THE PROBLEM OF COLD LIGHT

HARVEY A. NEVILLE, UNIVERSITY OF ILLINOIS

The exact nature of light is not understood, but our present conception of it is something of a compromise between the wave theory and the earlier corpuscular theory. From a consideration of the recent discoveries of Planck, Thompson and Einstein it is concluded that light consists of discrete particles or atoms of energy, each with a specific energy content $E=h\nu$, moving with velocity c, and having a mass e/c^2. (h is Planck's constant $=6.55 \times 10^{-27}$ ergs per sec. ;ν is the frequency of vibration.)

Light energy is emitted by matter when in an excited state. This excitation may be induced by various means, the most general being by increasing the temperature of the system. A black body is non-luminous up to 500° C. due to the limit of sensitivity of the human eye. If the eye were sensitive to longer wave lengths of the infra-red, lamp-black would appear highly luminescent among other bodies at the same temperature. All substances whose temperature is above absolute zero emit simple thermal radiation. The higher the temperature the more rapid the vibration of the atoms and electrons and therefore the shorter the wave length. At sufficiently high temperature the wave length of the emitted radiation corresponds to the range of the visible spectrum.

The total radiation of a body increases directly at the fourth power of the absolute temperature; as stated by Stefan's law $R=kT^4$. As the temperature rises the maximum-power radiation recedes to shorter wave lengths. The expression of this relation, known as Wien's law, is
$\lambda_c=kT^{-1}$ or $\lambda T=k$.

A body which is emitting light by purely thermal radiation, in agreement with the two laws just mentioned, is said to be *incandescent*. A body which is emitting a greater total radiation than can be accounted for by its temperature alone is said to be *luminescent*. It is light produced in this way, unaccompanied by the theoretical amount of heat, that is referred to as *cold light*. For example, the flame of carbon disulfide has a temperature of only 150° C. but it is luminiscent and can affect a photographic plate. Pure temperature radiation at 150° would be far in the infra-red and entirely devoid of any photochemical action.

Artificial illumination at present depends entirely upon the emission of light from incandescent solids or gases. Because of the high temperature required to maintain this condition, by far the greater proportion of the energy supplied is converted into heat and wasted rather than emitted as light. Heat, light and electricity are all forms of radiant energy; the essential distinction is a difference in wave length. The visible spectrum, comprised between the extreme violet and the extreme red, is but a small portion of the complete spectrum. *Chart I* shows the relation of the various forms of energy radiation and the distribution of the energy from several sources of radiation.

CHART I

Note that all wave lengths in the visible spectrum are not equally visible. There is a maximum of visibility nearly corresponding with the maximum of the sun's radiation. The visibility curve is indicated in the small rectangle.

The sun emits a practically continuous spectrum corresponding to that from a black body at a temperature of 6,000° K- which is therefore taken as the temperature of the sun. Its maximum-power radiation is at a wave length of 5,600 Å* which is in the yellow-green of the visible spectrum. About 25 per cent of the radiation of the sun is in the ultra-violet, although only about 3 per cent of it reaches us, the very short wave lengths being absorbed or dispersed by the atmosphere. Practically all the rays of wave length shorter than 3,000 Å are eliminated in this way.

The radiant energy of the fire-fly is entirely within the visible spectrum. This is an example of an ideal cold light. It has been impossible to detect the evolution of any heat from this source.

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* Å=Ångstrom unit=10^{-8} cm.

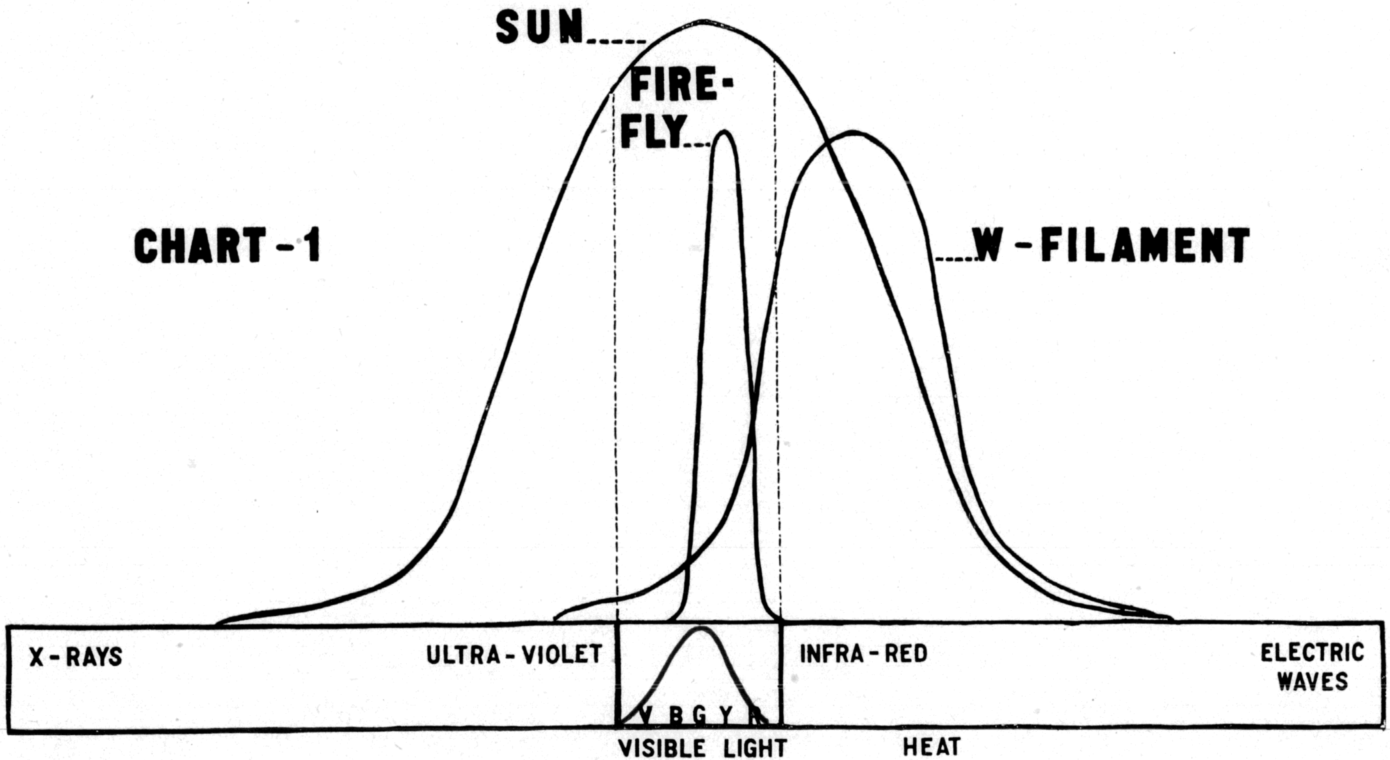
CHART - 1
SUN
FIRE-
FLY
W - FILAMENT
X - RAYS
ULTRA - VIOLET
V B G Y R
VISIBLE LIGHT
INFRA - RED
HEAT
ELECTRIC
WAVES

If the radiations of an ordinary carbon or tungsten filament could be converted into shorter wave lengths, it would produce a light as efficient as the fire-fly and of a more desirable quality. Electrical transformers are used to step-up voltage; if there were a radiant energy transformer to step-up vibration frequency, the infra-red rays could be converted into visible light. The curves illustrate the immense waste in producing light by present methods.

It is clear that for economic reasons research should be directed toward finding a more efficient means of producing light—that is, to reduce the amount of heat that is generated when a body is caused to become luminous, or to devise some method of producing light other than by purely thermal emission.

Electricity is by far the most convenient, safe, and satisfactory means of producing light yet devised; and it seems likely that the solution of the problem of efficient lighting, at least for a long time, will consist in some application of the electric current. A comparison of the relative efficiencies (or inefficiencies) of various means of illumination shows that, although electrical means are better than others, they are still extremely wasteful.

In measuring *quantity* of light, as in the case of electricity, there is an intensity factor and a capacity factor to consider, besides several other factors which determine the *quality* of the light. The unit of light intensity is the *candle-power*, the unit of quantity or flow of light is the *lumen*. In proper illumination a balance between the two must be attained. Efficiency calculations based upon the two factors separately and upon data from different sources agree only roughly, but all values point to the same conclusion—that our best sources are very poor when compared with ideal conversion of energy into light.

Coblentz[1] has determined the mechanical equivalent of light and has shown that the theoretical conversion of power into light of maximum visibility (yellow-green light) is 617 lumens per watt. The conversion of solar radiation is only 86.5 lumens per watt, so the sun, considered as a light producing source, is only 14 per cent efficient—though in this case we are grateful for the heat also. *Chart II* shows the efficiency of various light sources calculated on the basis of power consumption for light produced. A candle power of brightness should give a flux of 4π or 12.56 lumens but in practice a lower value is usually obtained.

CHART II

Tungsten at its melting point, 3670°K, would emit 57 lumens per watt (an efficiency of 9.24 per cent) but its rate of evaporation is considerable even below this temperature. Progress with incandescent filaments depends upon finding a material with a lower rate of evaporation and a higher melting point. Thus carbon, which has been displaced by tungsten as a filament material, may come back into use, since it has a much higher melting point, if certain of its disadvantages can be overcome.

Another possibility is to find a suitable gaseous envelope which will reduce the loss of material due to evaporation. Or it may be possible to control the emissive properties of matter to procure proper selective radiation. It has been pointed out that the maximum possible efficiency of selectively radiating rare-earth oxides in an ordinary Bunsen flame is thirteen times that of the incandescent mantle. It is known that most of the white refractory oxides, such as lime and magnesia, as well as the oxides of the rare earths are thermo-luminescent. That is, when heated they emit a greater amount of visible light than can be accounted for by their temperature

The luminosity of electrical discharge in gases must be considered. Incandescent solids emit continuous spectra while incandescent gases give selective emission. If this radiation happens to be in a part of the visible spectrum that is desirable as illumination, the luminous efficiency may be very high. Lamps are being operated on this princple in England at a consumption of 0.5 watt per candle power. Their development has just begun, and since a very high intensity has not been attained they are being used mainly as glow lamps and for advertising display. The Germans claim to have developed this method of light production to a still higher efficiency.

We are familiar with the use of the same principle in the spark-plug tester containing neon gas.

So far only luminescence produced by thermal or electrical means has been considered. Some other light-producing phenomena will now be indicated.

When light strikes a body it may be in part transmitted, reflected or absorbed. That which is absorbed may be re-radiated in longer wave lengths. This is called *fluorescence.* The light energy may actually be stored and emitted later—which is called *phosphorescence.* The only distinction between these two phenomena is that phosphorescence may continue after the incident beam is cut off while fluorescence does not. In some cases the incident beam is of longer wave length than the emitted beam. Here the vibration seems to have been stepped-up to a higher frequency. This phenomenon is known as *calorescence.*

Phosphorescence and fluorescence in substances is thought to be due to minute traces of impurities. Perfectly pure substances are incapable of phosphorescence. A certain proportion of the impurity gives a maximum effect. Thus phosphorescence is governed by the following conditions:

1. The amount of the impurity present.
2. The nature of the impurity.
3. The temperature of the substance.
4. The intensity and duraton of the light stimulus.

Ultra-violet light is more active in producing phosphorescence and fluorescence than is ordinary light. Ultra-violet light can thus be converted into visible light. The mercury arc and the magnetic arc give a light rich in ultra-violet. Quartz is used rather than glass for the mercury arc because its high melting point (1700° C.) allows a higher temperature for the arc and hence a better efficiency, and also because quartz allows a thousand times as much ultra violet light to filter through as does glass. All radiations of wave length less than 3300 Å are absorbed by glass. Quartz is permeable to light of wave length above 1850 Å.

The production of light in chemical reactions, or *chemiluminescence,* is fairly common. The crystallization or precipitation of certain salts may be accompanied by luminescence. Slow oxidation of organic matter, such as rotten wood, decayed fish and meat, and the oxidation of phosphorus are luminescent. The glow of phosphorus is often erroneously referred to as phosphorescence, but it has been found to be due to the second stage in the oxidation of phosphorus—that of P_2O_3 to P_2O_5. The *bioluminescence* of bacteria, the fire-fly and the glow-worm, is likewise produced by oxidation. The production of light by the fire-fly has been studied thoroughly by Prof. Harvey of Princeton[2]. He has been able to extract two substances from the fire-fly, luciferin, an oxidizable material, and luciferase, an enzyme which is a catalyst for its oxidation. When these substances are mixed in contact with air or an oxidizing agent, light is produced. Prof. Harvey points out that the heat of the reaction is extremely small and the product of the oxidation is oxyluciferin and not carbon dioxide and water. Hence the reversal of the reaction and regeneration of the luciferin should be easy.

The light of the fire-fly is of interest principally because it proves that an ideal cold light is not an impossibility. In this paper it has been endeavored to emphasize the extreme inefficiency of present methods of light production. A careful study of the natural phenomena outlined above may suggest means of improving luminous efficiency. If we follow the advice of Louis Agassiz and "study Nature, not books," some success in this direction will no doubt be attained.

CHART 2—LUMINOUS EFFICIENCY.

Source	C-P/W	L/W	Per Cent
Perfect	49.1	617	100
Sun	6.9	86.5	14
Mercury Arc	3.12	39	6.35
Flaming C Arc	2.08	26	4.24
W. in Argon (3,000° K)	1.66	20	3.4
W. in Vacuum	.8	9	1.45
Nernst Rare Earth Glower	.41	5	.8
C. Filament	.28	2.7	.57
Inc. Mantle (C_2H_2)	.2	2.5	.4

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