Underwater Illumination

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Abstract: *General differences between the illumination of an object in air and in the ocean are introduced. Terminology used in connection with illumination is discussed and explained with application to the ocean environment. The main types and basic description of lights used in the exploration and research of the oceans are discussed. The basic operation of incandescent, High Intensity Discharge (HID) lamps and Light Emitting Diodes (LEDs) are explained. The basics of the theory and design of parabolic, elliptical and spherical reflectors and their function with respect to underwater light fixtures is discussed. Important factors in the selection of suitable lighting for underwater illumination are discussed.*

Good lighting is an essential element of any underwater operation that requires visual observation. Natural light from the sun disappears within a very short depth beneath the surface of the water and the need for artificial lighting becomes evident. This paper will examine the basics of underwater illumination. It is intended to be a broad, general look at the subject. The goal is to provide individuals in the early planning stages of underwater operations with a basic knowledge of the challenges they will face and the solutions that are available.

Visible light occupies a small band of the larger spectrum of electromagnetic radiation. Figure 1 shows the relative wavelengths of various forms. Radio waves with wavelengths equivalent to the length of a football field and infrared radiation occupy the lower, less energetic right side. Short wavelengths on the other end of the scale include ultra violet radiation, x-rays and gamma rays. The visible light band runs from approximately 400 nm to 700 nm. When bundles of light energy, known as light photons travel from air into another, denser medium such as water or glass, they are refracted and attenuated. This has two effects that are familiar to anyone who has ventured beneath the surface and peered through a glass lens. Refraction causes the magnification of objects. Attenuation is the combined effects of the absorption and scattering of light. The attenuation of light is more pertinent to the current discussion.

A portion of the light striking the surface of a body of water from the sun is reflected and another portion will penetrate. How much light penetrates depends on many factors including the clarity of the water and the angle of the sun to the surface, which changes as the day progresses. As photons continue through the denser medium, they are attenuated. The more particulate in the water the faster the light is absorbed. How quickly light photons are absorbed in water also depends on the wavelength of the light. The longer wavelengths are absorbed more quickly while the blue-green ones penetrate further. UV light is heavily scattered. This results in an uneven loss of color across the visible band with depth. The loss of color intensity begins with the longer, or red wavelengths of light first. Figure 2 shows a typical absorption spectrum. Objects that appear red on the surface begin to take on a dull brown appearance a short distance beneath the surface of the water. Further beneath the surface, less color is perceived whether it is observed directly by the human eye or by a camera. Individual objects become hard to distinguish as they begin to blend with the surrounding hydrography into a single monochromatic scene. Eventually all of the light is absorbed and the vast majority of the ocean depths are completely dark.

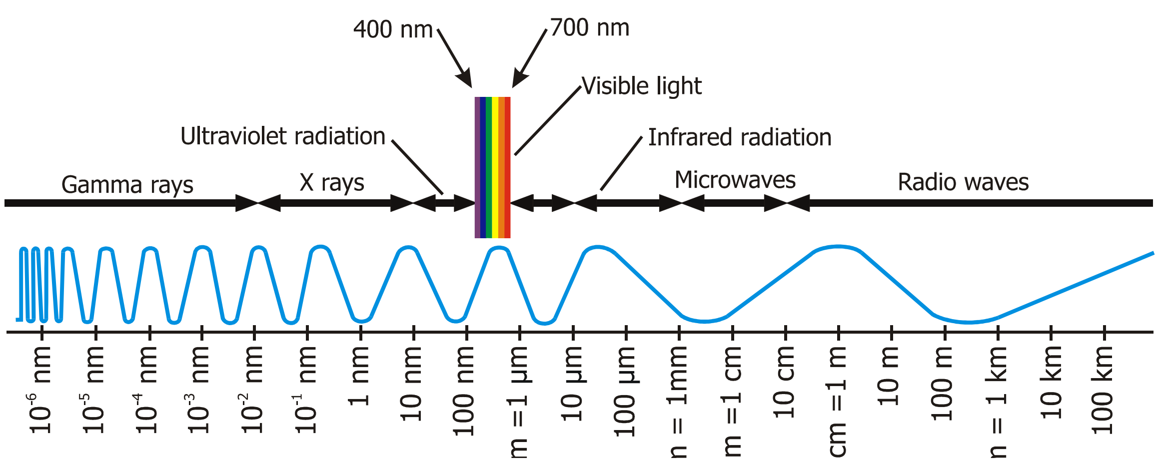


Figure 1 Range of electro-magnetic radiation including the visible light band.

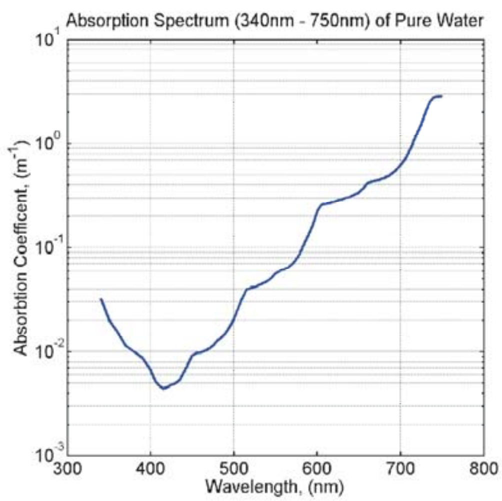


Figure 2 Absorption Coefficient data from Pope, R.M and Fry, E.S. 1997: Absorption Spectrum (380nm - 700nm) for Pure Water. II. Integrating cavity measurements. Appl. Opt. 36: 8710-8723

The addition of lights to a diver or vehicle introduces a multitude of new options. There are several different types of lamps that are commonly used underwater. These lamps fall into three general categories;

1. Incandescent lamps
   These lamps are the most common lamps and use a method to produce light from electricity that goes back to the invention of the electrical lamp. They produce light when an electrical current is driven through a piece of tungsten wire known as a filament. The filament heats up until it is literally white hot and light is emitted. However the majority of electrical energy driven into the filament is converted into heat and not light. This makes incandescent lamps less efficient than many other light sources.
   The tungsten filament is constantly losing tiny particles that evaporate and deposit themselves on the glass envelope. This causes blackening of the envelope and also, eventually causes a break in the filament (filament notching). This means that incandescent lamps have a shorter life span than non-filament light sources.
   Adding halogen gases inside the glass envelope allows a halogen cycle where the tungsten on the glass wall of the lamp dissolves back into a gas phase. This helps to combat the loss of tungsten by forming products that redeposit the tungsten onto the filament and not on the envelope. However, the tungsten does not usually end up in the same spot where it came from and so the filament will eventually break. Filaments are also fragile and susceptible to breakage from physical shock and vibration. This can often be an important factor in underwater applications.
   Quartz glass is used to allow the inner wall of the lamp to operate at a higher temperature than other transparent glasses could withstand. High temperatures are required for the halogen cycle to operate. Common examples include household bulbs and the quartz-halogen lamps widely used in auto headlights.
2. Gas Discharge lamps
   These lamps produce light when an electrical current produces a plasma in a gas that may include metals such as mercury and rare earths in the form of metal- halides (metallic salts). The electrons in the gas plasma are excited to higher energy levels by the electrical current and give off this excess energy in the form of light. The emitted light may be visible as is the case with High Intensity Discharge (HID) lamps or it may be ultraviolet as is the case with common household fluorescent lamps. In order to generate useable, visible light, fluorescent lamps are coated internally with a phosphor that emits visible light when excited by ultraviolet light.
   Gas discharge lamps do not have a filament, which means that they generally have a longer life span and are more resistant to shock and vibration than incandescent lamps. Gas discharge lamps require an ignitor and a ballast to strike and maintain the gas plasma. This special control gear can add to the weight and size of an underwater gas discharge light. Ballasts are either magnetic or electronic. Magnetic ballasts use large coils and capacitors to limit electrical current flow, and to generate the large starting pulse necessary to ignite and maintain the plasma in a gas discharge lamp. Electronic ballasts use solid-state technology to achieve the same end and

are generally much smaller and lighter. Gas discharge lamps are generally far more efficient than incandescent lamps in converting electrical energy to light.

3. Light Emitting Diodes (LEDs)
   These small compact light sources are semiconductor devices comprised of two types of semiconductor material, N-type and P-type. When a potential is applied between the two, electrons move to higher energy levels, emitting light when they drop back down to the original level. LEDs have no filament and newer designs can be highly efficient when turning electrical energy into light. They are generally housed in a small plastic envelope that is hard to damage.
   Common uses of LEDs include traffic signals, jumbo-tron displays, indicator lights in electronic gear and infrared (IR) LEDs are used in remote control devices for household electronics such as TVs and stereos. They do not require any special control gear but are generally small and a large number are needed to produce a useful underwater light. Placing enough LEDs in a compact, watertight, pressure housing while maintaining a low enough temperature for them to continue to operate efficiently is the main challenge for underwater applications.

Figure 3 : LED, Quartz-halogen and Xenon HID light sources.

Each type of light source has its own characteristics, advantages and disadvantages. Choosing the right light for your needs begins with a basic understanding of the terminology used to describe them. The light fixture is called a luminaire and the light source or bulb is called a lamp. This can cause some confusion because in everyday parlance the word “lamp” is more commonly used to describe a small luminaire, as in table-lamp. The same luminaire may often be available with a selection of different lamps. In our homes, when it comes to choosing the most common incandescent lamps that we use, we generally use the lamp wattages (W) for comparison. For example we may choose a 150-watt lamp for the porch whereas we would generally choose a 60-watt or lower wattage lamp for the living room. While lamp wattage is a useful gauge of the light output of otherwise identical lamps, it is a poor choice for comparing the light output of lamps in general. The wattage of a lamp is a measure of how much electrical power it consumes and not of the quantity of light that it emits. While power consumption is not usually a significant factor in choosing lamps for our home, it becomes very important when a lamp is being powered from a limited power supply. This is often the case in underwater applications such as when powering a luminaire from a bank of batteries. In this case a lower wattage lamp will provide more hours of operation from the limited supply of power.

A comparable unit of measure to the watt is luminous flux. The luminous flux, or quantity of light emitted by a light source is measured in the S.I. unit lumen (lm). One lumen is equivalent to the light flux per solid angle of a point source whose intensity is one candela (cd). The candela is the S.I. unit of light intensity. Just as a meter was defined by choosing a certain length, the candela was chosen to be the light intensity from a particular source[1]. The name candela gives a clue to the origin of the measurement, which harks back to a time when a candle of a fixed size and composition was used as the standard. The human eye is a good judge of light output and even the casual observer will easily distinguish between lamps of different intensity. To put lumens in perspective, a candle provides roughly 12 lumens of light output and a 60W soft white incandescent lamp provides 840 lumens.

A very useful measurement for comparing different types of light sources is lumens per watt (lm/W). This is a measure of lamp efficiency,

[1] The candela (cd) is the S.I. unit of luminous intensity and is defined as the luminous intensity in the direction of the normal of a black body surface of 1/600,000 square meter in area at the temperature of solidification of platinum under a pressure of 101.325 kilo-newtons / meter^2.

more often called lamp "efficacy" in the terminology used to describe lamps. In other words, it is a measure of how well a lamp converts electrical energy to light. To calculate lamp efficacy, simply divide the light output of a lamp by the lamp wattage. Table 1 shows lamp efficacy for some common lamps. Generally speaking, incandescent lamps are far less efficient than gas discharge lamps. Take for example the High Intensity Discharge (HID) xenon lamps commonly used in the headlights of many new luxury cars (shown on the right of figure 3). These HID lamps provide roughly 71 lm/W compared to 18 lm/W for the more common incandescent, quartz-halogen headlight. The HID lamps are usually 35 W lamps and therefore produce roughly 2500 lm whereas the commonly used 55 W quartz halogen will use more electrical power to generate only 990 lm of luminous flux[2].

The outputs of lamps are often compared by *lumen maintenance*, which simply shows how well they maintain their original lumen output over time. This data is usually provided in graphical form and is a plot of luminous flux as a function of time.

Table 1 Comparison of light source efficacy, (h) for some common sources.

Light Source	**Luminous efficacy (h), lm/W**
Candle	0.1
General Lighting Service Lamps	11
Quartz Halogen Auto Headlight Lamps	18
High Pressure Mercury Lamps	50
HID Xenon Auto Headlight Lamps	71
Fluorescent Lamps	100

The example of the auto headlights might be continued to explain what is meant by the term *color temperature* or *chromaticity* when discussing lamps. The HID auto lamps produce a light that, to the human eye, is bluer in appearance than the yellowish light of a quartz-halogen auto headlight. This perceived difference in light sources is indicated by an attribute called the color temperature or chromaticity that is measured is degrees Kelvin (K). Color is often used as a metaphor for temperature as in the terms *red-hot* and *white-hot*. As this analogy might imply, color temperature is directly related to the physical temperature of the tungsten filament in an incandescent lamp. As the physical temperature of the filament increases the lamp moves from red-hot to white-hot. Gas discharge lamps do not have a filament and so the term *correlated* color temperature (CCT) is often used. This simply means that the gas discharge lamp of a certain correlated color temperature produces a light with a similar appearance to a tungsten filament at that temperature. Table 2 shows some typical CCT values for common lamps. Color temperatures vary from about 2400K in the case of incandescent lights to more than 7000K in the case of some HID lamps. Lamps with a color temperature of more than 5000K are often called daylight color lamps. The term chromaticity is becoming more commonly used than color temperature or correlated color temperature.

Table 2 Comparison of chromaticity for some common light sources.

Lamp	**(Correlated) Color Temperature (Kelvin, K)**
Household incandescent bulb	2400
Quartz Halogen Auto Headlight	3000
Xenon HID Auto Headlight	3200
Fluorescent Lamp	5000
Video Projector Lamp	6500 +

One confusing aspect of this attribute is that lamps with a lower color temperature are often described as *warm* whereas higher color temperature lamps are described as *cool*. One explanation for this apparent contradiction is that warm light sources have a similar color to the light provided by an open fire while cool light is more reminiscent of moonlight reflected on a snowy surface.

Another measurable attribute of lamps related to color is the Color Rendering Index (CRI). This is a 0-100 scale that indicates how well a light renders colors compared to a reference light source. The higher the CRI value the better the

[2] Note that the total, system load has not been considered in this simplified example for clarity.

color rendering but a difference of 5 or less is not usually visible to the eye. Lamp to lamp comparison of CRI is usually only useful when comparing lamps of the same chromaticity.

Reflectors form a very important part of a luminaire. Apart from the case of general lighting, it is usually desirable to direct the light photons from the lamp into a beam that is useful for an underwater task. An efficient reflector will not only maximize the light output of the luminaire but will also direct heat, in the form of infrared radiation forward and away from the lamp. Some lamps are manufactured with an integral reflector. These lamps are generally called PAR lamps, where PAR is short for parabolic. While they may occasionally be used in underwater luminaires, more efficient, highly designed solutions tend to employ regular lamps and custom made reflectors that focus the light into optimal beams for underwater work.

The two dimensional cross-section of a reflector is usually a conical section. They may be spherical, parabolic, elliptical or some combination of these three. A spherical section has one focal point at the center. When a light source is placed at the center or focal point of a smooth spherical reflector in air, light rays are reflected back to the focal point. An ellipse has two focal points (figure 4). A light source placed at one of the focal points of a smooth elliptical reflector in air will reflect light onto the second focal point. A parabola also has two focal points and in a similar fashion to the elliptical reflector, a smooth parabolic reflector will reflect light from the first focal point onto the second one. However, the second focal point of a parabola is at an infinite distance from the first one, which means that the reflected light exits the reflector in parallel, horizontal rays (figure 5).

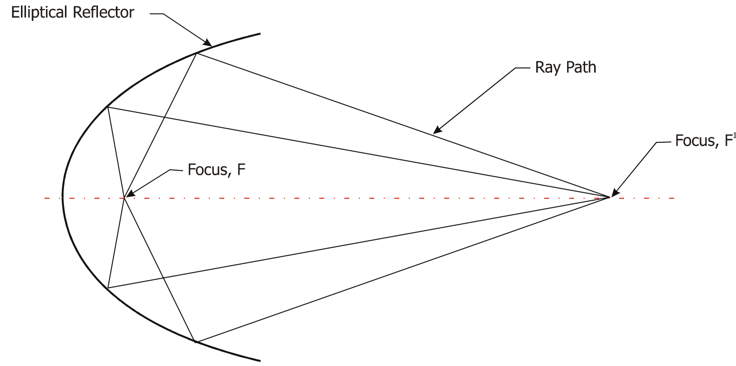


Figure 4 Idealized Elliptical reflector showing reflection of light rays emanating from the focal point F to the second focal point F|.

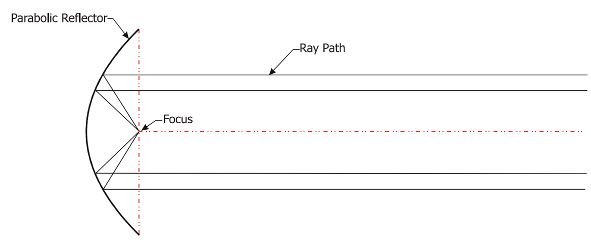


Figure 5 Idealized Parabolic reflector showing reflection of light rays emanating from the focal point F. The second focal point F| is considered to be an infinite distance away. Light rays leave the reflector in parallel paths producing a narrow beam

In underwater applications it is often necessary to place a large light source behind a small opening in order to optimize a pressure housing. A hybrid reflector with a cross section that is a combination of a parabola and an ellipse is useful in these cases (figure 6). Some highly engineered designs employ a “wet” reflector. These luminaires are designed using advanced techniques to produce reflectors that achieve the desired results when placed around the light source that is immersed in water. One of the great benefits of this type of design is the efficient dissipation of heat gained by having the light source in closer contact with the water. Another key benefit is that the pressure enclosure is much smaller when only the lamp, and not the reflector is inside the lamp housing.

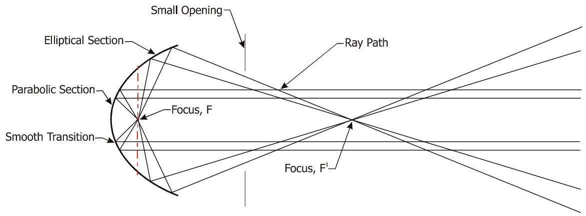


Figure 6 Idealized hybrid reflector, comprising of an inner parabolic section and an outer elliptical section. Hybrid reflectors are useful in underwater applications where light rays must be focused through a small opening.

Depending on the surface condition of a reflector, light will be dispersed, diffused or simply reflected. The majority of reflectors are made of very pure, highly polished aluminum. A specular reflector has a highly polished, smooth surface that will reflect light back at the same angle to the normal that it was incident at (figure 7). By adding dimples, or peens to the surface of the reflector the reflected light follows roughly the same path as it would when reflecting from a specular surface but it is dispersed or spread out as it leaves (figure 8). When a white surface, such as white Delrin plastic is used, the reflected light is diffused in all directions (figure 9).

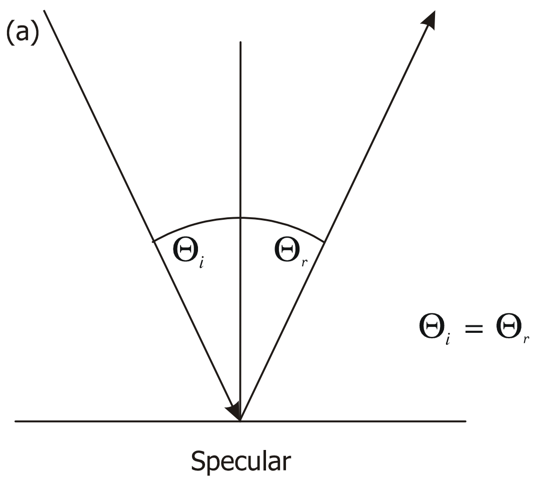


Figure 7 Reflection of an incident light ray from a perfectly specular surface.

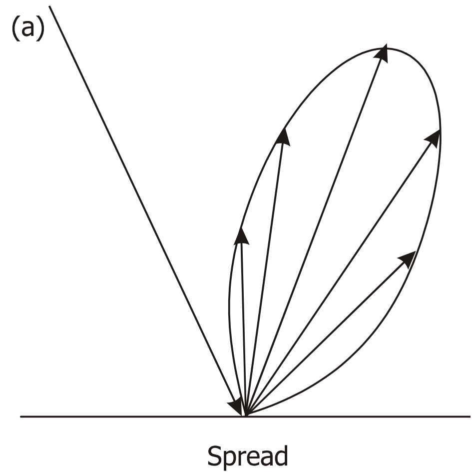


Figure 8 Reflection of a light ray (a) from a spreading surface.

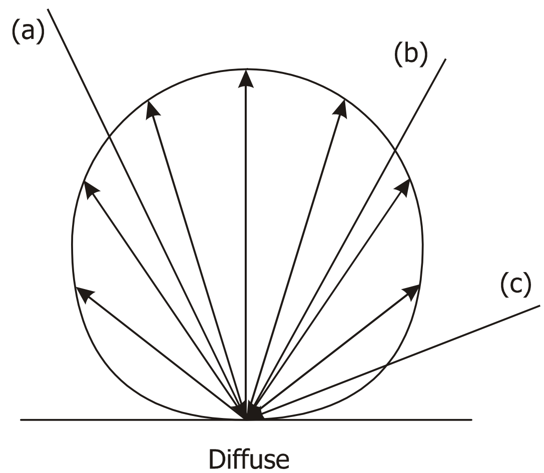


Figure 9 Reflection of an incident light ray from a perfectly specular surface.

Most luminaires will be available with a number of reflectors that usually fall into the two main categories of spot reflectors or flood reflectors (figure 10). Using the parameters discussed above, reflectors are optimized to produce clean narrow beams, in the case of spot reflectors or wide, evenly distributed beams in the case of flood reflectors. The choice of reflector will depend on the job at hand. It is common practice to have several similar luminaires with different reflectors mounted on the same vehicle for optimized lighting.

Figure 10 Smooth, peened and diffuse (white) reflectors.

Care must be taken in the placement of lights to optimize the ability to effectively illuminate a scene. Suspended matter in the water will reflect light back towards the camera or diver causing an effect called volume backscatter (figure 11). This unwanted effect may be minimized by separating the light source and observer by a short distance (figure 12). The common volume is the area where the light beam and the field of view of the camera or observer meet (figure 12).

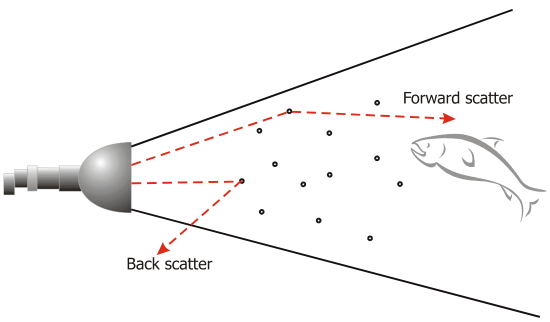
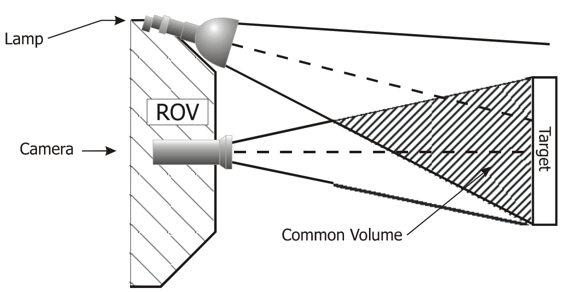


Figure 11 Light is scattered by suspended particles in the water. Some may be scattered back towards the camera producing unwanted bright spots in the image.



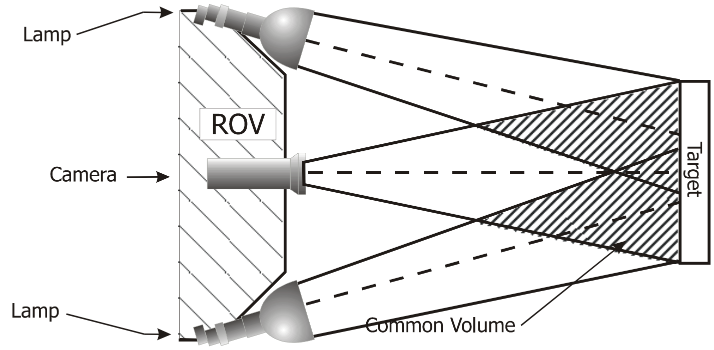


Figure 12 Separating the light source and the camera by some distance helps to reduce the problem of backscatter by minimizing the common volume of the camera and light(s).

In selecting a suitable light for underwater work it is generally desirable to use the highest color temperature lamp with the greatest efficacy available within the constraints of the job. HID lamps offer the best combination of these two factors but may be too cumbersome for some applications. For example a diver may wish to minimize the amount of equipment carried to lighten the load, prevent entanglement and generally simplify life. The same would probably apply for a small ROV. In these cases a low voltage, luminaire that uses a good quartz-halogen incandescent lamp is optimum.

In another scenario a fish farmer or scientist using lights in a closed volume of water with fish may be concerned with the amount of heat added to the water from high wattage lamps. In this case a lower wattage lamp may be optimum. Black and white cameras are more sensitive to visible light in the green region of the spectrum. Because of this, lights with a higher output in this band produce optimum results when used for black and white video inspection cameras. For close up (within a few focal lengths of the camera) work, volume scattering may not be an issue and a camera that combines it's own light source in the form of a small LED array may be the optimum solution.

Recent developments in HID lamp technology have allowed a great reduction in the weight and size of the bulky housings usually necessary to accommodate the ballasts required to drive them. Spurred by the large demand for HID auto headlights, several large manufacturers have developed small HID lamps with high efficacy and daylight color temperature that operate on low voltages. The underwater luminaires designed around these lamps are producing better and better solutions for all types of underwater work.

Depending on the power budget available for lighting, choices may be narrowed to a few types. Underwater luminaire manufactures will usually be very knowledgeable and willing to provide expert advice and assistance in locating a suitable solution.

References:

Pope, R.M and Fry, E.S. 1997: Absorption Spectrum (380nm - 700nm) for Pure Water. II. Integrating cavity measurements. Appl. Opt. 36: 8710-8723

Information regarding various lamps and their characteristics was taken from manufacturers spec sheets:

OSRAM form D-HC2S/R, Rev. 5/29/2003
OSRAM form D2S/R, Rev. 5/29/2003
See www.osram.com for more details