also need to be changed once in a while. Also if they are hidden in inconspicuous locations, then by implication they probably wouldn't be able to provide sufficient light to illuminate the exit route from the caves.

These safety lights also light up if a power failure occurs outside the normal daily operational periods. If this happens and these backup batteries become the only power source in use for long periods of time, eventually they will completely discharge. When this happens and the batteries fail, not only will there be no light but the batteries themselves can be irreparably damaged. In most situations there is likely be to a safety feature incorporated into the power supply circuit which prevents such a breakdown of a battery occurring. This solution is obviously preferable, as it is highly unlikely that a series of independent backup systems would all fail at the same time, as might happen if a single centralised backup system was the only reliable secondary power supply available. Given their advantages, the use of batteries as a backup power source is the most practical and tolerable option, despite their offensive appearance and continual demands for maintenance.

Normal cave safety lighting protocols and practices in Hungarian caves ensure safety lighting is not limited to individual sections of a cave, but operate throughout the whole cave system. This ensures individuals who become separated from others or fall behind a group, can safely catch up. In such circumstances, emergency lighting would be sufficient so long as it is an integral element of the master passageway lighting system as a whole, rather than simply operating along an individual section of an exit route. Where automatically operated lighting systems are used for passage lighting however, having sections of passage individually lit is possible because anyone who falls behind when the lights fail, would be able to rely on the residual light from surrounding decorative lighting, or from any remaining passage lighting which is still working, to see where they are going.

Fortunately the use of safety or emergency lighting combined with passage lighting doesn't demand any extra electrical apparatus in a cave, nor require any additional technical or power requirements. That being the case, there is no need for any specific locations to be available for additional installations. It is however important to realise that any standard emergency lighting system is not there just to provide sufficient light as and when needed, but also has an important advisory and directional role. The familiar illuminated green arrow and running person symbol, pointing towards the nearest safe exit, provide vital safety information to enable people to move swiftly and safely away from danger, sometimes to exits which are not necessarily the normal ones. As emergency lights function as both warning and directional lights, they must be conspicuous. It is therefore not appropriate for such lights to be fitted into handrails which light a walkway. When normal lighting fails, the public must walk straight towards the direction of the emergency warning light, as this effectively acts as a guiding star pointing towards a safe escape route.

Where there are no barriers and a walkway is completely flat and bordered by appropriate handrails, then a light source as prominent as a candle flame is sufficient every 100 meters to provide sufficient light for people to see where they must go. Obviously this is the minimum requirement though it is much safer and advisable to provide emergency lighting more closely spaced. In order to avoid any emergency lighting dazzling anyone, it is advisable as mentioned to mask any such light source behind matt glass, to ensure the glass is properly lit. Low intensity light sources should be used or alternatively and where necessary, a combined approach is preferable, using a beam of the light directed down towards the walking surface and a less intense light source at eye level from a fixture with a matt glass cover. If the only option is to use high intensity LED lights, those which have directly visible lighting diodes should be avoided.

The "Berczik" passage-light (Foto: Péter Berczik)

In olden times and in those underground caverns used by large gatherings of people glim light emitting low levels of light and having a long life span were used to direct individuals towards an emergency exit. More elderly people will probably still remember the turtle shaped light fixtures in cinemas located above each curtained exit door. These also worked with glim-bulbs. Inside these fixtures there are two electrical wire spirals positioned close to each other. Because there is no filament, the light cannot fuse and so it has a long lifespan. Equally because it is not excessively bright, it acts as a perfect positional light and an excellent visual marker.

In extreme situations when everything else goes wrong, a guide should always carry a hand torch and it’s also sensible to have a supply of candles available. (These of course would not be given to visitors, but simply placed along the relevant walkways.) Similarly most people either have a lighter in their pockets or one or more mobile phones with a bright LED light source, not only to take photos but also to use as a personal backup light.

Emergency lighting is particularly important in halls used by large numbers of people, such as the cave used as a concert hall in the Baradla, where more than a thousand people can occasionally assemble. In such circumstances the greatest threat is an unexpected incident, for instance a power failure or an electrical fire or at worst both happening at the same time, resulting in mass panic. If this happens people invariably rush about haphazardly and can trample each other. This is why it is so important to light all exits and the access to them properly, safely and ensure that trained staff are in place to cope calmly and efficiently with any such incidents.

3.3.3 Dynamic decorative lighting

A widely used variation of decorative lighting is the so-called dynamic lighting or show-lighting. This form of lighting is used in locations where visitors are encouraged to pause or stop at a particular location and with the help of different light effects, are told about the interesting details of the cave. Controlling lights in these circumstances can be achieved either using manual lighting controls or with an automated programme, even to the extent that the latter can be synchronized with music. During such events, passage lighting is not necessary and can be turned off temporarily, although alternative emergency lighting always has to be available.

Dynamic decorative lighting, is by definition lighting which only operates for short periods of time. Given the limited periods of light within a cave, problems with the growth of lamp-flora are not as much of a concern as is the case with general decorative lighting or the lighting of passageways. This doesn’t mean however that care and attention shouldn’t be given to the possibilities of creating dazzle and light blindness or the balance needed to create acceptable conditions for normal vision. However, in the case of caves with a large numbers of visitors and therefore the existence of ever present and almost continuous dynamic lighting, the threat of lamp-flora must still be acknowledged and considered.

3.4 Zoning of cave lighting

There are only a few caves, for instance the Karlsbad Cave in New Mexico, which have such large numbers of visitors throughout their entire periods of daily operation that lighting has to be provided almost all the time. For both energy saving reasons and because of our hatred of lamp flora, zoning a lighting system to provide lighting only when it is needed is a sensible option to solve these problems. This zoning technique can be used for decorative lighting and dynamic decor lighting, but not for safety and emergency lighting, as this must be continuously active and operate throughout all the areas of a cave used by visitors. Emergency lighting cannot therefore be zoned. Whenever any illumination scheme is being planned therefore, the only circumstances when zonal lighting can be used is where there is a desire to change or enhance a visitor experience of the underground world. In fact the use of zoned lighting is best limited to either decorative purposes or as passage lighting, so long as neither of these do not double up and act as safety lighting. For zoned lighting to act effectively a number of questions have to be considered. The length or area of the zone to be lit, where the lighting should be located, how it is fitted and how the lighting of each zoned area can be operated efficiently. Answering the last of these questions i.e. how lighting is switched on and off is particularly important, as it directly affects the approach adopted to resolve the first two issues.

3.4.1 Direct switching

This is the technique normally used in houses and work places using a simple mechanical light switch fitted into and forming part of a 230V or 127 V electrical lighting circuit. As the higher of these two voltage circuits can, without proper insulation in wet conditions, cause electrical arching, using this type of circuit is dangerous and should therefore not used in the general lighting systems of larger caves. Furthermore it is important to realize that lighting zones cannot be sub divided into several circuits (e.g. by sharing the load among different phases), because in such circumstances all the three circuits would need to pass through a triple switch-gear arrangement. Moreover, if a lighting system is to be controlled from several different locations in the cave, all the circuits would have to be wired to each of the switching points and an expensive switch gear installed. In addition, many more cables would be needed, each of which is costly, needs its own space and would be visually unsightly.

The same applies to low voltage lighting systems, where once again large diameter cables are needed to avoid significant power loss given that energy is being transmitted at lower voltages. As the length of the cable used is also an important factor, it is therefore better and more practical to create separate power circuits. For this arrangement, a primary power supply with a lower voltage and current is sufficient, as this layout doesn’t require such thick cabling. Despite all these disadvantages this option is frequently used in many European caves. Elsewhere long range operational control systems are used because they are more economical and their improved insulation provides better protection against the risk of unforeseen electric shocks.

3.4.2 What is a push-button system?

This manual arrangement is the most common lighting control used worldwide. It involves a low voltage primary circuit, usually 24 volts, being connected to a manually operated push button control mechanism. In the Baradla, a 42 volt power supply is used because this is the biggest and most beautiful cave, the consequence being it also has the most daring cave tour guides who are not worried about the risks from higher voltages. This type of switching system is operated by dual green and red button controls. When the green is pushed the power flows through the circuit, whilst hitting the red one immediately cuts the power supply. When the buttons are not coloured, guess work is required! In modern versions of this switch an independent illuminated button indicates the status of the power circuit. In terms of the overall design of these types of systems, the primary power supply is connected to a mains master junction box, either inside or outside the cave. This powers and controls the whole lighting circuit by means of a long range relay, the “contactor”, or alternatively the so-called “solid body relay”. The key factor associated with this arrangement is the fact the push-button controls, or indeed any series of them, can be located anywhere and therefore completely independent of the position of any associated lighting cables. That being the case a push button switch doesn’t have to be installed directly into the actual lighting system. For the same reason this means the extent of each lighting zone can be varied.

Positioning a series push button controls effectively means the lighting within a particular zone can be phased and synchronised so that sections are illuminated when visitors pass through them and can be switched off when they leave. It also means that by offsetting the controls at the beginning and end of each lighting zone, the lighting between different zones can be controlled to avoid unnecessary spillage of light either in front or behind the visitor. Push button controls are particularly appropriate, if not the best way to control a dynamic decorative lighting system, especially when they are synchronised with any commentary provided by the relevant tour guide. In such instances the button controls can be arranged on a switchboard panel so they can be manually controlled by the tour guide during their presentation.

Despite their advantages, using push button controls to operate a dynamic decorative lighting does create a series of problems. Clearly they are impractical as part of a zoning control system where visitors self-guide themselves through the caves, especially as there is often a tendency for many more visitor caves these days to be accessible to visitors without the need for a tour guide. Obviously it is impossible for visitors to know where control buttons are located or what each of them operates. Left on their own, especially when individuals rather than groups are moving round the cave system, individuals could end up switching lights off when others need them on. In such situations the normal solution would be not to use zoned lighting. The disadvantage of having continuous lighting is that unfortunately yet again it favours our eternal enemy, the lamp flora. This phenomenon can be studied e.g. in the Hölgrotten Baar in Switzerland.

Visitor groups of varying sizes also create a similar problem. The basic principle when deciding how to illuminate any lighting zone, is to design a system which functions effectively when the largest anticipated number of tourists pass through it at any one time. If this is not practical, then a series of push button controls will have to be used and positioned carefully to ensure that several zones or sections of them, can be switched off at the same time. This will ensure that anybody at the end of the group gets the same lighting experience as those at the front. Similarly, care will also be needed to ensure that any group which follows one ahead of it, doesn't arrive in a zone where the lights have accidentally been switched off following the leading group leaving that same area. The only solution if these situations are likely to occur on a regular basis, is for tour guides to leave the lighting in a particular zone permanently switched on at all the busiest times of the day. Unfortunately doing this will soon make the cave turn glow green, thanks to our friend, the lamp flora.

Large groups in excess of 100 people or more at the Baradla Cave require very long sections to be illuminated, which would not be necessary for the normal display period or for an average sized group of people. In such a case the illuminated section of the cave will be much longer than that which is visible by the average number of visitors.

Push button systems are not the only control option which can be used for lighting systems. Alternatives include both radio and infrared remote control systems. These types of system provide much greater flexibility and freedom for the tour guide, as they don't have to look for or even remember where each push button control is located. Having said that, with the best intentions and skillful installation, not even radio or infrared systems can cope with, or solve the problems associated with groups of different sizes.

So what is the solution?

It seems obvious, the best option is to use an automated control system. One which doesn't require anyone to manually operate it and which can be adapted to different circumstances and minimises the period a particular area is lit.

3.4.3 Automatic lighting control: Motion sensors and infra-red devices.

Everyone is probably familiar with lights above doors and gates, namely those which automatically light up when a person approaches. They are designed in a way which integrates and fits a motion sensor into a small and enclosed housing. This sensor can detect heat and movement in the surrounding areas, creating a protective, but invisible infrared light "grid." When a moving object blocks too many of the grid zones, the infrared energy levels change rapidly and the sensors are tripped. When this happens, the sensor creates a pulse of electricity which activates the light. The light then stays on until there is no further movement to disrupt the grid or the charge to the light is shut off by a timer delay mechanism in the unit.

These motion sensors were originally designed for use in alarm systems, similar to the devices often seen in movies about bank robberies. Those familiar with these films will know the way to prevent these types of motion sensor from being triggered is for the intruder to wear special glasses which make the invisible laser beams of infrared light visible. Being able to see these beams, then allows robbers to skillfully squeeze through or pass the arrays of visible light beam without breaking them.

The working principle of a motion sensor depends on two specific elements: an emitter and a receiver. The beam of infra-red light is effectively a ray of heat generated by the emitter, which has to be specifically directed to the cell of the sensor i.e. the receiver. As mentioned when anything breaks this ray, the receiver produces a signal, which then activates either a light or an alarm, depending which of these functions has been chosen when setting up the secondary circuit. In case of an alarm system this has to be switched off manually but a lighting system can be operated by a preset timer. Both these options have been used in caves and are proven to be suitable to the underground circumstances and also have the added advantage of a long life span. The main disadvantage of motion sensors however is that the radius of their field of view is often too restricted. This can result in cave lighting being switched off too soon and an area which needs to be lit being plunged into darkness. This can happen for instance when a group of people stop in one place and for some reason remain motionless for a long period of time. When no one moves, the sensor or the timer will switch off the lights and darkness returns.

Infra-red devices are however much more efficient than motion sensors. Their field of view and range in a cave situation is much greater and can reach as far as 50-100 meters. The range of the more expensive sensors can even operate over still longer distances, although these types of devices are rarely needed in caves. Infra-red devices or more correctly networks of infra-red beams, need to be carefully positioned. The best location is parallel to the walking surface, spreading as far forward along the target surface as possible, rather than as might perhaps be expected across it. So long as any rays of emitted light from these devices are blocked or as long as a device's time delay lasts, the lighting will stay on. This has the same effect as repeatedly pushing the button of a manually operated system (like the ones often used to light staircases in buildings). If a small group was to stay too long between two infra-red sensors, in order to avoid any lights going out, a tour guide could simply walk across the path of the rays from the next device triggering the same lights to switch on again. If the whole of a cave passage can be effectively covered by infrared devices, then the timers on each device can be set for a minimal time period, so as to enable both the period of lighting and the power supply to each light to be minimized. This would not only reduce the costs of the lighting but also the risk of encouraging the growth of lamp-flora.

This lighting arrangement is also better and more logical because the period of lighting of particular sections of the visitor route can effectively be minimized. More importantly, tour guides don't have to bother themselves finding and operating a series of manual control switches and cannot inadvertently switch the lights off on any group that follows.

Automated lighting can also be more carefully regulated according to the prevailing light conditions and requirements within a cave and therefore ensure the correct visual clarity. This helps to ensure any forward pointing directional lighting are activated and directed at the required eye level. Infra-red devices are best installed close to the ends of each lighting zone, so they can be activated at the correct moment and light the next area to be visited. This is particular important when it adds extra value and drama to the prospects of what is next to be seen.

If the end of one zone coincides with a turn or a bottleneck, then an infra-red device is probably not needed. Where lighting exists only on one side of a walkway, (that is the movement is only in one direction), or it is possible to establish a system suitable to light both directions and in addition the cave is corridor shaped, the use of automated lighting controls is by far the best, most comfortable and certainly the most nature friendly way to provide good lighting.

Infra-red devices also have the added advantage that they can be set to have a comparatively slow reaction time and are therefore unlikely to be easily triggered by bats or birds flying close to or passing them. When not in use it is also possible to deactivate infra-red devices completely to prevent them being accidentally or unnecessarily triggered. Switching these types of control systems off completely is however not advisable, because infra-red sensors rely on an internal heating mechanism to operate and the heat generated within them, also prevents the unit from corroding in damp conditions.

The infra-red control system cannot be used however where there is movement in the two opposite directions in the same space and the lighting for each of these directions is different (see later). Clearly in this situation any individual infra-red detector would be totally confused and wouldn't know which circuit it is supposed to activate, or in which direction lighting is needed or intended. In this situation the only option would be to use either manual push buttons controls or some form of remote control method.

Although infra-red devices require a significant amount of cabling, their price is relatively small compared to the total cost of installing an infrared system as a whole. If such a system is installed it is advisable to cluster any such cabling into a bundle and position it within an easily accessible fixture or conduit, such as a culvert or an appropriate length of protective piping. This additional cost will soon be recouped, not to mention successfully helping to avoid the growth of lamp-flora, a benefit which could never be sensibly or economically costed.

3.5. The role and importance of lighting trials

When considering the role and value of lighting trials, the following thoughts are not concerned with the process of testing e.g. a new light type, nor demonstrating to a potential buyer the capabilities of certain technical or organizational skills, or even simply organizing a demonstration light shows in a cave. To the contrary, trialing any lighting system is far more important than any of these activities, as it lies at the very heart of all effective cave lighting engineering and the success of a proposed system as a whole. Every aspect of the type of lighting, its capacity, location and capabilities to illuminate the various target areas of a cave, have to be thoroughly tested and verified as appropriate, for a trial to be effective.

Cave lighting cannot and indeed should not be designed in someone's head or on paper. Although experience helps anyone imagine and visualize the effects of a certain type of lighting, there are always so many other local conditions and practical circumstances in each individual cave which have to be considered and accounted for. The most important of these is always the need to check the exact positioning of a light so it produces the effect expected or required. Lights certainly cannot be positioned anywhere. Indeed there are usually many more places where lights should not be placed than where they can be successfully located! That being the case it is far more sensible to first assess the range and suitability of potential locations for lights before even starting to think of the most appropriate forms of lighting which should then be used. Ignoring this cardinal first principle has in many instances resulted in many horrific mistakes and costly failures. What is worse for instance than trying to camouflage lighting fixed directly onto cave formations, as the following image clearly illustrates!

(Foto: G. Salamon)

Almost as bad are the various attempts to construct large artificial lighting gantries. These inevitably become so conspicuous that they divert people's attention away from the very features the lights are trying to illuminate. The primary and absolute rule of cave lighting is therefore: if you cannot light something from a sensible and acceptable location, don't light it all. Quite often these features like this won't be in complete darkness anyway because light will be reflected onto them from elsewhere in the cave. However in all instances moderation is necessary for the simple reason as we know: lamp-flora is just waiting for its opportunity to thrive. So if anyone tells you they can plan and visualize in their heads where lights should be placed, the surfaces to be lit, the necessary levels of illumination, where shadows, dazzle or waste-light will fall and in particular where lamp-flora will grow, so that everything will be perfect during the system's construction; don't believe them and certainly don't work with them.

I once met someone who said he could work out all of these permutations and install his virtual system of lighting very easily. The end product was a cave lighting system which was far better forgotten than remembered. A successful failure, which reflected every possible mistake anyone could ever make and even imagine. At the end of the day, the one single piece of advice which is undeniable and cannot be overstated, is the value of undertaking as thorough and comprehensive lighting trials as is possible before installing and using the preferred system.

3.5.1 When should lighting trials take place?

Well, one thing is certain, lighting trials should be undertaken before any construction work begins. If so, when is the appropriate time to do so? The answer is… the sooner the better. If time is allocated for a proper trial during the initial engineering phase, then the planned system and the eventual result will not only be better but more specific and far more realistic, not to mention the fact that the overall estimated cost of the scheme will be more accurate and the necessary budgets to implement the work more likely to be secured. If lighting trials are not undertaken during the initial planning phase and the proposer of a scheme is convinced his final lighting scheme will be appropriate, expect his guesstimates of the numbers of lights, control switches and quantities of cables required, to include some contingency allowance to cover potentially unforeseen circumstances and his additional costs.

It also goes without saying the greater the number or variety of types of lighting arrangements being proposed, the greater the risk of underestimating the total costs of the scheme. When older and less complex types of light sources and light fittings are reused, these are more capable of being adapted, since different light sources can often all be incorporated into a standard PAR38 lighting unit. Similarly, if a multipurpose halogen light fitting is used, these can also be adapted to enable alternative mirrors and bulbs of different rating and capacity to be used. LED lights however cannot be separated from their parent light source, are very expensive and are usually not available in shops, as their production is both time consuming and expensive. This is why credible and realistic planning is so important if the overall quality of the end product is to be assured.

If none of these options is possible, unfortunately your lighting installer will have to work with whatever exists. If so, expect him or her to become frustrated, complain, swear and curse those who have been so short sighted as not to recognize the difficulties they face. If the installer is also the person who has designed the system then he or she can only blame themselves for creating these problems. Being clever, cutting corners and trying to save money, never works.

Regrettably it is a sad reflection of the state of the lighting profession and the culture of cave-lighting in particular, that there are no accepted international or universal standards for this type of activity. Hence those doing this work are often incompetent, but continue to work in this way without harming their own reputation. Because of this lack of standards, many contractors overestimate the cost of a job, so as to ensure they either cover any unforeseen or unexpected costs or simply to make a handsome profit. However, if a particular contractor foresees a 25-30% surplus of lights, the lighting trials can be postponed to the first phase of the construction works. Using specialized companies with acknowledged professional expertise and considerable experience is always the most sensible and cost effective approach, even if there are sadly few such competent organizations in existence anywhere in the world.

The best solution during the planning stage of any scheme is therefore to have a few prototypes of each light manufactured prior to or during the planning phase, which are both fit for purpose and also fit for the location where they will be used (less from the rarely used ones, and more from those, which have a 40° viewing angle). These lights have to be equipped preferably with their own individual or collective 230 V power supply and rely upon more sophisticated control mechanisms, to enable their brightness and illumination levels to be easily adjusted, i.e. they have to be dimmable.

It is also feasible and sensible when planning a new lighting system to ensure that an over generous supply of the most suitable types of light fittings and shades are always available. Failure to have enough fixtures and fittings will inevitably mean crude alternatives have to be used; the shade from someone’s hand, a note-book, or some other temporary object to block any unwanted or irritating light.

3.5.2 How many lights are needed to test a system’s overall effectiveness?

This is quite an easy question to answer; the bigger the area or cavern, the more lights that are needed. In principle there should be sufficient light to set and assess a single view from a fixed point or which imitate the continuous movement of the visitor from certain points. When moving forward with the tests in a one-way corridor, the lights which are no longer needed behind a particular spot can be placed ahead of it to illuminate the newly emerging sections of a route.

When visitors first enters a large area, it is suggested that only “basic or minimal” lighting is used to illuminate those details which will immediately captivate a person’s imagination. When that person stops, more dramatic décor lighting can then be progressively used, perhaps even with accompanying music. Eventually levels of lighting can be increased to reveal the whole spectacle of the area to be viewed. Effectively the full drama of the cave should be a finale and only revealed when all the lights come on, so it provides a powerful emotional experience to the viewer. If it doesn’t, then why worry as their entrance ticket for their visit and experience has already been paid for? If the lighting operates in this way, testing larger spaces can be done in smaller individual sections.

Static lighting uses fewer lights than dynamic lighting but the advantage of this latter approach is that it can be organized in individual sequences, preferably lighting in a counterclockwise direction, as this is easier than having lighting appearing from different directions around a hall (maybe the opposite direction is appropriate for those who are left-handed). Test lights are taken down from the back to the front of a space, i.e. from the right to the left, but always keeping one zone of viewing continuously lit. In such situations reflected light accumulates, but this can be counteracted by dimming during the final installation, if the diffused light is too strong, i.e. it is unnecessary in achieving the desired effect or view.

When testing lighting, each fixture should be temporarily but securely fixed in its anticipated final position. If helpers are available, they should pinpoint this ideal position, then holding and directing the light correctly, someone else can check the effect from every possible angle and viewpoint. This will involve deciding if the light gives the desired effect and it doesn’t blind the viewer or create any disturbing shading etc.

In the meantime the people testing the lights will probably be shouting and quarreling with each other: “*Hey, don’t move the light; don’t stand in front of it…“* just to ensure everyone has a bit of fun. When the final position for the light is agreed, it can be temporarily fixed. If the substrate is firm, drill a 6 mm hole, insert a similarly sized dowel and then a wood screw is all that’s needed to fix it in place. Even if it isn’t fully fixed, at least there won’t be any underground winds to dislodge or blow it away, so its direction can be fixed. When 4-5 lights are in place, the final direction of each of them can be fine-tuned and dimmed as necessary. Similarly, the type of the light can be altered if required and the angle of illumination adjusted. In the event the position of the light doesn’t prove suitable, it can be moved and the original drill hole filled. The eventual aim of this process is to position all the lights at the same time, so that the impression of a synchronised view is created for the viewer before the designers move on from that particular view point.

Why should lights not be fixed on dripstones? Actually the answer to this question is common sense… people come to caves to see dripstones not lights! Moreover, dripstones are all individual formations, none of which are the same, believe me, as I am the world champion in dripstone breaking. During the exploration of the Vörös-ág in the Baradla Cave system, crawling along six hundred meters of narrow passages with soda straws hanging from the ceiling, I managed to break many of them off with my helmet. The evidence of my sin, i.e. the dented helmet can now be seen in the Kessler Memorial House at Jósvafő village.

Whilst it is reckless to drill holes in dripstones, equally any cables positioned amongst them can further damage these formations. Similarly dripstones continue to grow bigger and thicker, not just on their top or at their ends. Amazingly during the 20-25 year lifetime of a light, a layer of dripstone sediment can accumulate on the surface of the light’s safety glass or especially on polycarbonate and decrease its luminance by up to 20-30 %. Cleaning this deposit off a light’s protective polycarbonate cover is not easy, because it is soft and easily scratched. If during the reconfiguration of a lighting system a proposed lighting spot is no longer needed or used, an ugly spot will remain that takes decades to disappear. So placing lights on walls with formations on them should only be done in extreme circumstances. When it is absolutely necessary to place them on the surface of a wall, they should be fixed to a support placed between the light and the wall, in order to minimize any possible damage.

3.5.3 How to create the best lighting effect

In his classic lighting technology notes, András Arató [1] (2003) does not specifically mention cave lighting, but in the chapter on garden lighting he offers the following advice:

- Too many lights in a small area doesn’t create a pleasing impression or mood. Good garden lighting is achieved by creating alternate light and dark areas.
- However the entrance to a house, its street number, the garage or a cellar door, the passage from the gate to the front door and the stairs, are all different and they should all be well lit.

Transposing this logic and principles to the technical requirements of cave lighting means:

[1] He is much better known as “Hide the Pain Harold”.

- Once again, too many lights in a small area won't create a pleasing impression or mood. Good cave lighting is only achieved by creating alternate light and dark areas.
- However, narrow passages, barriers, pavements and stairs, especially the first and the very last ones, should all be well lit.

Although not all pirate captains were one-eyed, many of them wore a black patch over one eye. Why, you might ask? Because if they needed to go quickly into or below the ship's deck, e.g. to the gun deck, their covered eye would already be adjusted to the darkness and so all they had to do was remove their eye patch to be able to see. I'm sure some of you realize at the entrance and exit of the tunnel, there is more and much stronger light than inside it. This means it takes longer for a person's eyes to produce sufficient rhodopsin to adapt to the darkness. That is why caves need stronger lighting than usual at the entrance. At the exit however it is not as important and in the worst case scenario people leaving the cave will only be slightly dazzled for a few seconds when they emerge into the daylight.

After all of this - the secrets of good lighting

First and foremost: it should be harmonious. As has been previously emphasized, the general lighting used in modern housing, factories, ballrooms, theatres, etc. is not an option. Cave lighting has to reflect an environment that is normally in total darkness; a never ending night. It is therefore important not to try to light everything but leave the darker and more mysterious details unlit. Doing this will help to accentuate those areas that are illuminated and highlighted. Contrast is very important, but as we have seen, it should be regulated not only to avoid the problems of lamp-flora, but also in order not to confuse a person's eyes.

Secondly: Lighting needs to be technically correct and pleasing. Priority should be given to showcasing and highlighting the unique characteristics of any cave. The rock strata and their structures, the tectonic pre-formations and the corrosive or erosive features all need to be displayed in an understandable way. In particular the most decorative, rarest and biggest formations need to be featured. Equally, particular attention should be given to any unusually shaped formations which resemble something else or have names which suggest supernatural associations. These features are what make any cave tour unique, entertaining and memorable.

Thirdly: Pay attention to detail. As the lit area of a light often has a sharp edge, the loss of its trail can be partly compensated by back lighting or by directing light to a place where it dissipates softly out of view, e.g. where a wall meets the floor, a crack, or on a sloping surface. Similarly, using an elliptical macro lens on a LED light can also be very useful, since it creates a long and narrow beam of light which is very good for lighting narrow cracks, without risk of creating a lamp-flora on any nearby walls. LED lights are also capable of highlighting long or tall dripstone formations. Since their light is projected entirely onto the dripstone and no rays stray onto surrounding rocks, they don't create a shadow behind the stalagmite and hence no back spotlighting is needed. In this way an impressive contrast can be created with a low light intensity. (In this situation the formations are effectively lit from two directions with any voids being filled with light.) If this technique is used, special attention needs to be given to hiding or avoiding any shadows caused by objects such as handrails.

When focusing on the most important decorative lighting, the aim is to create a view which looks attractive, balanced, detailed and realistic. To achieve this, a number of technical solutions should be considered. Using the minimum amount of lighting required has already been discussed. In addition, it is wise to illuminate a surface with a minimum of two lights pointing in different directions, one of which should be brighter than the other. By selecting the most appropriate lights, adjusting their respective distances and strengths, the overall lighting effect can be successfully controlled. This technique ensures a much detailed view and avoids creating unnecessarily and disturbing shadows.

In some old cave lighting systems, for instance in the Postojna Cave, formations and walls are lit by huge reflectors, pointing in a direction which is perpendicular to the passageway, making that view look rather plain. Using low level horizontal light (where a ray of light hits the ground at a shallow angle), should also be avoided. If such lighting is needed, it should only be used if a very special effect is required, for instance to showcase a pattern that cannot otherwise be seen. In these circumstances, the light should be sufficiently far from the object being lit and any excess light shaded from the surfaces which are not to be highlighted. Using low horizontal light however usually results in an extremely high luminance near any fixture attached to a wall. This light will however fade over distance, in proportion to the inverse-square law, resulting in a very unevenly lit surface. In practice this means under no circumstances should a light illuminate anywhere which is directly under, above or next to itself, as this will create a comet shaped plume of light on the wall or on the ground. This is not only ugly but also encourages the growth of undesirable lamp-flora.

As mentioned, the strength of the lighting is directly proportional to the distance squared from an object. So if a surface can be seen from 4 meters, there needs to be at least 10 Lux of illumination and correspondingly 40 Lux within 2 meters, 160 Lux within 1 meter and 640 Lux within 50 cm. These conditions will however guarantee not only unpleasant dazzle but also an abundance of lamp-flora. At a distance of 25 cm 2560 Lux are projected on a wall, resulting in such a large difference in light intensity that no human eye can tolerate it without serious distress. This situation will also make a visitor feel very uncomfortable without understanding why. The correct angle for lighting is therefore often a compromise and should be preferably between 30^o and 90^o.

To illuminate a reasonably bright and pale colored dripstone, a surface measurement of 20-30 Lux is adequate, as long as this doesn’t create an excess of waste light. (To define the optimal luminance in candela/square meter – cd/m2 – it would be preferable to follow the engineering standards, but this equivalent of light intensity is more difficult to measure.) When walls are white, light is more easily reflected and so darker formations need either a greater amount or more intense sources of lighting.

The challenge therefore is always to create the most comfortable and agreeable view possible. In the case of a pale colored formation, less light is better than too much. It is also always more sensible to balance any subjective judgement and opinion regarding the acceptability of lighting, with actual measurements.

Lights should never be fixed directly to a wall. Where they have to, they should always be placed on non-corrosive metal rod shaped supports, preferably made of stainless steel, of an appropriate length and attached to an inconspicuous mounting. Attaching them in this way ensures adequate separation from the cave wall and also helps avoid the growth of lamp-flora. Wherever possible the number of lights should be kept to a minimum and arranged in clusters. This arrangement enables different directions to be lit from a single spot and all the associated cabling to be kept to a minimum.

Lighting should also be adjusted to meet the requirements of guided-tours. When a group enters a room, the lights should never be the first thing seen. To achieve this effect it is not advisable nor sensible for lights to be facing towards the direction people are approaching. To avoid lights shining directly into people's eyes, i.e. by keeping their heads in the dark, lighting should be located either at ground level or from above and angled so it shines above the eye-level of an average height person. Whilst this may seem quite difficult, in practice it is more easily achieved. The advantage of this approach is that it provides light both across and on the two sides of a passage. Although this is makeshift, it is well suited to single direction passageways, but obviously not for two way corridors. In this case, a separate forward and backward facing lighting system is needed. The disadvantage of this is that visitor groups must meet at the intersection of the two respective areas being lit. There are many lighting arrangements like this in the Anna Cave at Lillafüred (Miskolc, Hungary), where 1-2 meter high walls have been artificially created and built into the rock (tuff), because the natural formations being viewed are generally located and seen above them.

One might wonder why lighting plans are not based on 3D laser scanned models of a cave. First, this technology is not available everywhere and secondly these models don't show either the real colours or the reflectiveness of a cave's surfaces. Unlike the human eye and brain, models cannot determine whether lights are in reality correctly placed, nor if any planned cabling would look visually pleasing. Such models are however useful to plan walkways. Ultimately the only way to plan and test a successful lighting system is to do it in the cave itself.

3.5.4 Hiding lights (lamps)

The first thing to do during any cave lighting trial is make sure that all lights are out of sight. It is natural for any installer to be proud of their work and their choice of lighting fixtures, but visitors being hopelessly uneducated and indifferent to these technical challenges, would neither realize the complications of these procedures, nor indeed care about them. Hiding modern LED lights is always easier than other forms of lighting, as they are much smaller and aesthetic and therefore less intrusive than an average filament light, halogen or metal-halogen reflector. Using them is therefore always more preferable and certainly more convenient.

Hiding or disguising lights is important for two reasons. Firstly, it avoids unnecessary man-made equipment being visible in the natural environment of a cave. Secondly, hiding them prevents lights dazzling or blinding the viewer, although once again there is always the risk that enclosing them can encourage the growth of lamp-flora. So generally the more inconspicuous a light, the better. Several methods for hiding lights have been developed which I'll summarize in no specific order or as a result of any systematic approach.

3.5.4.1 When should lights not been hidden?

Shielding or hiding lights should never be used when narrow, jewelry box like areas of a cave with lots of formations in them are to be lit. In these circumstances shielding is not necessary because the shield appears as a single visual object that is much bigger than the light itself. It is usually positioned close to the visitor and can damage the formations. Alternatively if it is too well designed, it could be easily be mistaken for a natural formation and create a false impression. In these circumstances, quasi-shielding of lights is a helpful approach i.e. avoiding illuminating one light with another, a mandatory rule which unfortunately is almost always and invariably disregarded.

3.5.4.2 Using natural coverings

The most common suitable and practical way of hiding lights is to use natural objects. These can be stones, dripstones, side-branches, or the natural curves and bends of tunnels or mines. In this situation, lights should be placed invisibly in shaded sites, indeed sometimes lights can be placed inside cavernous dripstones. When I was young, we did this in the Földvári Cave, because it was not a frequently visited cave, so there was little risk of lamp-flora growth. In other cases, using lights in this way or by placing strong light sources behind the dripstones helps showcase their transparency and drama. This solution can however create lighting which is too intense and cause too much heat close to the light source.

It is important to remember however that LED lights create the same heat output as strip lights. The only significant difference is the fact the heat from the light is emitted backwards, which can encourage the growth of lamp-flora, which obviously has a detrimental effect on the growth of the dripstone. In older lighting systems, constructors often used the method of lighting from above by applying boat shaped lights fixed into the hollows of the upper bed. This arrangement was neither too bright nor took up too much space, allowing visitors to pass under them without bumping their heads. Unfortunately these fixtures soon became very convenient and comfortable places for lamp-flora to flourish. In their attempts to resolve this problem, unqualified installers often replaced these lights with PAR38-models. Unfortunately this made the situation and the green coloration of the cave walls and the dripstones even worse.

3.5.4.3 Semi-natural light-covers

Another technique is to artificially deepen holes or hollows in particular where the ground wouldn't be damaged, for instance in spaces which are filled with artificial or allothigenous material. Cables can also be easily placed under ground in such spaces. In the Dachstein-Rieseneishöhle cave system, this approach was widely used, but in a very specific way. Most of the reflectors were buried in the side walls of the passages, enabling them to illuminate only the nearest wall or the surface of the ceiling. Although little can be seen on the surfaces where their bright light shines, all the other views of the cave, including the floor or walkway are lit by rays of light reflected and dispersed from the upper layers of walls, these effectively acting as mirrors. Unfortunately this method is neither an energy-saving solution, not particularly attractive, nor is it nature friendly, as it encourages the development of lamp-flora, even at temperatures of 0°C. For this arrangement to work effectively any hollow or cavity which is used, needs to be asymmetric so several light sources can be used within the same void.

Semi-natural shields can also work effectively by rearranging materials which exist near the light. In the Baradla cave, one meter high, straight or arched walls made of locally collected stones and dripstones embedded in concrete are still visible. These were built to hide the old “stadium lights”. (This reflector style of lighting was manufactured to illuminate the huge former People’s Stadium in Budapest and originally equipped with 500 and 1000 watt bulbs, but later fitted with mercury lights in the Baradla. They had the potential and a high risk of causing severe electrocutions.) Similar techniques to disguise or hide lighting can be found in many caves around the world.

Nowadays such very old-fashioned approaches are still applied in many caves, because they are thought to look natural, whereas they certainly are not. Because the removal of these old systems can result in considerable damage to the cave walls, many of them are left in place and become symbolic features reflecting the cave’s cultural heritage. The specific difficulties of concealing lights doesn’t happen as much with modern, small light sources. They can often be easily hidden and because it is permissible, small stones can simply and quite easily be repositioned to disguise them, if these stones have already been moved from their original locations.

3.5.4.4. Complete artificial covering

When contemplating this challenge, two extremes are possible, with a number of variations between them. The most objectionable solution is to use an artificial coating to disguise and blend the composition and tone of the covering with the general character of its immediate surroundings. Such an approach using synthetic resin camouflage has been applied in the Postojna cave and also in the Baradla cave to disguise natural stones walls.

The best solution is to use any available cave feature or infrastructure to hide the lights. It is important however not to make insensitive compromises when considering how best to deploy lighting technology. All the important principles have to be followed and respected, in particular the rule of fill lighting. It is also a good practice to install LED light fittings into handrails, as they can create perfectly even lighting and avoids visitors casting their own shadow onto the walking area of those in front of them. This solution however should not be used for the purposes of emergency lighting!

The most common solution however is to position lighting under the walkways. This is usually not a problem when these surfaces are made of steel or a man-made synthetic construction. Lights can be fixed preferably onto the pier, as this moves less under the heavy weight of the visitors. If the walkway is an open lattice structure, where necessary shields may be used to avoid people being dazzled. If lighting is positioned under concrete walkways, then a type of “kennel” shaped hooded structure can be used to hide the reflector. This not only provides enough space for the light fitting but also enables any power cables to be positioned and hidden inside it, without fear of damaging them.

Any lights positioned in this way, should be located as close as possible to the external opening so as to avoid wasting light and encouraging the growth of lamp-flora.

One extreme example used in a Spanish cave to conceal lights was to build a concrete kerb like edging alongside the walkway and use it to screen the lights. In a Portuguese cave the same thing was done but here these kerb structures were built from wood. Both look fine on plans and in photos, but how durable they are, waits to be seen. Wood can withstand the climate of a cave for long periods of time, up to 50-100 years or more but what it looks like after this period of time and what fungi have grown on it by then, is another matter. In an Italian cave the reflectors were built into the walkway and camouflaged with the same material used to surface the walkway.

The best solution seems to be to place the light behind a natural barrier or under a walkway. So long as the light fitting doesn't look like a separate light, it is not vital that such a light should be hidden. As good lighting shouldn't emit surplus light either backward or in a sideward direction, it is not necessary to hide or cover it. Indeed attractive lights should be visible and be seen to show a cave's eminent visitors just how much care and expense has been invested in them to give the visitor a memorable experience! (Frustratingly however they don't often notice them or even care!)

As it is obvious a light is not a characteristic feature of a natural cave, it is nevertheless often visible. Trying to camouflage them therefore is in reality a phony imitation of nature. If there isn't an aesthetically pleasing or environmentally friendly way of hiding them, it is better not to try. The most sensible option in this situation is to use lights that don't emit any surplus light, thereby avoiding the promotion of the growth of lamp-flora and keeping the visitors' heads in darkness. Wherever possible lights should be black in colour so they can't be seen and because dark colors absorb any rays of light falling on them. If the light has a deflector, tube or grid attached to it that should also be black.

From the above, it is clear where the floor of a cave is concreted from wall to wall, this is neither sensible nor conducive to creating good lighting. In these circumstances, if it isn't possible to raise and replace this walking surface, there are only two practical options. The first is to install head-height lights with any light emitting sources pointing upwards. Alternatively lighting passages will have to be achieved using individual lights mounted in holders. Another possibility is to adopt an old fashioned method, i.e. using a combination of lights which have globes with a large surface area, so as to create a more general diffuse light, with areas with no light and shading, hence preventing lamp-flora from thriving. The absolute worst and a truly hopeless solution is to totally embed light sources into the ground. These lights not only dazzle and blind people but get dirty within moments of anyone walking over them. Whilst this problem is so obvious, I only mention it because I have seen it in at least two caves in Germany.

Given my experience of cave lighting, it's apparent that any proficient expert testing a lighting system would not first consider what has to be seen, but where lights could potentially be located. He or she visualizes how an efficient and attractive lighting system can be created using the cave's existing natural features and structure to their best advantage. Quite often when approaching the task in this way, not all the options may be needed. As a last resort the expert will select only those places which are appropriate for lights which have to be covered if no suitable natural alternative is available. When positioning a light it is also important to ensure any cabling connected to the light fitting, can also be suitably hidden. If illuminating a particular attractive view requires a solution which compromises that view, for instance fixing lights to a large stand or pillar, then the sensible option is to choose a lighting arrangement that is not quite so preferable.

The junctions between sequential lighting systems, the electrical circuitry (i.e. which lights go to which circuits), the means of controlling the lights (in particular when a system is not automatic) and the location of any push-buttons, all have to be decided as a part of a lighting trial. The eventual locations of infra-red sensors can then be confirmed following the final decision as to which and how various passages are to be lit. The exact location of any internal equipment, distributors, audio-systems and emergency phones should also be confirmed during the lighting trials. As these are all important features of a cave's lighting system, they will need an independently operated lighting arrangement. However, such kind of technical equipment should be normally kept in shadow.

3.5.5 Hiding cabling

There are often numerous different types of cables, wires and utility ducts required in a cave. In addition to the essential electrical, signaling, communication and monitoring cables, there are also likely to be water pipes. For instance in the Baradla a high pressure water pipe supplies the Vörös-tó Visitor Centre with drinking water, as well as a closed compression sanitary and waste water disposal system. Whenever possible all such essential mains water supplies should be housed in parallel utility ducts capable of being opened, (although not frequently accessed), or at least in an accessible underground chamber with openings or removable covers at various intersections, junctions and by means of access cabinets. Where metal structures such as bridges, walkways and stairs exist, a suitable place to fix and run cables is normally either at the base or on the side of such structures. In the past these utilities were buried and often covered with concrete, making their maintenance or replacement very difficult. In such cases because detailed locations plans are often not available showing the exact position of these services, any proposed replacement of them has to be preceded by extensive and detailed site investigation and survey. Cables connected directly to light fixtures should wherever possible be camouflaged. This can be difficult especially when thick and old 230V safety cables have been used. Sometimes when they have been drawn through a flexible protective tubing, unfortunately they become very visible.

Because LED lights have low energy requirement and operate at low voltages (12/24 V), their cables, although quite thin, are strong and therefore do not need so much protection. Consequently, when positioning them it is best they are placed in a route which is recognizable and can therefore be easily traced, for instance along a crack in the surface of a rock. If the cable has to cross a light colored surface it is advisable to camouflage it with a similarly light colored cement mix, but never gypsum! If the cable passes over a soft artificial surface for instance a calcareous tufa, its surface can be scraped away slightly and then channeled and the debris reused to back fill the surface to its original level. Countersinking lights into a wall should be avoided. When there is no alternative, they should be installed in such a way that they don't directly light each other… you already know why, don't you?

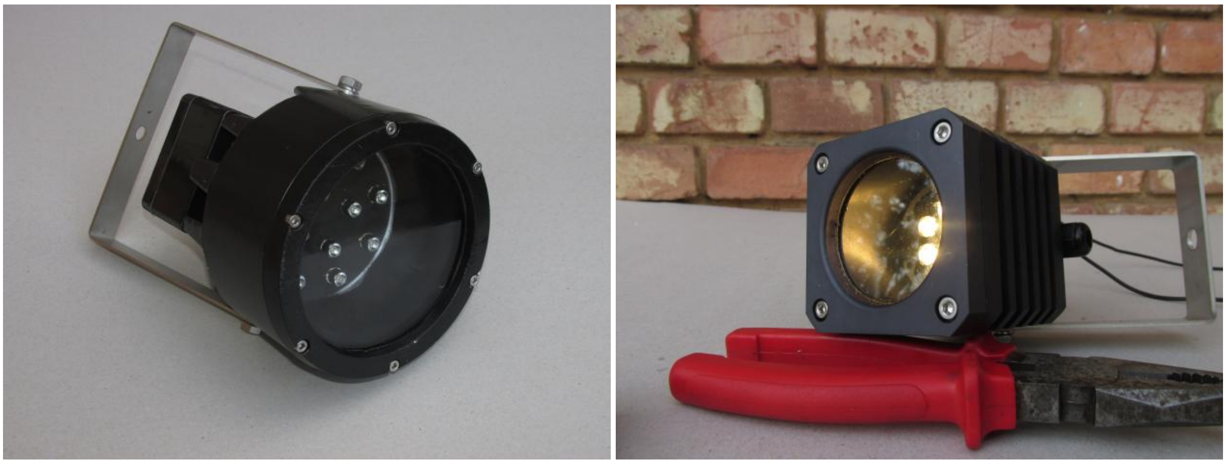
3.5.6 Directional lighting or shading

The issues of light direction, shielding against blinding, dazzle and lamp flora should all be differentiated, although in some cases the same solution can solve each of these issues. Moreover, directional lighting must be used even if there is no particular threat from excessive dazzle, because the pupils of a visitor's eyes need sufficient time to adapt to any significant changes in light intensity. The problem of excessive dazzle must always be avoided or solved, whilst the latter is not as crucial. In the case of the old type of reflector lights, the risk of blinding was not so much of a problem because their light source and its associated filament were normally positioned in a funnel or tube. Unless an individual looked directly at the filament (the actual light source), there was little likelihood of them being either blinded or dazzled, so long as the light source is far enough away from them. This also explains why, unless poorly adjusted, these light-sources don't create a pool of surplus light around themselves which might lead to the growth of lamp-flora.

A different problem has arisen however as a result of the introduction of the PAR38 light sources, because light leaks from them both in a backward direction and to the side. Even though this is most likely to be at a low shallow angle, it can potentially cause dazzle and the growth of lamp flora. A few companies such as Bega, manufacture lighting already equipped with deflectors. Without these, separate shielding plates have to be made and fixed to the lighting unit. Neither the metal or plastic versions of these additional shields have proved particularly practical or popular, as they not only make the replacement of bulbs difficult, but sometimes make the light itself look very clumsy.

This same problem also arises with LED lights, as producers have not recognized the need for nor incorporated shading as an important design feature. Because the angle of lighting can be optimized using macro lenses, manufactures produce lights to which a macro lens can be fitted in front of the light fitting. Some LEDs emit high-intensity light that is much more powerful than that of the equivalent halogen light. So if someone were to look at one of these, the intensity of its light would blind them, even if it is viewed from a shallow angle (e.g. the Baradla-light). There are two ways of solving this problem. The "follow-up" solution is to place a guide panel on to the light thereby creating a shade for it.

"Baradla"-light (Photo: P. Berczik)



"Berczik"-lights (Photo: P. Berczik)

The alternative "preventive" method which avoids this problem, is for the light to be designed in such a way that it has an outer rim a few centimeters wide, which hides the LED much better from a person direct line of sight (see Berczik-lights). Irrespective of the technique used, the inside of the deflector should always be either black or a very dark colour, so it absorbs any excess light. Without this dark surface, the light will at worst cause blinding or at best, result in an offensive and disturbing effect, colour, or create an unwanted pool of light.

3.5.7 Lighting and infrastructure in a cave

Any equipment needed in a cave should be installed in a coordinated manner so that artificial features, utilities, walkways, barriers, cabling systems and lights are all integrated. It is of particular importance that the replacement of end-of-life equipment is undertaken without causing significant damage to the cave itself. In practice however this is often not the case when financial limitations dictate that obsolete equipment has to be renovated on a random basis, for instance when a walkway needs repairing and then sometime later, hand rails are changed or lights modernized at different times. In such cases the opportunity to provide a single structure to house these utilities enabling any one of them to be easily repaired at any time, has been missed.

It is always easy to blame the lack of the necessary budget for adopting poor or inappropriate standards, but sadly there are a number of caves, where the visitor space and its surroundings are well equipped and maintained, while the cave itself is neglected and soon becomes technically obsolete or even dangerous. Good cave lighting systems depend not only on being well designed and skillfully installed, but sensibly and professional engineered, so that suitable spaces for positioning lights and cabling are created.

Based on Hungarian experiences, the renovation of any redundant equipment should be undertaken in ways which consider and integrate all the construction principles, aesthetic perspectives and implications of the task, at the same time. Ensuring the necessary resources and financial consequences of this challenge however is the task of those in higher management positions.

3.5.8 Documenting the testing of lighting systems

The process of testing cave lighting should be documented in two complementary ways.

One on site in the cave and the other on paper. When any light is removed from its original position, a wooden peg should be left in the hole, sticking out approximately 2-3 cm from the surface on which it was fixed. On this peg, a small label or tag made from light colored insulating tape should be attached. Written on this label in indelible ink, the type of the light used should be noted. At the same time the location of this light should be indicated on a map of the cave, together with the direction the light from it was pointing and the estimated level of dimming tested. The note should also record which circuit the light was connected to, especially where circuits are multidirectional. This will make it clear whether the circuit is an input or an output and importantly whether the lighting is static or dynamic. Any other important or relevant information should also be noted on the tag, but only to a level which remains understandable and is not confusing when read in the future.

The cave map and the series of tags therefore effective act as a complementary inventory of technical information. Individual memory and personal knowledge is also valuable. If the person installing the lights is not the same as the individual testing them, without this information he/she will not know what the original intention or lighting concept was. They will therefore not know which lights should point and shine in which direction, especially as any map of a cave can never provide a 3D representation of the anticipated lighting arrangement. Believe it or not, people recall memories and remember the vivid impressions experienced during the tests.

3.5.9 Who should undertake lighting tests?

To avoid any disagreement, arguments or misunderstandings, the involvement of the client's representative during a lighting test is strongly recommended. Indeed, this is highly time-consuming, because many things need to be explained to the client and even more so if she/he is an outsider. They must be able to understand that it is perfectly possible to have adequate and pleasant lighting using far less lights than she/he might think is necessary.

It is also helpful but not essential, if the electrical designer who helped install the lights is present, even though their engineering logic, calculations, catalogues and drawings may not contribute much to the eventual success of the practical aspects of the work. The engineer's role is to ensure the sizing of cables, fuses, power boards and the design and the installation of the necessary control system, are all undertaken correctly.

In addition, it is much more sensible if two experienced people who both understand the overall anticipated lighting concept, direct the process so they can make sense and decide through mutual agreements whether particular ideas may or may not be feasible. The presence of two people enables time and effort to be assigned efficiently. One person can inspect the locations of lights, whilst the other checks the lighting effect, as invariably most lights will be positioned quite some distance from where they will eventually be seen by a visitor. Likewise having two experts means that lighting can be viewed from a series of different positions at the same time to ensure there are no circumstances which are likely to cause dazzle or blinding. Having said that, if three or more "smart" people (including the client) take part in the test this can easily and often lead to endless debates and differences of opinion.

Although extra manpower and assistance is not necessarily needed for the installation or dismantling of lights, the management of cables and distributors may require extra assistance as this task can take a great deal of time and energy. Based on the size of the cave, it is advised to check all the relevant details with the help of between one and three unskilled workers.

3.5.10 What else is needed to test lighting?

Apart from the correct number and type of lights, a significant amount of cabling and extension wiring is often required. When 24V lights are used there is also a need for a sufficient number and variety of the correct power supplies. In addition hammer drills, screws, dowels, plastic insulation tapes and permanent markers are all necessary. Perhaps the most important piece of equipment however is a ladder.

Even though lights can be placed in very inaccessible places, this is not advisable because even the long-life LEDs can fuse, especially in the absence of appropriate protection against power surges. When working in a dolina, a rope, climbing equipment and a body harness are all essential. For lights in very inaccessible places, it is advisable to install fixed points to which ropes can be securely and safely attached. Hopefully these will have already been put in place when the lights were original installed. As testing lights is dangerous, obviously it is highly advisable for anyone doing so to wear a safety helmet. Maybe I should mention one further matter, a light meter is crucial as it is better and more accurate than relying on your own eyes. If such a device is available, use and trust it!

3.5.11 How long does testing cave lighting take?

The amusing and simple response to this question is… “*Enough time to do the job properly*”.

With experience, the time required becomes comparatively easy to estimate. Even so it is always better to overestimate than to be over optimistic. From experience, testing the lighting of smaller and less spectacular caves often takes disproportionately more time than it does for larger ones. Testing the lighting of the Vörös-tó section of the Baradla Cave, a 2 km cave corridor with big chambers, took an experienced team seven days. By contrast the 70 meter Lóczy Cave took three days.

Naturally, any time spent doing this work always has a monetary value. The fee of electric engineers who design cave lighting systems only with software, might take 10% of the whole budget. However, the key planning and determining decisions should be preferably based on the findings of lighting trials; assuming of course this cost is already included in the budget!

3.6 The final fix of lights and cables

This operation is part of the implementation the installation of a lighting system. Whenever possible, it should be carried out by at least one of those individuals involved in testing the system, so they can direct the process.

The structures and consoles which are eventually fixed to a cave's wall or to the ground are usually slightly different from those used when testing the lighting system. During this final installation it is crucial to make the minimal amount of damage to the cave. For this reason it is preferable to fix any lights mounted on the ground are attached to substantial concrete plinths or plates. Where these features become very noticeable, they should at least be camouflaged with stones or clay.

In former times, the need to replace light bulbs happened quite often. When doing so, technicians frequently removed these lights (sometimes still attached to their concrete base), and unfortunately only replaced them roughly in their original position, therefore ignoring the accidental creation of unwanted shadows or light pools. Whilst it is possible to mark the correct direction of the light on the concrete base, often the complete structure is replaced. In the past this was a headache, but today that's no longer the case as modern LED lights have a 20-25 years normal life expectancy and therefore the only reason they have to be disturbed is for cleaning.

3.7 Cleaning lights

Although cleaning is usually the responsibility of the maintenance team, it is better to take this task into consideration during the planning phase. Believe it or not, cave lights get dirty quite quickly, so it is also advisable to clean them regularly.

As lights have liquid dripping constantly and directly on to their plexi-glass like plastic / polycarbonate surfaces, without regular cleaning, a film of dripstone can soon build up on any glazed panels. Also because the water dripping onto lights often contains clay, it makes any glazed area covered with such a coating, less transparent. Any water dripping on the ground can also splash clay on low level lights, especially those embedded in the ground. In the Baradla, *Mesoniscus graniger*, the Cave Isopod and small animals elsewhere in other caves, make this situation worse by defecating on the lights.

When testing the current lighting system of the Aggtelek section in the Baradla, despite it becoming apparent that certain lights emitted very intense light, Mrs Kosák, the designer of the system assured us they would soon get dirty, and the light intensity would therefore be reduced optimally by approximately 30 percent. Despite dimmable lights can be adjusted proportionally to compensate, because of the problems of light emission being reduced by a layer of dirt, it is much better to integrate their regular cleaning into the maintenance plans.

In the past, the glass panels of big reflectors were removed and dipped in a weak solution of household hydrochloric acid to remove both accumulated dirt and any deposits of lime scale (from dripstones) which had developed. It is not advisable nor usually necessary however to dismantle new, modern lights, as these are IP 68 certified and are therefore both waterproof and dustproof. When the protective glass on lights is made from polycarbonate plastic, its surface is soft and easily scratched. For that reason such panels should always be cleaned very carefully using an eco-friendly cleaning solution such as acetic acid, as this will not damage its polycarbonate surface.

4. What are LEDs good for and what are they not?

Finally we come to the star of our age: a lighting device proclaimed as a new wonder, namely the LED or Light Emitting Diode.

LEDs which have been developed in the last few years are capable of easily competing with traditional lighting equipment. Like the fluorescent powder in fluorescent lights, LEDs use mixtures of material capable of emitting white light with a good spectral composition. (The diode itself emits red, yellow or blue monochrome light; the secondary coating, similar to fluorescent lights, emits white mixed light.) Although manufacturers and distributors often specifically highlight in their marketing material the energy saving and long life benefits of LEDs, these advantages are not completely accurate. Although the luminosity of the best LEDs is about 80-100 lumens/watt, this does not match that of a good fluorescent light. Similarly, the likelihood of a major breakthrough to enable this threshold to be increased, is unlikely. LEDs will therefore always fall short of the theoretically maximum achievable and magical figure of 680 lumens/watt. This can only be realised with monochrome yellow-green light i.e. in the 555 nm wavelength.

Originally the lifespan rating of LEDs was predicted as being of the order of 100,000 hours. More recently however, experts have changed the way in which the lifespans of lights are rated and now tend to equate it with the life expectancy of a complete light fittings rather than just that of the individual LED itself. This is principally because today the LED is an inseparable and integral part of the whole light fixture rather than just an independent part of it. Accordingly, LED based lighting fixtures have an average life expectancy rating of 25-50,000 hours.

As you would also expect, the lifespan of any lighting fixture depends to a large extent on conditions in which it is operating and in particular the nature of the cooling features provided by the design of the lighting fitting itself. A LED with a life expectancy of 25-50,000 operating hours clearly means it has a lifespan which is two and a half times that of a compact fluorescent light.

Similarly and to its advantage, a LED as it reaches the end of the predicted lifespan, only loses 30% of its initial light emission strength and hence its efficiency! LEDs also have the distinct advantage that their light output although decreasing gradually over time, does so slowly. When they reach between 70-80% of their original performance level, failure thereafter accelerates rapidly. Regardless of this difference in performance, LEDs are still more than ten times more expensive than fluorescent lights. For the purpose of lighting flats or halls where homogeneous, true colour reproduction and cheap lighting is needed, fluorescent lights are therefore much more suitable and less expensive than LEDs.

If fluorescent lights in ceiling mounted fluorescent fixtures are replaced by LEDs, the high-intensity spot of light it produces will most probably cause a number of issues. These can however be counteracted by using a frosted glass “diffuser”. Unfortunately the disadvantage of using such a diffuser is that the light’s performance also reduces by approximately 20-30% and as a consequence any energy saving advantage of the LED is lost.

When comparing the efficiency of LEDs with that of a sodium (Na) bulb, LEDs do not significantly exceed the lifespan of such bulbs. Moreover, LEDs are not as effective as a sodium light in terms of light utilisation. A low-pressure sodium lights can approach or even achieve 200 lumens/watt, but by utilizing monochrome light, they do not produce true colour reproduction. For street lighting, however, they are perfect and considerably cheaper to buy and to operate than LEDs.

So far as heat emission is concerned, a LED emits practically the same amount of heat as a fluorescent light. Any heat generated is produced on a very small surface on the opposite side of the light emitting area. Accordingly, effective heat dissipation and cooling of LED bulbs is extremely important. Therefore if a LED light manufacturer refers to the factory specifications of the LEDs as an indicator of its life expectancy, don't believe it, because it clearly means that the LEDs haven't been properly tested and therefore do not have a reliable lifetime rating… a real advantage though in your business negotiations.

The tests often used by manufacturers are also unreliable because they are usually performed over a short periods of time and under unrealistic high load conditions. The results from these "pseudo-tests" are then hypothetically extrapolated to produce a theoretical figure for the actual life expectancy of the light. Given the nonlinearity of the performance degradation curve of the bulb, this produces a somewhat inaccurate overestimate of its true performance value. Nevertheless, the method is standardised and is perfectly suited for comparing different products.

In summary, LEDs provide expensive and impractical solution compared to fluorescent lights, metal halide light sources or sodium lights. So why are they still in use? What are their benefits and which of their features make them best suited for cave lighting?

One reason why fluorescent lights, with very good energy characteristics and good colour rendering are not used in reflectors, is because their light is emitted over large surface areas and is therefore not as easily or properly focused. However, they are perfectly suitable for lighting large areas and halls. Like halogen lights, LEDs not only emit very intense light from a very small surface area, but also emit their light in a single and uniform direction (usually at a 120-degree angle). This enables their light to be perfectly directed using ballast lenses.

Beam angles between 9 and 120 degrees can be easily achieved using asymmetrical (ellipsoidal) lenses. Such lights are highly suited for shade-free illumination of individual formations, such as stalactites or for the illumination of deep fissures, without risking the growth of light flora or the overexposure of the feature being lit. If a single LED doesn't emit sufficient light, several or even arrays of LEDs can be placed on the same lighting array in clusters. Each LED can have separate ballast lens, but share a common operating electronic and cooling system. In such circumstances the pool of light created would be homogenous and not break up to produce a series of small individual and identifiable light spots. In addition, because different ballast lenses can be positioned next to each other within same light fitting, LEDs offer extra lighting versatility within the same lighting unit.

A further advantage of LEDs is the fact they are not sensitive to regular or frequent switching or mechanical stress, such as shock or vibration. They also have the clear advantage over halogen reflectors in terms of their size and light utilisation, as they are 3-3.5 times stronger and because of their increased longevity, have a 20-50 times longer lifespan.

In a cave, it is also very important to have light sources that can be switched on quickly after they have been switched off. Today, very good colour rendering and energy-saving metal halide lights along with relatively good sodium lights are available, but unlike LEDs, once they have been switched off they need to cool down for several minutes before they can be switched on again. Frequent switching on and off also reduces the lifespan of both incandescent lights and fluorescent lights. LEDs once again have the advantage they can be switched off and on immediately and quickly without the process of regularly switching them on and off having any perceptible effect on their lifespan. Despite all these advantages there are still no convincing arguments in favour of the LEDs, as the initial capital investment costs of purchasing them is unfortunately high when compared to halogen reflectors. From an operational point of view even this difference in their cost efficiency will always be difficult to recoup over their active life. However, LEDs have a unique advantage among the range of other electric light sources, because of their ability to be dimmed.

LEDs are the only light source which can be dimmed and regulated to provide variable brightness, while its colour temperature does not change. This enables LEDs to produce the desired lighting without compromising its quality or the need for many different types of light bulbs. Although incandescent lights can also be dimmed, as the voltage decreases, the colour temperature of the emitted light also decreases and turns noticeably red. Anybody who sits in a theatre watching chandeliers dim, will have noticed and experienced this change. These chandeliers have no compact fluorescent lights because they are not dimmable. Regardless of how it is achieved, an ability to dim lights is valuable, has extreme aesthetic benefits and is of environmental importance especially in avoiding the problem of the growth of lamp flora.

Another important benefit of LEDs is the reduced energy loading of this type of bulb, means their lifespan increases. A further advantage is the fact that any light loss due to dirt, scratches and aging, can be compensated during their operation. The ability to dim LEDs is therefore the most important advantage and benefit of this system of lighting over all other types of lighting arrays.

Nevertheless, there are numerous examples of cave lighting with non-dimmable LED-lighting fixtures and arrangements! Several technical solutions exist to enable LED lighting fixtures to be dimmed. These range from simply incorporating a screwdriver operated mechanism into the body of the light fitting, through to more sophisticated remote electronic energy reduction solutions. The best solution however should always be the simplest and cheapest. A screwdriver is invariably to hand and easier to find than an electronic technician. Regardless of this, the critical factor in all circumstances is to ensure the ability of the operator to control and adjust each light individually and manually.

4.1. Temporary attempts to implement LED lighting.

There are numerous examples and occasions where retro-fitting and replacing existing lighting systems with LED light sources have been attempted. This may involve for instance 7, 9 or even 12 LEDs being incorporated into and reconfigured to work in a conventional E14 or

E27 incandescent light socket ("E" refers to Edison, the inventor of these sockets). Where they are retro-fitted into a fluorescent light fitting, the number of LEDs might be greater. Replacing a fluorescent light with a LED is therefore a clear waste of money!

In caves, LED light sources can be used to replace and retrofit PAR 38 bulbs to provide a warm white, i.e. 2700K colour temperature light which can be relatively pleasant. However, despite the assurances of manufacturers, they do not achieve the same performance as the incandescent bulb they are intended to replace (of which only 80 and 120 W are available). According to the manufacturers their light utilisation of 40-45 Lm/W hardly exceeds the value of halogen incandescent lights. Their relatively poor performance is obviously due to the problems associated with cooling and clearly this maximum output is the best that can be realistically achieved.

This is principally due to the fact that in the case of retro-fitted light sources, the rectifier power supply is installed in the same housing as the light and requires not only its own specific power source but also has to be effectively cooled. These type of light source are rather expensive and often quite impractical because they tend to be too heavy for the plastic fittings in which they are mounted. This results in the deterioration and eventual separation of the light from its surrounding housing. It is therefore advisable to inspect the manufacturer's specification, as these are often self-contradictory. For instance, one manufacturer suggests replacing a non-existent 90W incandescent light with an 18W and 810Lm (lumen) LED light source, whilst offering a 14.5W and 900Lm rated light source to replace a 120W incandescent light. Clearly something is significantly wrong with this logic and the associated sales talk! Another manufacturer claims that a LED retrofit of a PAR38 with a power consumption of 12W provides 1200Lm of brightness, can supposedly produce a light source with the power of 100Lm/W and a lifespan of 35,000. Experience shows this is impossible! In the end, no matter what the manufacturer says if it is not the truth, the magnitude of the exaggeration doesn't matter!

Because incandescent lights cannot be dimmed and their original electrical systems are not designed for this purpose anyway, replacing them is neither advisable nor cost effective as any energy savings are outweighed by the higher initial purchase price. Another disadvantage of PAR 38 light fittings is the fact that their anti-moisture rubber seal cannot be safely retro-fitted to another light source and therefore they have no safe or reliable electrical insulation properties (although in some countries manufactures have ensured this safeguard exists). Once again this demonstrates why it is advisable to refrain from using this type of lighting in new installations.

4.2 Should we opt therefore for LEDs?

Yes, but only under certain conditions! LEDs alone are not a recipe nor indeed a guarantee for good cave lighting … they are simply the best option which exists at the moment.

Using LEDs incorrectly can produce at best poor quality and at worst terrible lighting, as any experienced eye would immediately detect in many of the illuminated caves around the world. What's more, in some cases replacing what was originally fundamentally excellent lighting with LEDs, has yielded very poor results, as for example has happened in the caves of the Aggtelek Karst in Hungary.

Since the colour rendering of high-quality LEDs suitable for cave lighting is around 80 CRI (i.e. about 80%), this also means this light source is perfect for promoting the growth of lamp flora. Any claims to the contrary are pure advertising gimmicks, or put more simply just lies! LEDs can however be a good weapon in the fight against the lamp flora. Because of their size and extreme flexibility, their light can be precisely targeted and their numbers minimised to create optimal and harmonious lighting, compared to any other form of lighting. Of course, this would only be possible if the parameters and rules listed above are all followed.

4.3 Colour temperature: a marginal issue?

In informed discussions about cave lightning, it is often emphasised that cave formations "*should be shown in their natural colour*". Cave formations develop, change and obviously exist in absolute and perpetual darkness. Accordingly, their natural colour is black and any induced variation of this is therefore completely artificial. The quest for some kind of absolute and authentic naturalness is therefore a completely fictional mission and discussions on the topic purely academic. (I'm joking, of course.)

The actual colour of any object is a genuine characteristic. All objects absorb electromagnetic rays of a certain wavelength and reflect others. Sometimes they allow particular rays of certain wavelengths to pass through them whilst other don't. Each object is therefore different and its actual colour is obviously a product of its specific light absorption or reflective properties. We see and perceive this range of colours subjectively so long as light of an appropriate wavelength is present and interacts with the targeted object and thereafter with our eyes.

So to present a cave to its best effect and to make as many colours as possible visible to those visitors who paid good money to experience these marvels, many selective variations of different coloured light need to be used. Using a blend of lights, in particular white light is the best approach, because white light is made up of "all the colours of the visible spectrum". As white light contains the complete range of colours, it can be very diverse depending on the proportion and blend of its different components. Just as it's possible to make different cakes with the same ingredients, so can the constituent elements of light be mixed to create different effects.

Fortunately because a human's eye-brain relationship and coordination adapts extremely well to minor variations, subtle changes in colour can be skilfully produced and effectively displayed by those who know how to do so, enabling the experience of those viewing to be enhanced.

A simple experiment anyone can perform demonstrates this fact. Use one eye to look through the coloured viewfinder of a camera or camcorder at the environment around you, or through a SLR camera fitted with some sort of lens filter for five minutes. At the same time, observe the same environment with your other eye without any optical accessories. After five minutes remove the camera and amazingly the world around you will appear in different colours in each of your eyes for a couple minutes. Unfortunately, this phenomenon will eventually disappear, even though we may wish it to remain.

Generally, sunlight has a colour temperature of 5600K. However, this is just a standard for colour photographic materials and in reality it varies depending on the time of day and the prevailing weather conditions. If the light we use in caves, differs too much from the sunlight in terms of its spectrum and components, certain colours then start to dominate. As a consequence we will not see objects as colourfully as would be expected. Unfortunately the human brain, unlike a camera, cannot correct this impression because there is no comparable image to act as a reference and hence to match and re-calibrate with the original colours. Colour vision, as we have seen, is therefore highly subjective and individual. Since we are unable to see through anyone else's eyes, we can only assume the colours we see are the same as those others see; colour blind people excepted of course.

When traditional incandescent lights were used for cave lighting the issue of colour temperature was not truly relevant. The variety of lights available was rather poor and the difference in their colour temperature was not a significant factor in their choice. The standard incandescent light has a colour temperature of 2700 Kelvin, whilst a halogen light's is 3000 Kelvin, when the filament is glowing at this temperature.

When comparing the light from the two incandescent lights, the halogen seems to be slightly "whiter". Interestingly, light which is richer in red and yellow and has a lower colour temperature, is known as "*warm white*", whilst rather confusingly, warmer light which is richer in blue and violet, is called *"cold white"*. This is probably as a result of artists traditionally describing some particular colours as being warm whilst others as cold. Red is probably called hot because we associate red with fire. Likewise because the older types of fluorescent lights emitted less heat than the incandescent light and their light was bluish in colour, perhaps this explains why this particular colour light was described as "cold".

Incandescent lights emit a natural light spectrum and therefore by definition have a colour rendering index of 100. So incandescent lights that have different colour temperatures are not comparable with each other. The Colour Rendering Index (CRI) is therefore a way of categorising non-incandescent lights, such as fluorescent lights, discharge lights, LEDs, etc. By implication therefore lights emitting monochrome light, such as an energy efficient sodium bulb (which is actually unique), obviously have a colour rendering index of 0 (zero).

It is a well-known fact that white light is a mix colour and combines "*all the colours of the rainbow*". Passing light through a glass prism proves this point as it effectively splits the light into its constituent colour components. In reality, however, you don't need a full combination of all the colours of the rainbow to experience a white colour mix, even less so, if you are trying to produce light colouring which matches sunlight or incandescent light. For instance, a mixture of two complementary colours can also appear white. On the other hand, poorly blended white light at best produces imprecise colouration and at worst combinations of incorrect colour ratios produce completely different colours. For instance, the light from an old type of fluorescent light produces white light which is the same colour as a sheet of white paper, but the identification of other colours is more difficult. Elderly people might remember the times when garments were taken out of a shop in the full sunlight to see their true colour, as opposed to their false colour visible under indoor fluorescent lighting.

Non-incandescent lights also try to achieve true white colour mixtures similar to sunlight or incandescent lights. For this purpose, two measuring units are used, both of which are somewhat subjective. The first is the so-called “relative colour temperature”, i.e. when the light of a non-incandescent light can be mistaken for the light of an incandescent light which has similar colour temperature. Since no incandescent lights exists with a value over 5000K, this rating is based on a theoretical scale. This value is supplemented by the Colour Rendering Index mentioned previously.

The CRI is determined on the basis of colour comparison tests undertaken by various individuals by matching non incandescent with incandescent lights of the same colour temperature. What makes things more complicated once again, is the fact that the bulbs used for these tests only exist up to the aforementioned upper limit of 5000K. Above this value, the CRI of a comparative light source is by definition less than 100 (normally calculated using a formula), so the theoretical maximum is not achievable within this higher range.

There is however a colour range within and to which the eye and brain can still adapt to different colour mixes. This enables us to see white objects as white and not as yellow, pink, or purple. As any photographer knows, this cannot be achieved using light sensitive photographic films because colour film is always calibrated to the specific colour temperature range of between 2200K and 8000K. But this is still not a complete explanation. To see the world, or in the case of a cave, for the features within it to appear sufficiently colourful and variegated in the white light, an appropriate light source must be comparable to the spectrum of so-called “blackbody emitters” (solar incandescent lights). The degree of this similarity is again expressed by the CRI.

When the CRI of modern white LEDs is stated as approximately 80, we have a pretty realistic understanding of the properties and capabilities of this light source. However, it still remains the case that only an actual comparison with an incandescent light of the same colour temperature, will prove its actual similarity. In certain instances a cave may appear more beautiful in the light of a cold white LED, even though its CRI is the same as that of warm or neutral white light. This phenomenon can be explained quite simply.

If two white materials are placed next to each other, the one with the cold blue character always looks whiter than the other, even though when viewed separately they both look perfectly white. This is why bluing agents were used for washing in the past and nowadays purple optical brightener is added to washing powders. It also explains why when both warm and cold white light are used in a cave, we always perceive the colder light as whiter. It further explains why when illuminating stalactites using anything other than cold light, warm white light makes them appear yellow or even reddish.

In such direct comparison tests, when similar objects are illuminated in parallel with lights of different colour temperatures, usually the cold, bluish character light is preferred. This difference isn’t so important in everyday life because the human eye is able to adjust the white balance levels of light down to 2200-2500K and objects known to be white actually look white, unless a light source with a higher colour temperature prevails in one's eyes. When this happens the human brain automatically adjusts its internal white balance mechanism to those levels, so long as these conditions remain. This phenomenon occurs quite often because cavers usually use cold white LEDs in their torches and headlights.

So, what is the moral of this story?

1. If the lighting in your cave is traditional and you can only upgrade it gradually, choose warm white LEDs, as this will not disturb anything you would normally expect to see under the original lighting conditions.
2. If you want to offer an "as close to reality" impression of an object as possible, do not mix light sources with different colour temperatures, as this is effectively be the same as cheating and using colour lighting. As a result, the visitors would perceive the same colours as different and different colours as one and the same.
3. If you are going to create a completely new lighting system, the colour temperature of the lighting doesn't really matter, although it is important to use a form of lighting which has only one colour temperature. Equally, the colour temperature of the safety or the integrated emergency lighting should be the same as the colour temperature of any decorative lighting. Also remember when making your decision about the most suitable lighting to use, the energy efficiency of cold white LEDs is slightly higher than warm whites.
4. If your choice is based on ground testing, ensure you have a break of at least one day between testing lighting with different colour temperatures. It is also important not to accidentally use a different light source with colour temperature other than the temperature of the lights being tested, not even a hand held light, otherwise the true appearance of warm white will be distorted and not apparent.
5. Although the CRI value of all LEDs is almost the same (80) it should be stressed that warm white LED replicates the red colours of the spectrum better, while the cold white LED tends to exaggerate the blue and violet colours. In the light of cold white LEDs, any clear and transparent straw stalactites will appear icy bluish, while the warm white light will produce their normal appearance. (This phenomenon is similar to the effect of purple "disco lights," which are sometimes used separately in some caves.)
6. The nature and composition of any lamp flora may depend on the colour temperature of the ambient light chosen, but its mere existence or appearance does not. The development of alternative light sources should be targeted at achieving comparability with the CRI of the sunlight or the incandescent lights. This approach is unlikely to change in the future, consequently it is not worth considering this issue when planning measures to prevent the growth of lamp flora.
7. Even the colour temperature of a guide's hand help torch or illuminated pointer should be the same as the colour temperature of the surrounding decorative lighting. At the very least it should not be any "colder" but preferably have a higher colour temperature.
8. The eventual choice and use of the light sources of the appropriate colour temperature should be a logical, subjective and the personal decision of the owner or operator of the cave. All the criteria mentioned above should be taken into account.

Any final choice should not however be influenced by contractors, lighting manufacturers or traders. Their motive is simply to sell their stock!

Since the eye, when adapted to darkness most effectively detects the shorter wavelength (blue) colour, we can generally assume a warm white LED light, richer in red components, is more appropriate for highlighting reddish colours. This phenomenon (the reds appearing dimmer than conventional incandescent lighting) is probably not observed when lighting composed of cold white LEDs dominates, because in these circumstances caves are mostly over-lit and therefore the eye cannot easily adapt to the prevailing darkness. This phenomenon is very subjective and difficult to detect even under test conditions, but theoretically it determines the preference for warm white LEDs. Interestingly, warm white LED light sources with a colour temperature of 2700K have been installed in caves everywhere in Hungary.

4.4 Should colour lighting be used in caves?

This question appears rather rhetorical. Why use colour lighting in caves at all?

The cave is a natural environment, not a theme park and therefore is there really a need to demonstrate the wonderful effects of red, blue and pastel purple light, modern technologies can produce? Decades ago these light sources were widely used in Hungary, but now these are considered old-fashioned just like wearing 1950s' loden coats or miniskirts. However this question still remains very relevant.

In some less developed areas, caves are simply considered as natural resources to be exploited, places where their natural heritage value is not respected. Lighting is used to brighten them and enhance their qualities as an artificial visual art form or show. (Tourist mines have a definite advantage over natural caves because people can link personal stories and historic features and thus these places are often valued as cultural heritage.)

Even if the lighting used is not specifically coloured, light sources of different colour temperatures are often used in the same cave. This is effectively the same as lighting the cave with different coloured lights. As a result the senses of the inquiring visitors get confused, because the same colour will be seen differently and different ones the same. In a number of caves the childish mistake is made to light yellow objects with yellow light (sodium metal halogen), while the pure white objects with blue-white (mercury) lights. The result is misleading and disappointing. The visitor gets the impression that objects are white, but illuminated yellow. In the alternative situation everything appears to have a bluish hue, while the contrasts, i.e. the difference between white and non-white detail, are reduced. What is more concerning is that yellow objects get a strange greenish tint.

This problem is further aggravated when light sources of different colours, or more precisely of different colour temperatures, are mixed. As a result the eye-brain coordination loses its true reference point and can no longer decide which colour is being viewed. This is similar to the custom in wine tasting of consuming something neutral between wine samples in order to declutter and cleanse the taste buds, so as not to influence the next new taste with the previous one. This also explains why we eat garnish with the meat, for instance a good tasteless garnish like noodles with a stew, to create a neutral taste in the mouth. This neutralising effect effectively then creates a contrast with the flavours, so that each mouthful of food offers a new experience. In the same way, this is exactly what good lighting seeks to achieve, a medium which is neutral, colourless, tasteless and has the same colour temperature, so as not to feel ostentatious.

In addition, the use of mixed light sources in caves with different colour temperature makes colour photography impossible, since the film, or the digital sensor of a camera simply cannot distinguish as much subtle variation as the human brain. If we know that an object is white, we are not disposed to seeing it as purple or green, even if in fact that is its actual colour. However, it will be unmistakably purple or green on the photo and if it is white, the other colours will also change to some other colour. As in a picture, just as in the brain, only one white balance can be fixed at any one time. (Actually under certain conditions it has been demonstrated that the brain is capable of producing two different white balances, one in each eye.)

As there are LEDs available with different colour temperature, it is tempting to use them for this type of manipulation. However it takes years of experience to realise it is better to illuminate objects with lights emitting the same colour, because this gives the most realistic and beautiful visual impression. People are amazingly curious about reality and because they often pay generously for a good experience, they deserve to see what is there and not something we decide will artificially impress them. Resorting to using lighting with different colours regrettably seems to be a sad reflection of the fact that someone considers a cave is not beautiful and interesting enough in its own right and it is necessary to theatrically enhance the view.

Unfortunately LED technology has triggered a new chapter in the story of colour lighting, since the so-called RGBW LEDs (where red, green, blue and warm white colour is integrated into a single module) can very quickly produce all the imaginable colours possible without any difficulty. Who could refuse such a temptation?

Today there are technical specialists who sadly design and programme colourful but tasteless musical lightshows to earn a living and therefore someone has to provide and sell these types of LEDs. Now let’s be honest; would such a show be harmful to our cave? For sure no more than a lighting array which uses a normal white light. Anyway, if the lighting configuration coupled with professional and educational interpretation presents the true reality of the caves to the audience, then why should we deny people this extra amusement or enjoyment? After all these same people I’m sure, probably find colourful firework displays entertaining? Who are we to say what is authentic and what it is tacky? Fastidious individuals should close their eyes and theoretically specify what constitutes a realistic index rating of trash!

Regardless of what we think, after all this form of amusement does less damage to the cave than a live concert! Conservationists say that anything which is not harmful should be allowed. The point is that showmanship has to be separated from the professional presentation of the cave, just as much as the unavoidable yarn that wizards, witches and dragons emerge from the formation of dripstones.

5. The proper lighting of caves and the lamp flora

A variety of publications are available in libraries and on the internet about the lamp flora phenomenon. What follows therefore is only a selection of thoughts about the relationship between appropriate lighting and lamp flora.

Plants utilise green light least from white light and reflect it most. This is why they appear green to us. As they absorb other colours, one can therefore only assume they use them. As a student, I visited the surface headworks at Lázbérc (N.E. Hungary), where some of the stain glass in the building's windows were green. The reason for this we were told, was because in green light the growth rate of algae is slower. (Algae in drinking water also give it an unpleasant taste and smell and can lead to its discolouration.) Once a colleague of mine from Greece told me they deliberately wanted to illuminate their show cave with green light to minimize the lamp flora. My immediate reaction was one of horror and dismay. As a matter of principle I believe caves should not be lit in order to discourage the growth lamp flora, but simply to make them look attractive. Green light is not beautiful, or in the words of my favourite village sage, it is "aesthetically ugly".

Another cave in Greece is lit with yellow light for the same reason and as a result, lamp flora though barely visible to the naked eye, was present and could be clearly seen on photos taken using flash photography. Displaying the beauty and true colours are the primary functions of show lighting, otherwise visitors could be guided around using ordinary hand held torches. Given these threshold conditions, it is important to find the correct methods and balance to provide the appropriate levels of illumination, whilst at the same time minimising the growth of lamp flora.

If we pause and think of ourselves as plants, nature always looks for the most practical and effective way of operating. It has been scientifically proven that plants are able to adapt to light of different wavelengths. If they receive a wavelength that matches their needs, they will evolve and adapt to those conditions and focus their biophysical and biochemical life support mechanisms in ways which enable them to use that particular light source efficiently. They do not develop or sustain features or processes which are unnecessary, but maximise the opportunity to use those resources which provide the most suitable and accessible nutritional food sources and which require the lowest energy input. In the case of light, it is those wavelengths of the light spectrum which are most easily capable of being intercepted and absorbed.

Plants are clever enough to select the most favourable wavelength, those which provide the highest value added return with the lowest energy input. This principle applies of course to the light which has the full range of wavelengths across its entire spectrum. Does this mean that by using modern light sources which have an incomplete wavelength spectrum, we can make plants starve? Not really, because plants and cyanobacteria have an ability to find a wavelength suited to their specific needs. In the case of the three-peak light tube or in the one and a half peak LEDs, which both have a white spectrum similar to the humps of the dromedary camel, they are able to detect and absorb sufficient energy for their survival and everyday needs in an alternative way by using antenna pigments.

We also have to bear in mind that algae are clever “r-strategists”; organisms with short life cycles but with a high capability and potential for genetic adaptation and so reproduce and increase their numbers very rapidly. So yes, from a theoretical point of view, any modified lighting which is introduced as a new or alternative light source will at first reduce lamp flora. However after a certain period of adaptation, be it biochemical, genetic, or even ecological, change in the species composition occur and the growth lamp flora will eventually increasingly intensify.

How can we avoid this phenomenon?

- After any changes to lighting equipment, lamp flora must be immediately eradicated.
- Any new or alternative lighting source should be operated at the lowest possible light intensity appropriate and suitable for the environment of the cave.
- Particular attention should be directed towards reducing periods of active lighting.

By offering these few thoughts, I have tried to show and help the casual reader realise that although lower plants are clearly not master chess players in the class of Judit Polgár, like her they are very professional and specialists in their own trade, namely photosynthesis. In fact you should never expect miracles when installing new lighting sources. One thing is certain for sure, without proper care and learning from the experience and the mistakes of others, you might get quite the opposite effects and outcomes to those you either predicted or expected! Our world does not operate like a business, the latter is often controlled by understandable forces, something which is certainly not the case with nature (perhaps not so in business either!). Humility and constant observation of the key principles of cave lighting must always to be borne in mind.

The main benefits of LEDs are energy saving, controllability, long life expectancy, spontaneous responses to regular powering on and off and the flexibility of arbitrary brightness control of light with the same colour temperature. These are all obvious. Lamp flora can only be successfully be reduced using LEDs if the benefits of these characteristics are understood and the appropriate principles to counteract its growth applied in practice. Lights should be directed, dazzle, and over concentration or focusing of pools of light avoided, as should the overemphasis of shadows, contrasts and the waste of excessive light. Light intensity needs to be optimised and lights switched off when they are not needed. Don’t light anything more than is necessary just because it may be cheap to do so!

If pigments such as Chlorophyll A were able to absorb only one specific wavelength of light, namely the 440 nm blue and 662 nm red lights, then our task would be very simple. We would merely develop an ultra-specific colour filter, such as a clever negative laser, which removes those two wavelengths from the light spectrum. That would solve our problem. If that was possible, colour temperature and the overall impression would not change substantially and those eminent members of the lamp flora plant community would be in a serious trouble.

In reality however, these wavelength values must be considered as absorption maxima and the guilty Chlorophyll A and B pigments recognised are able to absorb photons in the full spectrum of violet, blue, yellow and red colours. Following this circle of logic, we end up back at our starting point, namely the question of using green light. Should we choose this option, we must accept our cave will appear even greener than it would without this lighting, i.e. leaving the lamp flora to populate on its own. This type of lighting system was used for a short period in the Cango Caves in South Africa but was soon replaced because of the problems mentioned previously.

Beta-Carotene that plays an important role in vascular plants (in particular pteridophytes and “higher” plants) absorbs green light quite well, as it functions effectively within the 415-500 nm wavelength range. As mosses theoretically do not contain Chlorophyll B, they cannot utilise light from the blue to the yellow ranges of the light spectrum. Because of this, one would not expect them to grow as well in a cold white LED light. This proposition is however one for the scientist to study and ponder. Regardless of the answer, perhaps this notion is simply a measure of Dutch comfort, as there are more than enough algae in our caves in comparison to mosses!

5.1 Fighting lamp flora

This challenge has to be thought of, recognised and implemented as part of a typical cyclical or iterative feedback process involving the continual and systematic application of experience, learning and adaptation.

Any correct solution shall always be based upon the initial and proper configuration of the lighting system and thereafter the process of correct installation. Those responsible for lighting caves must think not only about the correct lighting, but also all the necessary infrastructure and equipment when designing and constructing footways and their surfaces. Sufficient and discrete spaces must be provided for the cables, branching, controls and junction boxes and last but not least for the light fittings themselves. The best solution for locating directional lighting and the views to be illuminated, is from under the surface of the walkway. That is exactly why “wall to wall” concrete and other similar surfacing approaches are particularly unsuitable, as they make it impossible to discretely install most forms of normal lighting.

Once we have the proper lighting configuration, we can start the cyclical process of fighting our friend: the lamp flora. As the poem below written in the style of Vladimir Mayakovski[2] says

Good lighting
Eradication of old lamp flora
Monitoring of lamp flora
Better lighting
Eradication of lamp flora
Monitoring of lamp flora
Even better lighting
and so and so on…

[2] Mayakovsky is a futuristic Russian-Soviet poet (1893-1930) who used staggered lines in his poems.

The deployment of "*even better lighting*" therefore involves the correct adjustment of lights, the reduction of excessive light intensity and the installation, replacement or adjustment of the mountings housing directional light. In more severe cases the replacement, removal, or relocation of lights, the modification of lighting sections, the designation of circuits, or even the potential re-routing of the visitors' pathway, should all form crucial elements of the logic and basic building blocks of any improvement plan for our cave lighting system. For the reasons described previously, although humans and lamp flora have common evolutionary backgrounds and therefore have somewhat identical taste, this is where any similarities end. Because the adaptation capabilities of plants are far better and more effective than ours, I believe it is impractical to change the lighting spectrum.

"Monitoring" in reality is a kind of surveillance and in its simplest form, surveys only the presence and extent of the lamp flora. More detailed monitoring can however identify the composition of the larger taxonomic groups for instance cyanobacteria (Blue-green algae), green algae, mosses and pteridophytes. The most sophisticated surveys will however provide even better information at a species level and allow us to understand the quantity, density, proportion and composition of these plant communities. With this level of knowledge we can happily publish more informed scientific papers to increase our own personal prestige and self-esteem.

You may wonder why this cycle of monitoring is important and should be repeated on a regular basis and why regular eradication of the lamp flora is not sufficiently well understood to solve the problem. Those who have experienced or tried to do this demanding job will be fully aware, eradication and removal is the weakest link in the surveillance process. Without proper care it is difficult to avoid damaging not only the natural ecology but also man-made assets in our caves, such as cave paintings. No matter what method is used to remove lamp flora, a carpet of moss growing on a clay layer cannot be eliminated without damaging or even removing its substrate. Lamp flora growing into the dripstones will disappear for a while, but will remain visible for a long time and affect the development of those structures.

Indeed the removal of lamp flora by any mechanical or physico-chemical method can seriously or even disastrously damage cave paintings. Likewise the outcome of various attempts to remove lamp flora without using chemicals, is at best been less predictable and at worst hopeless and can ultimately result in the further growth and wider distribution of these plants. Since all the chemicals, in particularly those containing chlorine are certainly poisonous to the wildlife of caves and also because their use can leave a cave smelling like a hospital or disinfected toilet, their use should be minimised. This most effective approach is prevention rather than cure, adopting the preconditions of proper lighting and quick intervention when lamp flora first appears. The smaller the surface to be cleaned using chemicals, including those which are so-called environment friendly and chlorine free, the better for the cave, the manager and the visitor… in fact for everyone.

6. Conclusion and acknowledgements

And so I come to the end of the thoughts, experiences and conclusions about the lighting of caves I briefly wanted to share with you.

Specific academic references are intentionally not included in this paper, because I have no desire for this to be considered a scientific publication. For those interested and wishing to know about these issues, a few clicks on the internet will provide all the relevant research and literature. In writing this article based on my own and wide ranging experience I have deliberately tried to avoid, albeit not always successfully, being strongly critical of the various lighting solutions used in concrete caves, or towards contractors. It was certainly not my intention to damage anyone's reputation nor more importantly to get myself into trouble in ways which would prompt the heavy hand of dispute or legal action.

To the contrary I simply hope at least some readers will benefit from my suggestions. Should you have any unanswered questions or wish to challenge any of my statements, please do not hesitate to email me at salamongaborsalamon@googlemail.com) in any European language, although I cannot guarantee my reply will be written in the same style.

Finally and respectfully, I would like to express my sincere and grateful thanks to Viktor Gotthardt, Anett Mogyorósy, Gábor Szilágyi[3] and Zsuzsa Tolnay, the translators who have transformed my overcomplicated thoughts, created and written originally in the most difficult language in the world, into a form and story which allows others to understand them. Likewise my special thanks and those of these translators are also expressed to the language lecturer, László Horváth for the corrections he made to Chapter 4 and particularly to Peter Ogden, who kindly refined and where necessary adapted the initial version of the "Hunglish" text into his mother tongue. Last but not least, many thanks to Judit Sándor for the proofreading of the final draft.

[3] Being also the team leader and co-ordinator of the translation project.