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LIGHT, PLANTS, AND POWER FOR LIFE SUPPORT ON MARS

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Regardless of how well other growing conditions are optimized, crop yields will be limited by the available light up to saturation irradiances. Considering the various factors of clouds on Earth, dust storms on Mars, thickness of atmosphere, and relative orbits, there is roughly 2/3 as much light averaged annually on Mars as on Earth. On Mars, however, crops must be grown under controlled conditions (greenhouse or growth rooms). Because there presently exists no material that can safely be pressurized, insulated, and resist hazards of puncture and deterioration to create life support systems on Mars while allowing for sufficient natural light penetration as well, artificial light will have to be supplied. If high irradiance is provided for long daily photoperiods, the growing area can be reduced by a factor of 3-4 relative to the most efficient irradiance for cereal crops such as wheat and rice, and perhaps for some other crops. Only a small penalty in required energy will be incurred by such optimization. To obtain maximum yields, crops must be chosen that can utilize high irradiances. Factors that increase ability to convert high light into increased productivity include canopy architecture, high-yield index (harvest index), and long-day or day-neutral flowering and tuberization responses. Prototype life support systems such as Bios-3 in Siberia or the Mars on Earth Project need to be undertaken to test and further refine systems and parameters.

Mars Crop yields Wheat Cereals Photosynthetic photon flux Light

RELATION OF LIGHT INPUTS AND CROP PRODUCTIVITY

General Relationships and Factors Promoting Response to Increased Light

Because formation of chemical-bond energy depends on absorbed light energy (18), crop yields are ultimately limited by the available light up to saturation irradiances. When all environmental parameters are optimized for crop growth, crop yield will be a function of photosynthetic photon flux (PPF), with variations in response curves depending on individual crops. Even with less than optimal mineral nutrients, water, carbon dioxide, temperature, humidity, and other more subtle factors, yield is still proportional to irradiance below saturation although maximum yield will be lower than when these factors are optimized. Thus, regardless of whether the other conditions for good growth are es-

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tablished, yields will always depend on the amount of light—but especially when the other conditions are optimized.

There are several factors that govern potential yield increase from increased light input in varying food crops. The first key to high crop productivity is the ability of the crop to respond to high irradiance, and this is mostly a matter of plant architecture (i.e., leaf orientation). Vertical leaves allow high irradiance from overhead to penetrate the canopy without causing damage (i.e., photooxidation) to the photosynthetic apparatus in the leaves. Horizontal leaves shade any leaves below and may themselves be damaged by high irradiances. Cereals with their nearly vertical leaves are especially well suited to high irradiances in growth chambers in which the light penetrates the canopy from directly above. Most dicot crops, including potatoes, tomatoes, legumes, and others, have horizontal leaves and are therefore less well suited to artificial light from above. Plants growing in sunlight with its changing orientation during the day are less subject to these limitations. Light from an array of overhead lamps comes from several directions simultaneously and may help in this regard. These important relationships suggest that cereals might supply the major part of caloric energy, but the absolute requirement for a varied and balanced diet, especially over long periods of time such as those that Martian explorers will experience, makes a variety of crops essential to any Martian farming scheme. Table 1 includes data on a few crops that might be grown in a Martian colony.

The second key to high crop productivity is harvest index (the percent of edible biomass to total biomass). Harvest index varies greatly depending on the crop. Legumes such as soybean often have a low harvest index (although this is not the case for the soybean in Table 1) while potatoes, sweet potatoes, and lettuce have high harvest indices. Cereals are intermediate at around 40–50%. The high harvest indices of some of the dicot crops partially make up for their inability to use high irradiances.

The third key to high crop productivity is the ability to tolerate long days, best of all, continuous light. Most crops meet this criterion, but rice and soybean require short days and long nights to flower and form seed, and potato needs short days to form tubers. Most tomato cultivars form yellow leaves at the tip and eventually succumb when days are longer than about 18 h (12). There are cultivars of these species that are more tolerant of long days than the common ones, but most of these have not been fully developed as yet for use in high-yield artificial environments.

Actually, a short-day requirement for flowering is not always a liability. By manipulating day length, yields can sometimes be greatly increased. In the field, certain soybean cultivars have a narrow range of latitude for maximum production, sometimes as narrow as 80 km. Farther south and the short days arrive before the plants have produced sufficient vegetative biomass for maximum yield, and farther north the short days come too late so that yield can be damaged by cold or frost.

Table 1. High Yields of Some Crops (Data From the 1980s)

Crop	Days to Harvest	Edible Dry Biomass (g m^2)	Harvest Index (%)	Av. Growth Rate (Edible) (g m^{-2} d^{-1})
Wheat (high average field)	120	500	45	4.2
Wheat (field world record)	140	1450	45	10.4
Wheat (Soviet Bios-3)	60	1314	?	21.9
Wheat (USU, 24-h light, 27°C)	57	1053	32.0	18.5
Wheat (USU, 24-h light, 17.5–22.5°C, 1°C week^{-}, 1200 plants m^{-2}, 1000 µmol m^{-2} s^{-1})	59	1423	44.4	24.1
Wheat (USU, 20-h light, 20°/15°C d/n, 2000 µmol m^{-2} s^{-1})	79	4760	44.1	60.3*
Potato (caged, side light, 24 h, 16°C)	147	5750	81.4	35.5
Lettuce (20-h light, 25°C)	19	545	78.0	22.3
Soybean (12-h light, 1000 µmol mol^{-1} CO_2, 26°/20°C)	90	~1000	46.0	11.1
Sweet potato (greenhouse)	120	~3000	55–70	22.4

Most of the numbers were given to F.B.S. as personal communications from colleagues working with NASA support, but the following references should provide entry into the literature of the various crops: wheat at Utah State University (5), potatoes at the University of Wisconsin (41), lettuce at Purdue University (14), soybeans at Kennedy Space Center (37), and sweet potatoes at Tuskegee University (22). Wheat grown at USU was fertilized with 1200 µmol mol^{-1} CO_2.

*Five to six times the world record!

In a controlled environment, soybean plants, for example, might be held under long day (or continuous light) until they have produced some optimum amount of vegetative plant—as much as possible without the lower leaves being shaded so much that they become an unproductive liability. Then the regime would be switched to short days, activating the flowering and seed-forming processes. Much of the stored starch and other nutrients would then be transferred to the rapidly developing seeds.

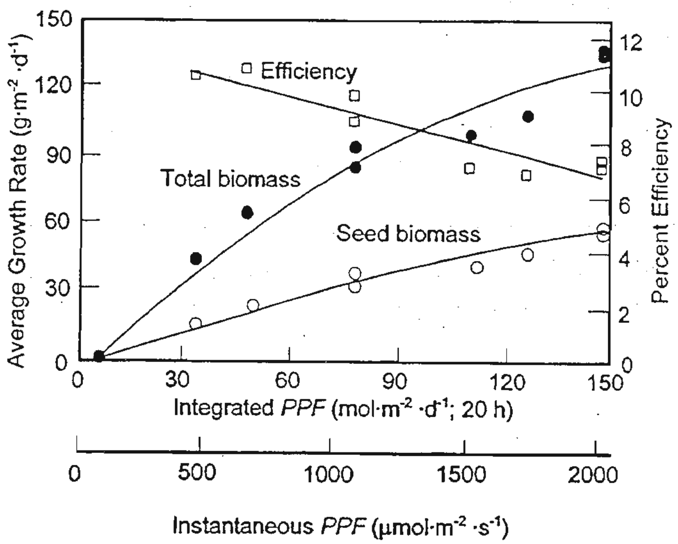

Figure 1. Total biomass, seed biomass, and photosynthetic efficiency of wheat grown under near optimal conditions (as described in the text) as a function of irradiance (photosynthetic photon flux = PPF). Average growth rate was calculated by dividing yields by the number of days from planting to harvest. Irradiance is given as integrated PPF on a daily basis and as instantaneous PPF. Efficiency was calculated as chemical bond (organic matter) energy as a percentabge of absorbed photon energy. [From Bugbee and Salisbury (5).]

Experience From NASA-Supported Research on Crops

Because the optimization of crop yield has been a priority in designing bioregenerative life support systems for space application, considerable work on examining the limits to crop productivity with high light levels was conducted within the NASA CELSS program (Controlled-Environment Life Support Systems; now called Advanced Life Support Systems) and the Russian space program during the past decades (28–30).

For example, wheat is a leading candidate grain crop for space application, and extensive research has been conducted on the limits of its productivity. The relationships between crop yield and light inputs in optimized environments for wheat are illustrated in Figure 1 (5). Wheat was grown in growth chambers with hydroponic culture including a vigorously aerated nutrient solution optimized for wheat. Carbon dioxide was at 1200 μmol mol^{-1} (equivalent to ppm), and light from high-pressure sodium lamps was varied from a relatively low level (ca. 400 μmol m^{-2} s^{-1} PPF) to the equivalent of noon-day summer sunlight with a clear sky (ca. 2000 μmol m^{-2} s^{-1} PPF). Photoperiod was 20 h so the total irradiance received by the plants was more than twice the irradiance possible from natural sunlight on Earth. The yield at the highest irradiance (60 g m^{-2} d^{-1} of edible grain) was five times the world record yield achieved in the field.

Figure 2 shows the curves for yield and efficiency from Figure 1 plus curves for the power requirement and farm size. Efficiency was calculated as chemical-bond energy (joules) in the produced biomass divided by light energy used to grow the plants. Maximum efficiency of about 11% was achieved at about 30 mol m^{-2} d^{-1} PPF (400 μmol m^{-2} s^{-1} PPF), and this efficiency approached the maximum theoretical efficiency based on what is known of the photosynthetic process. Efficiency dropped to about 8.6% as irradiance increased to 140 mol m^{-2} d^{-1} PPF. The implication for this particular example is that, for a given total yield, moving from the most efficient point to the point of near light saturation reduced the growing area by a factor of about

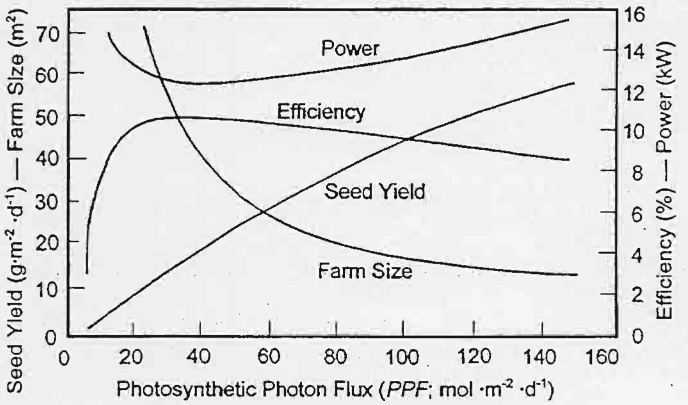

Figure 2. Seed yield and efficiency curves from Figure 1 as a function of daily PPF, with addition of curves for power requirement (correcting for loss of photosynthetic efficiency at low and high irradiance) and for farm size (estimated on the basis of wheat seed yield per meter square as a function of PPF, assuming wheat to be the sole source of calories). [Based on Bugbee and Salisbury (5); see also HortScience 26(7):827–833.]

3.6 at an energy penalty of about 22%. Bruce Bugbee and others (including one of us: D.B.) have verified the results with wheat many times. Although research with other crops has also been carried out, additional research is needed to fine-tune responses to high light intensity for the various crops that will be needed for a balanced and diverse diet.

Much NASA-supported research on crop productivity has been carried out at three NASA laboratories: Kennedy Space Center (KSC), Johnson Space Center, and NASA Ames Research Center. Various crops have been studied under a variety of conditions. [Two papers provide recent entrance into the literature reporting these studies (36,40).] KSC, for example, has a so-called Biomass Production Chamber (BPC) that provides 20 m^2 of growing area in a volume of 113 m^3 (38). This is a closed chamber in which gases emitted by plants and other sources can be allowed to build up. Lighting is provided by 96, 400-W high-pressure sodium lamps; irradiance levels depend on plant heights and specific configurations. The chamber has been continually modified since its original construction in 1988. Table 2 shows some representative results from the BPC. In general, yields are lower than those shown in Figure 1, but that may be because of crop spacing limitations and the build-up of toxic gases, especially ethylene (see discussion below). Yields may be quite representative of those that could be expected in a Martian crop facility.

Russian Bios-3 Crop Response Experience

Russian scientists in Krasnoyarsk built a prototype of a closed system called Bios-3 in 1972 (29). Growing plants (both algae and higher plants; finally only higher plants) regenerated the atmosphere by photosynthetically removing CO_2 and adding oxygen, simultaneously producing food for the crew. The structure consisted of a rectangular volume (14 × 9 × 2.5 m = 315 m^3) divided into four compartments, one for crew quarters (including controls, kitchen, small laboratory, etc.) and three for growing plants (29). The 63 m^2 of bench space for crops was irradiated with 6-kW xenon lamps, 20 in each of the three crop compartments for a total of 60 lamps using 360 kW of electrical power. Lamps were on continuously. Thus, 8640 kW h d^{-1} ((24 h d^{-1} × 360 kW) of power (energy = 31,104 MJ d^{-1}) was required just to provide light for plant growth. Large amounts of power (figures not known to us) were also required to operate the cooling system and other equipment.

Table 2. Productivities of Some Crops Grown in NASA's Biomass Production Chamber at Kennedy Space Center

Crop	Daily PPF (mol m^{-2} d^{-1})	Total Biomass (g m^{-2} d^{-1})	Edible Biomass (g m^{-2} d^{-1})
Wheat	57.5	31.6	12.6
Soybean	36.9	15.7	6.0
Potato	42.2	27.2	18.4
Lettuce	16.8	7.7	7.1
Tomato	38.6	19.6	9.8

Data from Wheeler et al. (40); see also (37,41).

The xenon lamps were placed vertically in glass water jackets to remove much of the infrared energy produced by such lamps. (Xenon lamps, while producing a spectrum much like sunlight—plus sharp peaks in the near infrared—are not as efficient as high-pressure sodium or metal halide lamps.) Irradiance at the plant level varied from ca. 900 to 1000 μmol m^{-2} s^{-1} PPF. This was measured by one of us (F.B.S.) during a visit to Bios-3 in 1992. By then, two xenon lamps had been placed in each water jacket in one growth room, and irradiances were ca. 1300–1600 μmol m^{-2} s^{-1} PPF; irradiances of 1600–2450 μmol m^{-2} s^{-1} PPF could be achieved by adjusting the voltage, but the cooling system for that room was incapable of removing the generated heat; temperatures remained at or above 27°C, too warm for high wheat yields. The light levels used during the final experiment in Bios-3 (i.e., ca. 1000 μmol m^{-2} s^{-1} PPF instantaneous) provided ca. 85 mol m^{-2} d^{-1} PPF on a daily basis.

Three long-term experiments were carried out with crew members sealed inside. The final experiment with two crew members ran 5 months from November 1983 to April 1984. Some 34.6 m^2 of bench space was allocated to wheat, which produced about 12.5 g m^{-2} d^{-1} of grain, below the expected yield based on Figure 1 but close to previous Russian (29) and KSC (Table 2) yield experience. Eleven other crops were grown: chufa (*Cyperus esculentus*, a sedge that produces a tuber high in oil), pea, carrot, radish, beet, kohlrabi, onion, dill, and cucumber; but potato and tomato yielded virtually nothing in the continuous light. The crop harvests during the 5 months provided about 80% of the crew's caloric needs; the other 20% consisted of meat products (mostly in dried form) stored at the beginning of the experiment or passed into the crew through a small airlock.

During the visit in 1992 to Krasnoyarsk, F.B.S. was shown a small chamber that utilized xenon lamps and a water filter, in which irradiances above 3000 μmol m^{-2} s^{-1} PPF were used to grow wheat. Yields slightly exceeded those obtained at Utah State University at 2000 μmol m^{-2} s^{-1} PPF (5), but efficiencies were considerably reduced as predicted by Figure 2.

Biosphere 2 Experimental Data

Biosphere 2 provides additional evidence of the importance of crop response to light (1). The amount of light actually received by crops in the Biosphere 2 agricultural zone was reduced by 50–60% because of transmission losses through the double-laminated glass and shading from the space frame and other structural elements (9,20). In addition, seasonal variation was high, with summer external light levels of 65–70 mol m^{-2} d^{-1} PPF being over 2.5 times greater than winter light levels. Internal light in the Biosphere 2 cropping area was at maximum 25–30 mol m^{-2} d^{-1} during the height of summer, and fell to an average of 10–15 mol m^{-2} d^{-1} during the short days of winter. Indeed, the total amount of sunlight reaching the Biosphere 2 agricultural crops was comparable to that received in tropical lowlands with high cloud cover (13).

During the first closure experiment from 1991 to 1993, during which some 80% of food for the eight-person crew was grown inside (1,2), there was a marked response in crop yields depending on light received during their growing season (31). A wheat crop grown with total light of 679 mol m^{-2} PPF yielded only 40 g m^{-2}, while a crop grown with 2022 mol m^{-2} PPF (nearly three times as much light) yielded 240 g m^{-2} or six times as much grain. Experience gained from Biosphere 2's initial closure experiment led to improvements in the agricultural system and helped make possible the increased yields and total food sufficiency achieved in the second human closure experiment (March to September 1994) (20). Learning which crops did well in shady portions of the agricultural area (e.g., taro and papaya grown for green vegetable use) led to a search for more shade-tolerant cultivars for use in the second closure. Increased knowledge was gained of the optimal seasonal timing of planting of the various Biosphere 2 food crops. In addition, of course, the fact that the second closure occurred during the higher light period of the year was a benefit to food production.

Lower light affected other bioregenerative life support systems in Biosphere 2 as well. The wastewater recycling system was a constructed wetland treatment system. The wetland plants were periodically harvested for fodder for domestic animals. This system's performance also reflected seasonal changes in productivity. During the lower-light months, biomass production in the constructed wetland was about 50% lower than in high-light months during the first closure experiment (25).

Other variables also affected crop productivity in Biosphere 2. These include elevated carbon dioxide concentrations (CO_2 ranged as high as 4000 μmol mol^{-1} in winter months), decreased oxygen during much of the first closure mission (declining to about 14% after 16 months), the ratio of direct to diffuse light above the canopy, absence of wind pollination, etc. (24,31). In light of the relationships presented in Figures 1 and 2 on the tradeoffs between light intensity and overall efficiency, it was found, as might have been expected, that Biosphere 2's overall biomass production relative to the received radiation (Radiation Use Efficiency) was less than had been achieved in some NASA supported research but above values attained under field conditions (35).

The Importance of Other Factors in Crop Yields and Performance

During 1995 and 1996 a team of investigators, including two of the authors (F.B.S. & D.B.). from Utah State University, NASA, and the Institute of Biomedical Sciences in Moscow grew the Super Dwarf cultivar of wheat on the Russian Space Station Mir (27). With ample light (ca. 400 μmol m^{-2} s^{-1} PPF, 24 h/day) the wheat grew exceptionally well, and about 280 heads were formed in an area of 0.1 m^2. However, all of the heads were sterile; not a single seed was formed. It is well known that ethylene can cause male sterility in cereals, including wheat [see (6)], and samples of the Mir atmosphere contained ethylene at 1.1–1.7 μmol mol^{-1} (ethylene/air). There were several possible sources for the ethylene, but numerous fungi growing in Mir were the most likely source (6).

Seedless wheat on Mir was caused by ethylene and not microgravity (6). Indeed, using Apogee wheat, which is less sensitive to ethylene than Super Dwarf, further experiments have now obtained a limited number of seeds in Mir, and those seeds have been carried through two generations (19). An important conclusion of these experiences is that there are many factors to consider, any one of which can lead to unexpected crop performance. Although it was well known that ethylene could cause problems, the seriousness of the problem was unanticipated.

There may be other factors that may be manipulated in Mars greenhouses to enhance crop yield. For example, atmospheric oxygen levels lower than the 21% in Earth's atmosphere diminish photorespiration and lead to higher crop productivity (18). As noted above, in the 1991–1993 closure experiment in Biosphere 2, oxygen levels dropped to 14.2%. This caused problems for the human occupants, but the humans did fine at oxygen levels down to 17% (1,2). At Utah State University, carbon dioxide levels up to ca. 0.12% CO_2 enhanced wheat yields, but levels from 0.26% to 1.00% decreased seed yields as much as 37%, although there was no decrease in total biomass production (11,26). Much additional work on responses of other food crops to high CO_2 remains to be done. The impacts of the lower gravitational field on Mars and the use of reduced atmospheric pressure within the plant growth modules are factors that are still virtually unknown in their possible positive or negative impacts on crop productivity.

It is also worth underlining that, in a bioregenerative life support system, it is not the plants that are the weakest link; rather, it is the mechanical equipment that is most likely to break down [e.g., (29)]. Plants can regenerate (reproduce) themselves after a crop failure, but machinery has no such ability; broken machinery must usually be repaired by living organisms (the crew members), using suitable tools and spare parts, all of which must be carried along on the mission.

Plans for "Mars on Earth" Ground-Based Test Facility

Steps are under way by several authors of this article to initiate a project called Mars On Earth (MOE) to design and develop a closed-system laboratory to test a total system approach to life support that will address many of the complex issues outlined in this article. MOE is an Earth-based simulation of a manned mission to Mars. Phase 1 of the project includes the design, construction, and operation of a prototype life support base—the Mars Base Modular Biosphere—that will support a crew of four people. This closed life support system will provide a test-bed for developing space-based life support systems, such as water and wastewater recycling, food production, air purification, etc., that will be needed for long-term life support on Mars (32).

The impact of a strategy of increasing light to significantly boost crop yields and reduce plant crop area required to supply a complete and diverse diet for four people is shown by calculations made for the Mars on Earth Biosphere Module. The diet is based on 3000 kcal $person^{-1}$ d^{-1}, providing at least 60 g of protein $person^{-1}$ d^{-1}, and 36 g of fat $person^{-1}$ d^{-1}. Preliminary sizing for the growing area needed to support four people with 50 mol m^{-2} d^{-1} PPF is 445 m^2, and with additional area for pathways/access plus leafy vegetables and citrus crops for additional variety in the diet, total area is increased to 525 m^2 (Table 3). Crop yields are based on extrapolations of potential yield increases from the best Biosphere 2 results during the 1991–1993 mission at 16–25 mol m^{-2} d^{-1} PPF (31). These extrapolations are conservative because the projected yields are considerably less than the potential yields shown in Figure 2 for light intensity at 50 mol m^{-2} d^{-1} PPF. Results from the Mars on Earth facility will be important in demonstrating what yields can be reliably obtained for the wider variety of crops required for complete nutrition, and in larger areas, than have been studied for space life support systems to date. The facility will also lend itself to experiments with differing light levels, once it is found which photoperiods and intensities are most effective for each of the crops producing a diverse, complete diet. [Based on the controlled environment and BPC studies noted above, NASA estimates that only 40–50 m^2 $person^{-1}$ should support one crew member if plants are irradiated with 30–50 mol m^{-2} d^{-1} PPF (38–40).]

USE OF INCIDENT SUNLIGHT ON MARS

Availability of Sunlight for Crops on Mars

Much is known about the environment of Mars (7). Because of Mars' highly elliptical orbit (207 × 10^6 km from the sun at perihelion; 249 × 10^6 km at aphelion), sunlight above the Martian atmosphere varies from 37% to 52% of the average irradiance above Earth's atmosphere (by the inverse square law; Earth at average 150 × 10^6 km). The atmosphere of Mars is very thin compared with that of Earth (less than 0.1% of atmospheric pressure on Earth) so light reaching the surface is attenuated less than is that reaching Earth's surface even without clouds. Thus, irradiance levels are higher

Table 3. Design Calculations for a Mars Base Modular Biosphere Facility; Diet and Agricultural Crop Areas; Scenario With 50 mol m^{-2} d^{-1}; 3000 kcal person^{-1} d^{-1}

Crop	Energy Required for Crew of 4 (kcal d^{-1})	Best Yield in Biosphere 2* (g m^{-2} d^{-1})	Light Level Biosphere 2 (mol m^{-2} d^{-1})	Yield Correction for 50 (mol m^{-2} d^{-1})	Estimated Yield at 50 mol m^{-2} d^{-1} (g m^{-2} d^{-1})	Energy Content* (kcal g^{-1})	Extrapolated Yield (kcal m^{-2} d^{-1})	Area Required to Feed Crew of 4 (m^{2})
Wheat	1,200	2.44	16	3	7.32	3.33	24.4	49.2
Rice	1,800	5.71	25	2	11.42	3.55	40.5	44.4
Sweet potato	3,000	16.0	25	2	32.0	1.06	33.9	88.5
Peanut	600	1.40	25	2	2.80	5.84	16.4	36.6
Soybean	600	1.32	25	2	2.64	4.03	10.6	56.6
Pinto bean	1,200	3.71	25	2	7.42	3.41	25.3	47.4
Beet (root)	900	23.2	25	2	46.4	0.44	20.4	44.1
Winter squash	900	42.5	25	2	85.0	0.64	54.4	16.5
Banana	1,200	49.8	25	1	49.8	0.59	29.4	40.8
Papaya	600	108.0	25	1	108.0	0.26	28.1	21.4
Totals	12,000							445.5

*The yields for Biosphere 2 are given as fresh mass. Thus, energy content is also based on fresh mass.

than the percentages suggest (see calculations below), but the down side is that the lack of an ozone layer in the Martian atmosphere permits harmful ultraviolet rays to strike the Martian surface much more than the surface of Earth. Dust storms and persistent atmospheric dust on Mars reduce the light levels reaching the surface, but clouds also reduce light reaching crops on Earth. We roughly characterize the light available on Mars as two thirds of that on Earth based on analysis from the papers of Appelbaum et al. (3,4) discussed in greater detail below.

Day length on Mars is 24.7 h, which means about 12.35 h of light at the Martian equator with varying durations everywhere else. The equator of Mars is tipped to the plane of the ecliptic 25°, about the same as is Earth's equator (23.5°), so Mars has seasons similar to those on Earth although the Martian year is 687 Earth days long.

Problems With Direct Use of Mars Sunlight

There are serious problems, however, in using sunlight on Mars for growth of crops. Because of the thin atmosphere and Mars' distance from the sun, temperatures drop as low as –100°C during the Martian night and reach a maximum of only about 20°C at the surface during a summer day. Because of the extremely low atmospheric pressure and extreme cold on Mars, crops cannot be grown except in protective enclosures. Multiple requirements for the enclosure seem to preclude the possibility that it could be highly transparent or translucent as would be required to directly use Martian sunlight for plant growth as in a greenhouse.

- Containing a viable atmospheric pressure requires high strength, and the severe consequences of even a tiny leak for loss of atmosphere dictates a very tough and robust envelope, which contradicts the relatively delicate nature of a highly translucent enclosure. This concern is discussed in detail in Dempster (10).
- Insulation against the extreme cold could be achieved by use of a foam layer many centimeters thick, multiple material layers, reflective metallic films and the like, all of which are incompatible with high light transmission. Even if it were decided to simply heat a thin uninsulated enclosure enough to overcome heat losses to the outside (at enormous energy cost), the moist interior atmosphere from evapotranspiration would result in condensation and thick ice formation on the extremely cold interior surface, which would obscure light transmission.
- The enclosure would have to resist ultraviolet degradation and abrasion from windblown dust without impaired translucency, and high-energy, ionizing radiation would require even more shielding—not likely to be transparent.

Another concept—the use of moveable insulation for nighttime—assumes that nearly all daylight hours are warm enough to not require the insulation. If a sunlit greenhouse also needs supplementary artificial light then the system for obtaining natural light (e.g., moveable insulation) is required in addition to the artificial light system. This increases mission complexity by an additional system compared with only using artificial light. Although avenues of research are being followed to achieve suitable Martian greenhouses, the problems outlined above are clearly very serious. These problems were discussed in a symposium at the Kennedy Space Center near the end of 1999 (39).

Another reason to use growth rooms rather than greenhouses on Mars is that, as discussed above, it is possible to greatly increase yields of many crop plants by increasing irradiance levels and durations well beyond those that are naturally available on Mars or Earth. This translates into much smaller crop-growing areas but a requirement for power and the complexities of artificial lighting. The final area allocations require data on how specific crops respond to irradiance levels. The following calculation outlines the magnitude of the power required and the size of a photovoltaic array to provide that power. The calculation utilizes available information on levels of sunlight on Mars, assumes an equatorial location, and averages for a full Martian year.

Use of Photovoltaic Cells as the Source of Power for Crop Growth on Mars

A mathematical model of available solar radiation on the surface of Mars was developed by Appelbaum et al. (3) based on consideration of Mars' varying orbital distance from the sun, measurements taken by the Viking Landers, and observations relating to dust storms both from Earth and from Viking Orbiter. The maximum annual average radiation is available at or near the Martian equator and is approximately 3 kWh m^{-2} d^{-1} on a horizontal surface. For comparison, the average horizontal surface radiation for 38 selected cities distributed over the United States is about 4.5 kWh m^{-2} d^{-1} including cloud effects (21).

It is highly significant from a solar energy design viewpoint that atmospheric dust on Mars both obscures and diffuses sunlight severely during dust storms, which may be local or global and which may last for many weeks. The model of solar radiation (3) includes a dust storm with a period of about 40 days during which the horizontal radiation falls to about 1.2 kWh m^{-2} d^{-1}, and only about 0.1 kWh m^{-2} d^{-1} is direct beam radiation, the dominant fraction being diffuse. A solar energy collection system that depends on focusing direct beam radiation would be reduced to about 3% of annual average output during such a storm. This argues strongly for flat solar energy-collecting systems in preference to focusing systems.

Study of the tables in Menicucci et al. (21) for Earth-based solar tracking surfaces in areas with predominantly clear skies (e.g., the southwestern US) shows that tracking on Earth may increase intercepted insolation, depending on season, by a factor of 1.3 to 2.2 relative to strictly horizontal collection, but the penalty is the structure and mechanism for mounting the collection surface at an angle with tracking capability. The tracking structure must have enough rigidity to resist wind forces. The value of tracking collectors on Mars is also greatly compromised by extended periods of diffuse radiation associated with dust in the atmosphere. In contrast, a horizontal collector conceivably could consist of a thin film rolled out on the ground, although obscuration by deposited dust is a concern (4,15–17). For example, Landis (15,16) and Landis and Jenkins (17) give both theoretical and Pathfinder results that dust deposition degrades solar collector performance on the order of 0.3% per sol (Martian day) without some means of cleaning. We suggest that it will save launch mass, cost, and maintenance and reduce mission complexity to simply increase the flat horizontal collector area as necessary in preference to any solar tracking arrangement on the surface of Mars. For all the above reasons we use a nonfocusing stationary horizontal solar collection system at the equator as our baseline reference for the following discussion.

The full analysis of equatorial sunlight conditions on Mars derived from the model (3) for this purpose is too lengthy to be included here but is available from one of the authors (W.F.D.) on request. The relevant results for a flat horizontal solar collector at the equator are:

- Annual average insolation at the equator is about 3 kWh m^{-2} d^{-1}.
- Insolation on an ordinary very bright day (a typical clear day during seasons when dust storms are improbable) will be 4 kWh m^{-2} d^{-1} with noon peak irradiance of 485 W m^{-2}.
- The brightest day (clear sky when Mars is closest to the sun; exceptional because dust storms tend to occur at this orbital position) has noon peak irra-

diance of 623 W m^{-2} and total insolation of 5.136 kWh m^{-2} d^{-1}.

As on Earth, insolation varies hourly with the sun's zenith angle. This further implies that if a plant-growth artificial lighting system is powered by a photovoltaic solar array, the lights can only remain on during sunlight hours unless an energy storage system is also included. The intensity of the artificial lighting system could be made to track the available power by turning on and off numbers of lamps, thereby using all the available power. A dimming arrangement may not be technically feasible and could also result in undesirable shifts in the spectrum of the lights. To assure full use of the available power through these variations, the solar array and the associated lighting system need to be large enough to give the crop at least enough photosynthetically active radiation (PAR) averaged annually to produce the required food while not wasting capacity (light not exceeding photosynthetic saturation) at the peak bright moments of the year. Completely satisfying both extremes with one fixed solar array may not be achievable.

We have now established the framework to design a complete lighting system without energy storage, which simply follows the available solar power on a horizontal solar collector. The following assumptions underlie this concept.

- Available electrical power will be proportional to irradiance on the solar collector.
- Plant lighting intensity can be made to proportionally follow available electrical power by some method.
- Edible biomass production is proportional to light level. The growing area and lighting intensity will be designed to yield adequate food supply for the Mars base on an annual average basis.

While these assumptions may seem restrictive and speculative, we emphasize that we are calculating the best case minimum solar array size for reference purposes. Insofar as the above assumptions are inaccurate, the required solar array size will increase.

High-pressure sodium (HPS) lamps will be considered here as the baseline reference technology for converting electrical energy to PAR. HPS is the most efficacious except for low-pressure sodium (LPS), which is about 10% more, but LPS does not have as suitable a spectrum and would require more supplementation with a blue weighted light source.

To arbitrarily set some parameters to create a scenario: Assume that the annual average lighting needed for adequate crop production is 50 mol m^{-2} d^{-1} PPF (enough for many crops without oversaturation; see Fig. 2) applied to a growing area of 445 m^2 (as to support a four-person Mars base per Table 2) plus 5% spillage allowed for edge effects for a total of 467.3 m^2. Further assume that the photovoltaic array converts the collected solar insolation to usable electrical energy at 10% total system efficiency, that HPS lamps convert electrical energy to light energy at 26% efficiency (34), that fixture efficiency can be designed at 85% (the fraction of emitted light that is directed to the plants), and that HPS light converts to PPF at 4.98 μmol s^{-1} W^{-1} (34). We then have $0.10 \times 0.26 \times 0.85 \times 4.98 = 0.11$ μmol s^{-1} W^{-1} of solar irradiance on the solar collector, which, multiplying by 3600 s h^{-1}, is 396 μmol per collector watt-hour or 0.396 mol kWh^{-1}. We explicitly show the contributing factors to facilitate modification of these calculations as research and technology evolve in the future. Following is a summary for this scenario.

- Total PAR required: 50 mol m^{-2} d^{-1} × 467.3 m^2 = 23,363 mol d^{-1} (average).
- Total solar energy kWh to be collected: 23,363/0.396 = 58,996 kWh d^{-1} (average).
- Collector area: 58,996/3 = 19,665 m^2 (1.97 hectare) based on 3 kWh m^{-2} d^{-1}.
- Dark dust storm day: PPF becomes 20 mol m^{-2} d^{-1} due to 1.2 kWh m^{-2} d^{-1} solar insolation (50 mol m^{-2} d^{-1} × 1.2/3.0).
- Ordinary very bright day: PPF becomes 4/3 × 50 = 66.7 mol m^{-2} d^{-1}. Peak instantaneous PPF on plants = 19,665 × 485 × 0.11/467.3 = 2246 μmol m^{-2} s^{-1}, which is comparable to clear-day noon sun on Earth at about 2000 μmol m^{-2} s^{-1} (Bruce Bugbee, personal communication). Full utilization of PPF by plants begins to lose efficiency above 600 μmol m^{-2} s^{-1} (see Fig. 2).
- The brightest day: PPF becomes 5.136/3 × 50 = 85.6 mol m^{-2} d^{-1}. Peak PPF on plants = 19,665 623 × 0.11/467.3 = 2884 μmol m^{-2} s^{-1} or about 1.4 × clear day noon sun on Earth. If such days occur, they will be infrequent due to prevalence of dust storms when Mars is closest to the sun. If this intensity is harmful, some lights can be turned off. Getting an annual average of

50 mol m^{-2} d^{-1} does not depend on any days brighter than an ordinary very bright day.

The above scenario offers advantages over others that would require storage of collected solar energy.

- Any system for storing and retrieving energy incurs efficiency losses. For example, electrolyzing water to hydrogen/oxygen, storing the gases, and then recovering electric power through a hydrogen/oxygen fuel cell might only return 40–50% of the original energy. Whatever fraction of the collected energy is ultimately used from the storage system will require a collection area roughly double the area for the same energy if used directly. Although photosynthetic efficiency to convert light energy to plant biomass is reduced at high irradiance levels (Fig. 2), it is probably still more efficient than storage and recovery of electrical energy.
- The energy storage system itself is a technological system imposing launch mass, cost, and maintenance. Its failure could be life threatening.
- Plant biomass grown by direct energy is the actual storage system for that energy. Plant biomass returns 100% of its stored energy as plant biomass. Preservation on Mars is as simple as keeping it frozen, which is trivial given the cold temperature resource on the Martian surface.

This gives new meaning to the old saying "make hay while the sun shines."

Alternate Scenarios

There are several lamp types other than HPS that may be considered for plant growth lighting. A comparative table for fluorescent, LPS, HPS, metal halide, microwave, and LED lamps and additional discussion can be found in Ciolkosz et al. (8) and Tubiello et al. (33). Considering all the issues including spectrum, however, none of the different lamp types appear likely to offer a substantial reduction in the electrical power requirement from that of HPS.

If an unvarying power source, such as nuclear power, were employed to deliver 50 mol m^{-2} d^{-1}, the total light could be delivered at constant intensity over a long day, say 18 h. This alternate scenario would call for 771.6 $\mu mol\ m^{-2}\ s^{-1} \times 467.3\ m^2 = 360{,}532\ \mu mol\ s^{-1}$. The solar collector to electric power efficiency of 10% is no longer in the sequence, so we calculate only the conversion from electric power to $\mu mol\ s^{-1}$ as $0.26 \times 0.85 \times 4.98 = 1.1$ $\mu mol\ s^{-1}$ for each watt of power supplied. The power requirement is 360,532/1.1 = 327,584 W or 328 kW. This also offers the benefit of plant growth near maximum photosynthetic efficiency by avoiding less efficient high PPF peaks.

Experiments have been done with optical fibers piping sunlight directly to growing plants (23). The observed light transmission efficiency was 32%, and it was suggested that in future development 65% may be reached. By comparison, the conversion of Mars sunlight to artificial light via flat-plate photovoltaic panels powering HPS lamps as described above might be only 2.2% (10% × 26% × 85%). The improvement by a factor of 15 to 30 times is striking. However, there are some inherent drawbacks. Tracking focusing collectors are required with the attendant need to brace upright parabolic collectors against wind, the complexity and potential failures of tracking mechanisms, plus launch volume and mass of the equipment. Another serious consideration is that the area of focusing collectors would have to be 1.5 to 3 times as large as the area utilized for plant growth to achieve irradiances for the plants roughly equivalent to outside irradiances. Perhaps the most serious obstacle is the extended periods of diffuse Martian sunlight during dust storms, which may reduce direct beam irradiance to the order of 3% of clear-sky direct beam as previously noted. Diffuse sunlight would not be collectable by the focusing system.

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