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Author(s): J. V. Lake
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Comparison of natural and artificial sources of light

By J. V. Lake
Rothamsted Experimental Station,
Harpenden, Hertfordshire

The area of crop plants required to sustain a man in an artificial extra-terrestrial environment is probably about 10 m^2. If the site is on the Moon, the natural light will alternate with periods of darkness, but will be brighter than any practicable arrangement of artificial lights. The latter can, however, be run continuously.

To control plant temperature, an artificial cooling system will be required with either kind of illumination. The energy to be dissipated will be about 700 W m^{-2} with natural light, or three times this amount with artificial light (high pressure discharge lamps).

A paper on this subject was to have been given by Dr P. Gaastra, but he was unable to attend the meeting. The notes that follow were therefore prepared so that the participants had an opportunity to consider some of the main features of the problem.

Energy and area requirements

The minimum energy expenditure of a man in an artificial extra-terrestrial environment is likely to be about 130 W (2700 kcal/day) (Pirie 1967) and from this can be calculated the minimum area of plants required to feed him.

The energy of combustion of one molecule of carbohydrate is about 7.70×10^{-19} J, equivalent to 2 quanta of blue light or 3 of red, but the smallest number of quanta required for the photosynthetic reduction of one molecule of carbon dioxide is about 10, so that the maximum efficiency of photosynthesis does not much exceed 0.2. As mentioned in the preceding paper, plants in an enclosure on the Moon will probably receive photosynthetically active radiation (wavelength 0.4 to 0.7 μm) from the Sun at a flux density of not more than 560 W m^{-2} and they will absorb about 0.85 of this. So the required plant area is $130/(560 \times 0.2 \times 0.85) \approx 1.7$ m^2. This must be multiplied by 2 to allow for periods of darkness and by a further factor of 3 for the known failure to achieve the maximum possible photosynthetic efficiency (especially in terms of edible material), so a realistic figure for the cropped area is about 10 m^2 per man.

With artificial lights, the maximum flux density of the illumination will probably be only 420 W m^{-2} and a more realistic figure is 350 W m^{-2}. However, there need be no periods of darkness, so that the minimum area required per man is about 7 m^2.

Another basis for calculation is the largest rate at which dry matter has been reported to be produced by a crop; this is 54 g m^{-2} d^{-1} sustained for a period of 14 days by *Pennisetum typhoides* at Katherine, Australia (Begg 1965). The energy of combustion of carbohydrate is about 15 kJ g^{-1}, so were all the dry matter produced by this crop palatable (none is) a man would require an area of $2700/(54 \times 3.6) = 14$ m^2 for sustenance.

Were animals introduced into the system to convert some of the plant material into a more palatable form, the required area increases to about 200 m^2 per man (Golueke & Oswald 1964).

NATURAL LIGHT

The first extra-terrestrial artificial plant environment is likely to be made on the Moon (Pirie 1967) and unless it is near one of the poles there will be alternate periods of light and darkness of 310 to 340 h duration. Many higher plants grow well in continuous light of this order of duration, but some of the food and oxygen derived from them will have to be stored for use during the period of darkness and corresponding storage must be provided for the human excreta, including carbon dioxide.

Plants may grow faster in diffuse light than in direct illumination of the same flux density (de Wit 1965), because diffuse light is spread more uniformly over the foliage. Light from the Sun reaches the Moon in a direct beam with negligible diffusion, but the plant enclosure could be covered with a transparent material providing substantial diffusion of the solar radiation without a significant increase in the loss by reflexion (Edwards & Lake 1965). For a ray of light at normal incidence, the transmission coefficient of the transparent material may be as great as 0.92 (0.04 loss by reflexion at each surface), but in practice the transmission is much less. For a typical terrestrial greenhouse, the coefficient is only 0.7 or less, because part of the light strikes the glass at an unfavourable angle of incidence, part is absorbed in the glass and part is absorbed in the opaque supporting structure. Some improvement is possible by rotating the house to maintain a favourable angle of incidence of sunlight on the glass, whatever the position of the Sun in the sky (Zscheile & Loomis 1968). The structural design of an enclosure on the Moon would differ from a glasshouse for obvious reasons, but whatever the design it seems improbable that the light transmission could exceed 0.8.

Only half the solar radiation is in the waveband useful for photosynthesis and the remainder will merely create an additional cooling problem. The plants will not be able to cool by radiation to space, as all suitable transparent covering materials absorb the 'terrestrial' black-body radiation emitted by plants and other objects at ordinary temperatures; sheets of materials such as polyethylene, thin enough to be nearly transparent to this radiation, would not be strong or durable enough to make an extra-terrestrial enclosure. The main means of natural heat loss will be by black-body radiation from the transparent covering material to space and this may dissipate about 400 W m^{-2}. If the flux density of the solar radiation is 1400 W m^{-2}, of which 0.8 is transmitted into the enclosure, there will remain $0.8 \times 1400 - 400 \approx 700$ W m^{-2} to be dissipated by an artificial cooling system.

ARTIFICIAL LIGHT SOURCES

These have been studied mainly in the context of terrestrial growth chambers and the state of the art was well described by Gaastra (1970). Only the more powerful light sources will be considered here, and much of the quantitative information is taken from Gaastra's paper.

TABLE 1. RELATIVE RADIATION FLUXES IN THE VISIBLE AND SHORT-WAVE INFRARED REGIONS (PARTLY AFTER GAASTRA 1970)

spectral region	extra-terrestrial sunlight	TL	SON
0.4–0.7 μm	100	100	100
0.7–3.0 μm	100	6	96
0.7–3.0 μm after 10 cm water filter	40	1	31

TABLE 2. MAXIMUM ENERGY FLUX DENSITY (0.4–0.7 μm) OBTAINABLE IN A PLANT GROWTH CHAMBER WITH VARIOUS TYPES OF LAMP (AFTER GAASTRA 1970)

lamp type	electrical power installed W m^{-2}	radiation flux density W m^{-2}
TL	1780	130
SON	3200	350
xenon	6000	240
xenon	10000	420

The ratio of photosynthetic to long-wave radiation is greater for artificial light than it is for sunlight (table 1) and the ratio of photosynthesis to transpiration is likely to be correspondingly greater. Much of the long-wave radiation from artificial light sources is absorbed by a water filter because its wavelength is between 1.0 and 3.0 μm. All lamps except incandescent ones are deficient, relative to sunlight, in near infrared (~ 0.73 μm) compared to red (0.66 μm) radiation, although high pressure gas discharge lamps (SON in table 1) are much better than fluorescent tubes (TL). These are the wavelengths that control many photomorphogenetic effects and for normal plant growth and development it is usually necessary to supplement fluorescent tubes or discharge lamps with incandescent ones supplying at least 20 % of the total energy.

No practicable arrangement of lamps can produce a radiation flux density as great as that of sunlight in the wavelength range 0.4–0.7 μm. At a distance of 40–50 cm below the centre of a lamp array with an area of several square metres, a representative value of the flux density is only 0.4 times the flux emitted by new lamps. Xenon arc lamps with an installed power of 10 kW m^{-2} give the brightest useful light (table 2), but they are very inefficient compared with other lamps.

Fluorescent tubes are more usually installed in plant growth chambers; they are relatively efficient, but not as good as high pressure discharge lamps.

Although the brightest illumination, and therefore the smallest area of crop per man, can be achieved using 10 kW xenon lamps, the inefficiency is probably intolerable and high pressure discharge lamps are more likely to be used. To give the same energy input as sunlight, in the 0.4 to 0.7 μm waveband, the artificially illuminated area will need to be $560/(350\times 2) = 0.8$ times the sunlit area (2 in the denominator allows for hours of darkness), so the artificial power installed will be $(0.8\times 3200)/(1400\times 0.8) = 2.3$ times the solar energy absorbed in a transparent enclosure. During the hours when natural light is falling on it, the lamp housing must presumably be protected from unwanted solar energy by a reflective coating. This, in turn, will make it a poor emitter of heat radiation so that nearly all the power dissipated in the lamps must be removed from the enclosure by artificial cooling.

Conclusion

The large power supply and consequent cooling load associated with conventional artificial lamps make them compare unfavourably with natural light. Unconventional methods of illumination are either too poorly understood in their physiological effects (e.g. flashing light to take advantage of photosynthetic dark reactions) or too poorly developed technically (e.g. a terrestrial source of coherent light directed at the Moon) to be taken seriously at this stage.

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