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Effects on Biological Systems of Reflected Light from a Satellite Power System

April 1981

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PREFACE

In 1968 Dr. Peter Glaser proposed a solar photovoltaic satellite for the generation of electric power to be used on earth. Since that time, this system has been developed and refined by the National Aeronautics and Space Administration (NASA) and by various contractors. In 1977 a Satellite Power System (SPS) Concept Development and Evaluation Program Plan (DOE/ET-0034, February 1978) was developed jointly by NASA and the Department of Energy (DOE). As a part of this plan, NASA, with the assistance of contractors, developed a preliminary reference system (Satellite Power System Concept Development and Evaluation Program, Reference System Report, DOE/ER-0023, October 1978), for use in assessment and feasibility studies. The DOE has responsibility for coordinating assessments of SPS, including those of effects on the environment.

One of the questions with respect to environmental effects of SPS has been whether reflected light from spacecraft and space structures could have undesirable effects on the human eye, plants or animals. SPS manufacture and operation would involve the construction of a staging base in low earth orbit (LEO) and of a construction base and satellites in geosynchronous orbit (GEO). Personnel and materials would be transported to LEO by personnel launch vehicles (PLV) and heavy-lift launch vehicles (HHLV), respectively. Then they would be transported to GEO by orbital transfer vehicles (OTV) which would be built at LEO. All the vehicles, the construction bases, and the satellites would have elements which might reflect sunlight to earth.

SUMMARY

The proposed Satellite Power System, (SPS) would put structures in space which would reflect light to earth. A report on the characteristics of this light was prepared by scientist at the Boeing Company. This report was used as the basis for studies of the possible effects of that light on the human eye, on plants and on animals.

For the human eye two of the "worst cases" of reflected light, which could occur, might cause eye damage if viewed for too long.

1. If, while in low earth orbit, the orbital transfer vehicle were misaligned to reflect the sun to earth there would be a maximum safe fixation time for the naked eye of 42.5 seconds. If tracked by hand-held binoculars or a small telescope the maximum safe fixation time could be reduced to as little as 0.84 seconds.
2. Reflection from the aluminum paint on the back of the orbital transfer vehicle, while in or near low earth orbit, could be safely viewed by the naked eye for a maximum of 129 seconds. With 7 power magnification the maximum safe viewing time would be only 2.5 seconds.

In the other cases presented in the Boeing Report there appears to be no danger of damage to the human eye.

For plants and animals, though in-depths studies of some species might indicate some problems, the tentative conclusions are that the intensity and timing of the light would be such that major problems would not be expected.

The Boeing Report proposes ways for reducing and/or eliminating the irradiances. These proposed design changes may increase cost and slightly reduce the efficiency of SPS but they do indicate that steps can be taken to ameliorate the reflected light problem. If such changes could be made, the possibility of reflected light impacts on biological systems would be much reduced or eliminated entirely.

CHARACTERIZATION OF SPS REFLECTED LIGHT - BOEING STUDY

The first step in determining the environmental effects of the reflected light was the characterization of thelight based on the preliminary reference system. This was done by scientists at the Boeing Company in Seattle and reported in "Satellite Power System Brightness Due to Reflected Light", DOE/ER-0081.

Some findings of the Boeing Study are abstracted below. For details of methodology, etc., see the complete report.

The development and operation of a Satellite Power System would place very large structures in orbit around earth for several decades. Sunlight reflected off such structures, particularly specular components from large flat areas, would be expected to create ground illumination that would attract observers. In order to assure that this illumination would not exceed the irradiance tolerances of the eye, reflections from these satellites would need to be carefully controlled by vehicle orientation and surface specifications.

The solar power satellites (SPS) at geosynchronous earth orbit (GEO) would have 55 km^2 of glass-covered solar cells that were oriented normal to the sun, as well as a 1 km^2 microwave antenna. Transportation of construction materials from low earth orbit)LEO to GEO would require Orbit Transfer Vehicles (OTV's) that had 1.6 km^2 solar panels oriented normal to the sun during their 6-month transits. The Staging Base (SB) at LEO, which would accommodate OTV fabrication and cargo transfer, would consist of 0.5 km arms protruding from a .44 km^2 open grid aligned with its orbit plane. Diffuse reflections would make the SB/OTV's readily discernible in the daytime and the OTV's and SPS's observable all night (except during eclipse). Sporadic specular glints would appear on the ground from the OTV's and SPS's near the midnight meridian, from the solar panel surfaces of OTV's during LEO fabrication around midday, and from OTV's near LEO at dawn and dusk.

The ground illumination from sunlight reflections off the Space Power System spacecraft was evaluated from the Preliminary Reference System. A variety of configurations, orientations, and operational conditions were considered in this analysis. Because of the expectation that these vehicles

Table 1.

Summary of Ground Irradiance

Case		Condition	Midday M Dawn/Dusk D Night N	Range km	Irradiance W/m^2
Controlled Orientation - Worst Case Geometry					
Diffuse	1	OTV/SB in LEO	M	910	2.4×10^{-5}
	2	SPS in GEO	N	35,700	8×10^{-7}
	3	OTV Powered Near Leo	D	2,570	4×10^{-6}
	4	OTV at 2 R_e	D	11,000	2×10^{-7}
		4 R_e	N	24,700	5×10^{-8}
Specular	1	OTV/SB in LEO around solstices	M	910	
		flat front solar panels			1.2
		flat back aluminum			19
		misaligned front (1.5°)			0.1
		misaligned back (1.5°)			2
	2	SPS Solar panel in GEO around equinoxes	N	35,700	
		flat surface			0.03
		misaligned surface (5°)			0.0003
	3	SPS antenna in GEO around equinoxes	N	36,000	0.01
	4	OTV Powered Near LEO	D	2,570	0.19
	5	OTV at 2 R_e	D	11,999	0.01
		4 R_e	N	24,700	0.002
Out of Control Orientation - Worst Case Geometry					
Specular	6	OTV in LEO	D	500	56
	7	SPS in GEO	N	36,000	0.4
		flat back aluminum			

would be viewed by many ground observers, those conditions that were thought to produce the brightness ground irradiance were selected for evaluation. For the most part, only normal operations with controlled orientations were assumed; however, two out-of-control abnormal orientations were also treated. A summary of ground irradiance levels that have been calculated is rpesented in the table.

The large size of the Space Power System elements would cause even diffuse reflections to appear as very bright light source. As presently designed, vehicles would be held together by beams, painted with highly reflective material. However, the dominant surfaces for reflected light would be the solar panels of the OTV and SPS. These areas would consist of highly specular, low reflectivity cover glass over dark absorbing cells on the front side and shiny aluminized plastic dielectric on the back. Consequently, most of the reflected light would be very directional; diffuse reflections would be proportionately much dimmer due to a lack of large diffuse surfaces.

The diffuse cases summarized in the table would all be relatively bright in comparison with stellar sources. For example, the SPS in GEO would be comparable to the stellar magnitude of Venus at its brightest. The OTV/SB combination in LEO would be visible during daylight hours but, of course, would be at too low an altitude to be illuminated at night.

The specular cases cited in the table would produce much brighter ground illumination. However, this irradiance would be restricted to small, fast moving spots. The actual duration of these "glints" of specular reflections varies from about one second for the OTV/SB in LEO to two minutes for the SPS antenna. An important consideration would be the sudden onset of the specular irradiance compared to the much dimmer diffuse irradiance. Enhancements of 10^5 are common. An exceptionally bright specular reflection would be produced by the backside of the OTV solar panels during LEO construction. Although perfectly flat solar panel surfaces were assumed as worst cases for the OTV and SPS, more realistic situations would be represented by the curved or misaligned surfaces that was also analyzed.

The truly abnormal conditions that out-of-control vehicles would create were also cited for completeness. There would undoubtedly be many safeguards in the orbit mechanics to prevent such an occurrence.

It is noteworthy that, at most, the enhancement would be only threefold in LEO and 15-fold in GEO beyond normal controlled operations.

Some perspective on the relative importance of these irradiance levels can be derived by a comparison with the solar irradiance. Insolation is about 1400 W/m^2, substantially greater than any of the reflections. However, the sun is an extended source subtending 32 arc minutes; whereas, the OTV in LEO subtends 11 arc minutes (500 km altitude) at the most, and well beyond LEO both OTV and SPS subtend less than one arc minute, the resolution of the eye. Thus, the power density in this direct solar image would be as much as 10-fold less than that for the OTV in LEO, and 1000-fold less than the OTV and SPS in GEO.

Apparent stellar magnitude provides another useful basis for comparison. Using the sun as the standard, the formula for the visual magnitude of a light source is given by

$$m = -26.7 - 2.5 \log_{10} [H(W/m^2)/1400]$$

where H is the ground irradiance. Thus, for example, diffuse reflection from SPS in GEO (D2) would have an apparent magnitude of -3.6, and specular reflection from the SPS antenna in GEO (S3) would have a magnitude of -13.8, comparable to the full moon.

The methodology for calculating sky brightness created by a diffuse source is also presented. This calculation requires elaborate tabular entries. The sky irradiance for a typical set of observation directions, displaced a reasonable angular distance away from the source, is on the order of 1% of the direct irradiance from the source. The sky brightness for other observation conditions would be evaluated on a case-by-case basis using the tables in the report.

These worst case irradiances might be reduced significantly and perhaps eliminated by appropriate modifications to the design and/or operation of the spacecraft. By slight changes in the vehicle orientation, the specular reflections from the large solar panels could be directed away from the earth. Another modification might be to introduce surface curvature or misalignment of flat panels that would diverge the specular beams. Finally, the specular surface quality of other structures might be eliminated (or sharply reduced) by etching or coating the materials to create a diffuse reflection.

BIOLOGICAL STUDIES ON THE EFFECTS OF REFLECTED LIGHT

When the Boeing Study was completed, persons with expertise in the biological effects of light were asked to report in the possible biological effects of reflected light from SPS. These studies were done using the information in the Boeing Study and current knowledge of light effects on biological systems. These reports follow.

EVALUATION OF EYE HAZARDS FROM THE SATELLITE POWER SYSTEM

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EVALUATION OF EYE HAZARDS FROM THE SATELLITE POWER SYSTEM

by

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1.0 Summary and Recommendations

A worst case analysis of the maximum safe viewing time from earth of elements of the Space Power System has been made. The results for the three worst-case elements based on the three highest illuminance values from the Boeing Co. analysis (14), are as follows:

(1) The Orbital Transfer Vehicle misaligned to reflect the sun to earth while in Lower Earth Orbit allows 42.5 seconds of safe fixation time. This could be reduced to as little as .84 seconds if it were tracked by hand held binoculars or a small telescope.

(2) The aluminum paint on the back of the Orbital Transfer Vehicle while in or near the Lower Earth Orbit reflects enough sunlight in normal operation to allow 129. seconds of safe viewing time, which would decrease to 2.52 seconds with 7 power magnification.

(3) The third highest irradiance on earth is from the Solar Power Satellite in Geosynchronous Orbit, where its orientation is assumed to be misaligned to allow specular reflections from the front surface. Due to the very small solid angle subtended at the earth and the averaging effect on small images of the eye's saccadic movements a nearly infinite safe viewing time was found in this case.

Considering the very brief safe gaze time in the worst case especially when viewed with binoculars and in the second case with binoculars, it is recommended

that specular reflections be reduced where possible as was also suggested in the Boeing Co. report (14, op. cit.).

2.0 Statement of the Problem

2.1 Background

The Space Power System (ref. 1) now in the concept stage, envisions a large surface of solar cells (SPS) continuously oriented towards the sun while in geosynchronous orbit (GEO). On the opposite side of the satellite will be a microwave conversion and transmission system to convert the photovoltaic energy to microwaves, which will be beamed to receiving stations on earth. A highly reflective, polished circular antenna wil be continuously aimed at the receiving stations. The solar cell surface will be planar and rectangular, and covered with glass, so that it, in effect, is an enormous plane mirror which, if misaligned, could reflect a large proportion of the sun's rays to the earth's surface presenting a potential hazard to observers on earth.

The antenna, though not as large, would be intentionally pointed towards the earth and would present specular reflections of a fraction of the solar disc, to an observer on earth for over two minutes at a time.

There will be a large staging base (SB) in lower earth orbit (LEO), from which orbital transfer vehicles (OTV) will carry sections of the SPS to GEO for final assembly. The SB, although much nearer earth, has no specular surfaces and probably presents no potential optical hazards.

The sections of solar panel carried by the OTVs when in or near the LEO would subtend a relatively large angle from earth and hence reflect a large portion of the solar disc, also presenting a potential hazard to observers on earth.

In the following sections, the irradiances on earth and their probable maximum durations will be subjected to a worst case analysis in terms of potential hazards to the eyes of human observers. We will first review the different radiation hazards to human eyes which have been revealed by research, and briefly discuss the development of maximum exposure level safety standards. Then we will calculate the energies to which eyes might be exposed by the SPS and evaluate them in terms of the safety standards.

3.0 Optical Hazards from Non-ionizing Radiation

Although the solar spectrum filtered by the earth's atmosphere contains large quantities of ultraviolet and infrared as well as visible energy, the relatively brief exposures obtained from elements of the SPS preclude concern with the ultraviolet which sun-burns the surrounding tissues of the eye (the conjunctiva) and damages the cornea and lens, but only in unreasonably large doses for the present concern. The visible and infra-red portions of the solar spectrum (above 400 nm) damage the lens and retina. The infra-red (750-1100 nm) although it may contribute to retinal burns, is largely dangerous to the lens of the eye, which absorbs a large protion of this energy producing irreversible opacities called glass-blower's cataract. Again, these changes require very long, repeated exposures and therefore may be dismissed as a hazard from the SPS.

This leaves the retinal injuries as the major concern for the SPS. There are three kinds of retinal hazards from non-ionizing radiation: thermal burns, photochemical lesions and color-blinding lesions. The thermal burn is a focal lesion, visible by ophthalmoscopy within several hours of exposure, which has been extensively investigated from the earliest days of nuclear weapon testing. It results from viewing the nuclear fireball without protection and also from accidental exposure to laser beams. It is characterized by a localized steam explosion in the retina at the highest energy levels and by coagulation of protein in the retinal pigment epithelium with associated lsos of the adjacent photoreceptors. Controlled retinal burns are commonly used as a treatment for retinal detachments resulting from trauma or disease. Small lesions are produced by laser or arc-lamp photocoagulators to produce scarring which "welds" the retina to the adjacent tissues. It has been shown (3, 4) that momentary heat rise in excess of $10^{\circ}C$ at the lesion site is necessary to produce a minimum thermal burn. This is impossible to achieve with unconcentrated sunlight on earth (5, 6). Since no element of the SPS contemplates concave, specular reflecting surfaces, it appears reasonable to dismiss the thermal retinal burn as a potential hazard.

The second class of retinal damage from light is called the photochemical lesion. This lesion appears after 24 hours, is less obvious by ophthalmoscopy, but may appear as a granularity of the fundus. Histology of the retina displays primary damage to the pigment epithelium, largely involving denuding and clumping of melanin granules, swelling and pyknosis of epithelial cells, and secondary damage to photoreceptors. Functionally, this results in partial or complete loss of vision over the effected area, although there is at least partial recovery in a matter of weeks or months. The photochemical lesion's action spectrum has been determined (7). It is produced by short wavelength visible light, with peak activity at approximately 440 mm in the blue. It's threshold (the minimum energy which produces the lesion half the time) has been determined (7) on monkey retina as 3×10^{-2} W/cm^2 for a 2 mm X pupil and 10^3 seconds exposure. It can definitely be produced by unconcentrated noon sunlight on earth which could exceed this threshold energy in a very brief exposure, depending upon the path through the atmosphere.

In fact, Ham (8, 9) points out that these experimental photochemical lesions closely resembles solar retinitis, such as produced by watching eclipses of the sun. Tso (10) has produced nearly identical pathology in human eyes voluntarily exposed to the unattenuated solar disc. It is, therefore, very important that we carefully evaluate the reflections from the SPS for the blue light actions spectrum of this class of injury. This will be done in the following sections.

The final class of retinal light induced injury, called the color-blinding lesion, was so named because it produces selective degeneration of one class of color receptors (11). It is produced by repeated, intermittent exposure to spectral lights. Short wavelength, blue lights destroy only the blue-sensitive cones, when the intermittent regime is repeated daily for 6 to 8 days. Similarly, green and red lights damage the green-sensitive cones, but they recover in between one and four weeks. Although the light intensities which produce these effects can be reached by unconcentrated sunlight, it seems extremely unlikely that the required alternate bleaching and recovery repeated day after day would occur from viewing the SPS, so we can dismiss this class of damage as a hazard.

Thus, it is clear that only the blue light produced photochemical lesion to the retina should be of concern as a possible hazard from viewing the elements of the Solar Power System from the earth. Therefore, in the following we will perform a quantitative assessment of the likelihood and conditions for such injuries for those elements of the system which produce sufficient irradiance on earth to be likely hazards.

3.1 Retinal Light Hazard Evaluation for Photochemical Injury from the Sun

The American Congress of Governmental Industrial Hygienists (13) has recommended maximum permissible exposure values for viewing both point and extended light sources based on an analysis of the evidence for photochemical injury. They recommend that exposure to extended sources - those which subtend a solid angle at the eye greater than 1 X 10^{-4} steradian - should not exceed 100 Joules per square centimeter per steradian of blue light. Thus:

$$\sum_{400}^{1400} L_\lambda \ t_\lambda \ B_\lambda \ \Delta_\lambda \leq 100 \text{ Jcm}^{-2} \text{ sr}^{-1} \qquad (1)$$

where L is radiance ($W/cm^2 \times sr^{-1}$) and B_λ is the action spectrum of photo chemical injury to monkey eyes determined by Ham et al (ref. 8), whose values are shown in Table I.

Maximum permissible exposure may be calculated as:

$$t_{max \, (seconds)} = \frac{100 \ Jcm^2 \ sr^{-1}}{L_\lambda \ B_\lambda \ \Delta_\lambda} \qquad (2)$$

The highest solar irradiance values which we could locate were obtained by measuring summer sunlight near the zenith in California. They are shown as the top curve in Figure 1. We have integrated these values, obtaining a total irradiance value of:

$$E_t = 7.7104 \times 10^{-2} \ \text{Watts} \cdot cm^{-2} \qquad (3)$$

When we integrate the same values with the B_λ function of Table I, we obtain maximum blue irradiance on earth from sunlight of:

$$E_B = 8.1345 \times 10^{-3} \ W \cdot cm^{-2} \qquad (4)$$

To obtain the maximum radiance of sunlight on earth, we must correct for the solid angle of the sun from earth:

$$L_B = \frac{E_B}{\Omega} = \frac{8.1345}{6.9 \times 10^{-5}} = \underline{118.4} \ Wcm^{-2} \ sr^{-1} \qquad (5)$$

where $\Omega = \frac{A}{r^2}$ (6)

r is the distance from the earth

and A is the area of the Sun. Thus, the maximum safe viewing time of the sun from the latitude of California at noon in the summer is

$$t_{max} = \frac{100 \ J \cdot cm^{-2} \ sr^{-1}}{118.4 \ Wcm^{-2} \ sr^{-1}} = 0.84 \ \text{second} \qquad (7)$$

An observer would exceed present industrial safety standards* for the area of the retina used - probably the vital fovea - if he fixated the sun for longer than .84 second, when viewed at the zenith from California. The safe time would increase with more northern latitudes, towards winter and at earlier and later times of day because the rays would pass through the earth's atmosphere on a longer slant path, resulting in greater absorption of energy and, important for our problem, much greater scattering of blue light. We estimate the zenith summer sun at 77×10^{-3} W/cm^2. Sliney (ref. 12) states that values of 10×10^{-3} W/cm^2, are subjectively still too painful to look at, but when the sun declines to less than 5° from the horizon in clear weather - corresponding to below 3×10^{-3} W/cm^2, it is comfortable for most people to watch the sunset. However, we should not rely in our analysis on this avoidance response to bright light, since people have repeatedly burned their retinas by gazing at the sun during eclipses.

For light sources smaller in solid angle than 1×10^{-4} steradian, the ACGIH plans to recommend a different formula for calculating maximum permissible exposure for prolonged viewing for the blue light hazard:

$$t_{max} \text{ (seconds)} = \frac{10 \text{ mJ/cm}^2}{E_B \text{ (W/cm}^{-2}\text{)}} \qquad (8)$$

Where J is Joules (watts/sec.) and E_B is the irradiance of the source at the measuring instrument weighted for the blue light hazard action spectrum (B_λ).

Notice that these units are independent of the solid angle subtended by the source at the eye. The value of 10 m J/cm^2 is also identical to the maximum permissible exposure for continuous viewing of a point-source, blue laser (13).

*It should be noted that since the ACGIH Maximum Permissible Exposure Value is an industrial standard, it provides a safety margin. Thus, we can say that exposures which do not exceed the standard are safe, but we cannot say that ones that exceed the standard will necessarily result in retinal damage.

4.0 Calculation of Radiance from the Sun Reflected by the Elements of SPS.

Clearly, from equation (7), if any elements of the SPS reflected the entire solar disc (∿0.5 degree in diameter) to populated areas of the earth, from near the zenith, it would present a serious hazard, if people were somehow induced to look at it out of curiosity. We would expect, of course, that they would find it too painful to look at for more than a brief glance, but the 0.84 permissible seconds is very brief; also, there have been cases of eclipse blindness, so we cannot count on glare as a deterrent.

Fortunately, according to the analysis of the SPS made by the Boeing Corp. (14) no element of the SPS reflects the entire solar disc, even including the error modes that they consider, where the front surface of the satellite reflects the sun to the earth because the satellite is out of control.

We have chosen from the Boeing report the elements and conditions which produce the highest irradiances on earth, using our own calculations of the blue light hazard function integral with sunlight to estimate the maximum safe viewing time. The worst case according to Boeing is misalignment of the OTV in LEO to produce specular reflections from the glass fronts of the solar panels. In analyzing this case, we must decide whether the extended source formula (2) or the point source formula (8) should be used. The OTV in LEO is 1.51 km across. At 910 km distance from the earth it subtends:

$$\frac{1510 \text{ m}}{910 \text{ X } 10^3} = 1.6 \text{ mrad}$$

which is $\frac{1.6 \text{ mrad}}{9.3 \text{ mrad}} = 0.17$ or 17 percent of the solar disc in diameter, roughly $1.9 \text{ X } 10^{-6}$ steradian in solid angle. Thus, this case falls within the point source definition of smaller than $1 \text{ X } 10^{-4}$ sr., so we use the point source calculation of equation (8). It should be noted that if this were an instantaneous exposure with a point source, the irradiance would be independent of the size of the source. It would be presumed to have the same effect as a large source, but on a smaller area of retina. However, with extended viewing times as are relevant to this problem, the eye's nystagmus or jitter is an important factor. It averages the retinal image over a large area-usually taken as 10-11 mrad, or at least 1/2 degree (15). So, the larger the retinal image of a point source, the larger the average retinal irradiance over the 1/2 degree (actually 180 μm dia.) area. We approximate this by weighting the irradiance E_B for the percent of the solar disc projected on the retina, (in this case 17 percent). To calculate the maximum safe exposure time (duration t_{max}), we take the irradiance on earth from the whole solar disc at zenith in summer weighted for B_λ :

$E_B = 8.1345 \times 10^{-3}$ W/cm^2 and evaluate

$$t_{max} = \frac{10 \text{ mJ/cm}^2}{E_B \times (.17)^2} = \frac{10 \times 10^{-3}}{8.1345 \times 10^{-3} \times (.17)^2} = \underline{42.5} \text{ secs.} \qquad (9)$$

For the next to the worst case, specular reflections from the flat aluminum back of the OTV panels in LEO, the same size retinal image pertains. A reflection factor of 0.33 must be introduced. So that:

$$t_{max} = \frac{10 \text{ mJ/cm}^2}{E_B \times (.17)^2 \times .33} = \frac{10 \times 10^{-3}}{8.1345 \times 10^{-3} \times (.17)^2 \times .33} = \underline{129.} \text{ secs.} \qquad (10)$$

The next most dangerous condition would be a misallignment of the satellite to reflect an image of the sun on earth from GEO. In this case, the blue irradiance would be weighted by:

$$\frac{(10.7 \text{ km}) \ (5.4 \text{ km})}{35{,}700^2} = \underline{4.5 \times 10^{-8} \text{ sr.}} \qquad (11)$$

$$\text{Thus } \frac{4.5 \times 10^{-8} \text{ (solid angle of satellite in GEO)}}{6.87 \times 10^{-5} \text{ (solid angle of sun)}} = 0.0007 \qquad (12)$$

Thus:

$$t_{max} = \frac{10 \text{ mJ/cm}^2}{E_B \text{ (mW/cm}^2)} = \frac{10}{8.1345 \times 1\text{-}^{-3} \times 0.0007} = 1.76 \times 10^6 \text{ secs.} \quad (13)$$

5.0 <u>Viewing the SPS from the Earth Through Optical Instruments</u>.

Up to this point we have analyzed hazards to the naked eye from the SPS and have not specifically considered the potential hazards to the eye resulting from viewing any of the sources of reflected sunlight through binoculars or a telescope. Viewing any hazardous light source through magnifying optics normally increases the hazard to the retina; the exact degree of increase is dependent upon whether the source presents a thermal or a blue-light hazard. If the hazardous light source already extends greater than 10 mradian and is only a blue-light photochemical retinal hazard, then the increased angular source size does not increase the hazard, since there is no image-size dependence for this injury mechanism. It is important here to note that a magnifying optical instrument increases only the image size; it cannot increase the retinal irradiance ($W \cdot cm^{-2}$) because of the Law of Conservation of Radiance, or Brightness (16). The blue-light hazardous viewing time (t_{max}) cannot be reduced below that of viewing the sun directly -- 0.84 sec. as shown in Equation (7). On the other hand, if the source is potentially a retinal thermal injury hazard, the hazard actually increases proportionately with increasing image size. That is, because of the poorer conditions for retinal heat conduction for a larger image, the retinal threshold of injury decreases inversely as the increase in image diameter. The studies of Ham and others, as reported by Sliney and Wolbarsht (16) show that a retinal thermal injury is not possible for the unaided 159 μm image size of the sun on the retina. However, if the sun were viewed by an optical instrument of sufficient power to increase the retinal image to 1 mm or greater (i.e., 7X or greater) a retinal thermal injury could result, on the tenable assumption of an effective 3 mm or larger pupil.

Although it is unlikely that one could track the OTV in LEO with a binocular or amateur telescope, it is probably as much a likelihood as an uninformed observer looking directly at the sun with a telescope -- which does happen, although most observers would be too dazzled to look at such a bright object for more than a brief glance. Since the misaligned solar panel in LEO subtends an angle of only 0.17 that of the sun, it would require 1/.17 = 5.9X more magnifying power to create the same hazard as viewing the sun with a 7X binocular. This suggests that a telescope with 38 power or greater could create a thermal injury hazard from viewing the SPS solar panel in LEO. A still greater magnifying power (3 X 38) would be required to render the less reflectant flat aluminum back panel hazardous to view from a thermal injury standpoint. Viewing any object in GEO would require an incredibly large telescope to create a 1-mm retinal image and is not considered a realistic concern. Thus we may conclude that ordinary field binoculars would not increase the hazard of viewing the OTV in LEO as much a thermal injury as from the blue-hazard, which would be reduced to a t_{max} of 0.84 sec.

The actual retinal irradiance gain relative to the retinal irradiance when viewing an extended source without magnifying optics is:

$$G = D_o^2 \tau / d_e^2 P^2 = \tau D_e^2 / d_e^2 \quad \text{for } d_e > D_e \tag{14}$$

or:

$$G = D_o^2 \tau / P^2 D_e^2 = \tau \quad \text{for } d_e < D_e \tag{15}$$

since, the magnifying power P is defined as the objective diameter D_o divided by the exit pupil diameter D_e; d_e is the eye's pupil and τ is the transmittance of the optical system (typically 0.6 - 0.8 for a binocular). In both of the above cases the "gain" in retinal irradiance is less than one.

6. Conclusions

In conclusion, then, in the two worst cases, where the irradiance on earth would be largest: 1. the OTV misaligned in LEO such that the solar panel surface would reflect the sun to earth, and 2. the aluminum back of OTV in LEO, would exceed the safety limits if they were fixated by the unaided eye for longer than 45.2 and 129. seconds, respectively. The third worst case the misaligned SPS in GEO to allow specular reflections is no threat, allowing 1.7×10^6 seconds of safe fixation. For the eye aided by binoculars or a telescope, the safe viewing time from the standpoint of blue-light hazard could be reduced to as short as .84 seconds with 5.9 power or greater magnification, assuming a 3 mm effective pupil. The safe viewing time could never become shorter than that.

Viewing the solar panel in LEO through binoculars or a telescope could produce a thermal retinal injury which could not be achieved with the naked eye. The magnification would have to be 38 X or greater and the instrument would have to preserve a 3 mm or greater exit pupil. It is unlikely that an amateur could track the satellite in LEO with a 38 power telescope.

In view of the brief safe gaze time in the two worst case, especially with binoculars, it is urged that specular reflections be reduced where possible and it is also advisable that the aluminized paint on the rear of the OTV be replaced with a less reflectant surface, as was suggested in the Boeing report, although it is unlikely that the OTV could be tracked in LEO for 129 seconds with the naked eye.

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TABLE I

SPECTRAL WEIGHING FUNCTIONS FOR ASSESSING RETINAL HAZARDS

FROM BROAD-BAND OPTICAL SOURCES

Wavelength (nm)	Blue-Light Hazard Function B	Burn Hazard Function R
400	0.10	1.0
405	0.20	2.0
410	0.40	4.0
415	0.80	8.0
420	0.90	9.0
425	0.95	9.5
430	0.98	9.8
435	1.0	10.0
440	1.0	10.0
445	0.97	9.7
450	0.94	9.4
455	0.90	9.0
460	0.80	8.0
465	0.70	7.0
470	0.62	6.2
475	0.55	5.5
480	0.45	4.5
485	0.40	4.0
490	0.22	2.2
495	0.16	1.6
500-600	10 (450-)/50	1.0
600-700	0.001	1.0
700-1049	0.001	10 (-700)/500
1050-1400	0.001	0.2

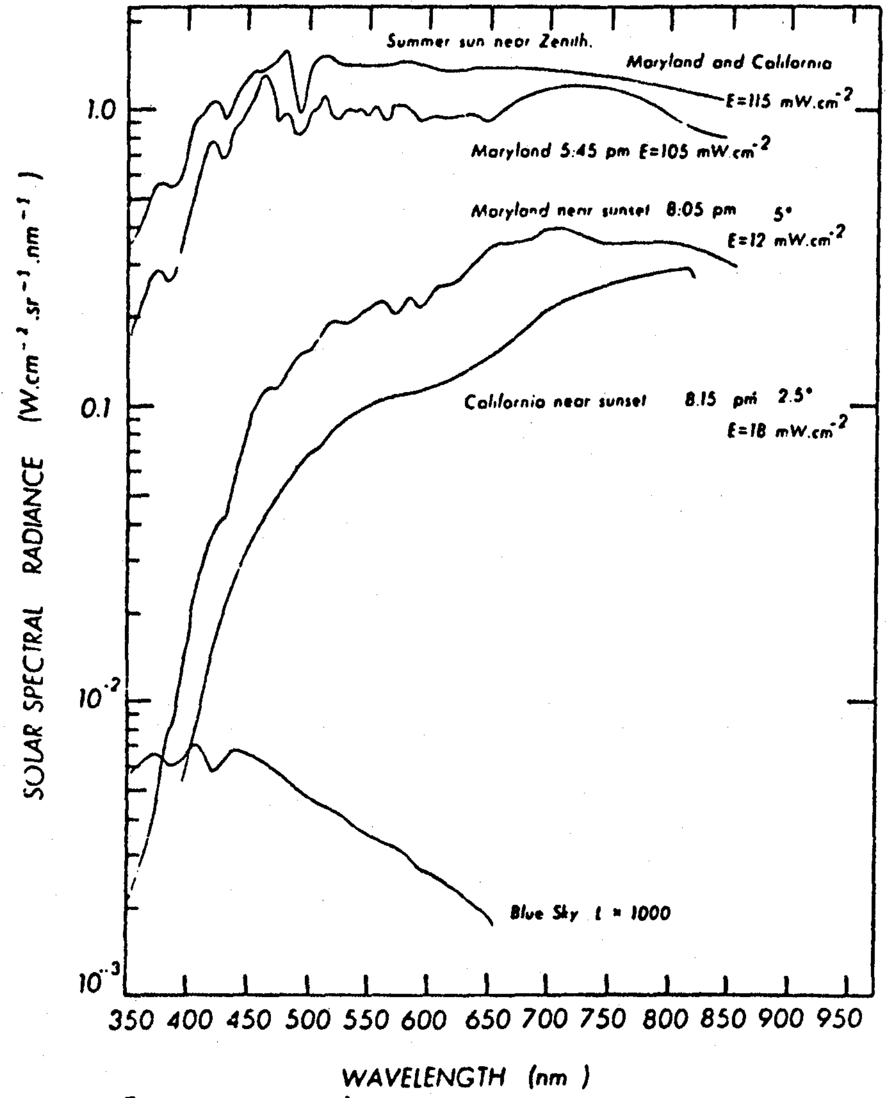

Figure 1 Spectral radiance of skylight and direct sunlight for several solar elevations measured in Maryland and California. The radiance which is important in terms of retinal effects is very low for the blue sky as compared to the radiance of the sun itself even at sunset. Note the dramatic change in spectral radiance at 350 nm as a function of solar altitude (from Sliney, 1977).

ASSESSMENT OF IMPACTS ON ANIMALS OF REFLECTED LIGHT FROM THE SATELLITE POWER SYSTEM

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SUMMARY

It is difficult to determine all of the properities of reflected light necessary to evaluate effects on the biology of exposed animals. In particular, the exact timing of the light with reference to the endogenous photo-sensitive rhythm, as well as the predictability of nocturnal illumination from the standpoint of daily and seasonal exposure must be known for each species. However, consideration of the fundamental nature of this light -- in particular, its intensity and duration -- suggests that further definition would not be productive. The estimated levels and duration of both diffuse and specular reflections are in most cases so low that no major detrimental action can be anticipated. Values of irradiance, for the worst case calculated, approach significant levels for many animals and surely surpass safe limits for some; however, the erratic nature of this light would ameliorate any long-term effects on most known processes. An immediate detrimental effect at the time of a reflected pulse of light, such as might result from the frightening of animals in the middle of the night, cannot be ignored, but, in most cases, the level of illumination produced by reflections would be insufficient to produce such alarm.

I. INTRODUCTION

The feasibility of using the proposed Satellite Power System (SPS) for an alternate source of energy is being evaluated by the U.S. Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA). If SPS becomes viable, there would be numerous spacecraft and spacestations involved. Light would be reflected from these structures to earth. This report considers the possible consequences of that reflected light on animals.

II. DATA BASE

A preliminary reference system, "Satellite Power System, Concept Development and Evaluation Program, Reference System Report", October 1978, DOE/ER 0023, has been prepared by NASA for use in making assessments of SPS. Scientists at the Boeing Company, using the reference system described in that report, have characterized the reflected light from SPS structures in a report, "Space Power System Brightness Due to Reflected Light", DOE/ER 0081. This report was used as the basis for estimating the potential impact of this reflected light on the biology of wildlife and domestic animals. Emphasis of this environmental impact review was focused on the potential effects of such light on various aspects of behavior and biological rhythms, and not on the possible direct ocular damage that might result from direct viewing of spacecraft, especially with magnifying equipment.

III. STATEMENT OF POTENTIAL PROBLEMS OF REFLECTED LIGHT

Several discrete types of biological activities were considered potentially important in evaluating the disruptive effects of additional environmental light.

1. Daily Behavioral and Physiological Rhythms: The vast majority of animals (except for perhaps some completely subterranean or cave-dwelling forms) exhibit some degree of daily activity rhythms, e.g., crepusular, diurnal or nocturnal. In many cases, the timing of these rhythms is at least partially dependent on environmental illumination, normally the daily photoperiod set by sunrise and sunset. Additional ambient light during normal daytime periods would not be expected to have significant or even measurable effects as long as it was of low to moderate levels compared to solar radiation. However, even relatively dim and brief light pulses during the "night" might act as potential stimuli to disrupt normal diurnal activity rhythms.

Additional detrimental effects of interrupted nights due to reflected light might occur through disruption of numerous daily physiological rhythms other than overt activity <u>per se</u>. Virtually every aspect of physiological function (metabolism, kidney function, mitotic activity, etc.) shows some degree of daily rhythmicity in animals, and, in many cases, these can also be synchronized by daily photoperiods. Abnormal light stimuli during otherwise dark periods (scotophase) could potentially reset such rhythms and lead to their dissociation from other processes. Such dissociation between separate rhythms may greatly modify the entire physiological status of the animal. For example, the quantitative and qualitative actions of pituitary hormones, such as prolactin, may depend on their daily phase relationship to other hormones such as adrenal steriods. If the daily pulsatile release of either or both are shifted, the animals may shift from a tendency to lipid storage to one of lipid utilization and increased migratory activity. Experiments in birds in which such phenomenon have been described have also shown that a single pulse of light during the night of a normally short day may cause the appearance of a new pulsatile release of pituitary hormone. However, in most cases, one would expect the physiological rhythm to be "reset" to normal phasing during the subsequent day. Thus, unless the nighttime interruptions were frequent, only minor consequences would be expected.

2. Photoperiodism and endogenous circadian rhythms: Perhaps the most potentially damaging aspect of abnormal environmental lighting would be its effect on daily timing processes that control long-term (e.g., annual) biological rhythms. Photoperiodism, the dependence on the length of the day to regulate various annual rhythms, is well established for a variety of seasonal physiological activities (e.g., growth, reproduction, molt, migration and diapause) in a diversity of animals, including fish, amphibians, reptiles, birds and mammals. It is important to recognize that a photoperiod change of only about 5-30 minutes may be sufficient to elicit a change in the physiological status of animals. The important aspect of this photoperiodic phenomenon in the present context is that the underlying time measurement mechanism is based on an endogenous circadian rhythm in photosensitivity. Thus, while the timing of seasonal cycles is normally dependent on the average daily photoperiod in different seasons, the circadian rhythm underlying the measurement of this photoperiod often depends on aspects of the daily light profile other than simply the total number of hours of visible light per day. In particular, experiments have shown that in most photoperiodic species

(including invertebrates and vertebrates) interpretation of daylength is dependent on when the animal is exposed to light relative to its internal sensitivity rhythm. For example, an animal need not receive continuous illumination for 14 hours daily to "perceive" the photoperiod as being 14 hours in length. Rather, a relatively brief period of light (several hours) at the beginning of the day, followed by an even briefer pulse (an hour or less) centered at 14 hours after the beginning of the first pulse, may be sufficient to elicit the same response as 14 hours of continuous light. A common experiment of this type would involve exposure of an animal to a standard daylength (e.g., 6-12 hours), followed by an hour of light during the night (designated interrupted night experiment); such a photo-regime would elicit physiological or behavioral responses characteristic of a "long" daylength. These results are especially relevant in the context of reflected light from the spacecraft: one must be concerned that illumination from reflections during nighttime hours might be sufficient to stimulate photoperiodic photoreceptors in such a way that an animal would initiate long-day processes in the middle of a season of short days (e.g., summer processes might be initiated in winter). The biological consequences of such untimely responses could well be disruptive and even lethal to an individual or population. Futhermore, experiments have demonstrated that such photoperiodic responses are sensitive to relatively low levels of illumination (1 ft. candle or less) and that even a single interruption of the night may be sufficient to initiate a physiological response, e.g., and increase in pituitary secretion of gonadotropin that is "intended" to initiate gonadal development. However, more regular daily interruptions would be required to maintain the accelerated long day response initiated by a single nighttime interruption.

3. Navigation: Experimental findings based largely on studies conducted in planetariums indicate that nocturnal migratory animals, especially birds, may rely upon celestial cues to aid in navigation over long distances. This mechanism may also be invovled in the unusual long distance migrations and site specificity of some open ocean marine animals including fish, reptiles (sea turtles) and invertebrates.

4. Nocturnal behavior: Nocturnal animals are generally keenly sensitive to low levels of illumination and abrupt increases in normal ambient levels of light may have a multitude of effects on behavioral patterns and general ecological relationships. For example, since nocturnal predators may hunt visually, any added illumination may assist them in locating and capturing prey. The fact that many small animals tend to reduce activity abroad or even remain secluded on nights of full moons suggest that such nocturnal illumination may be detrimental to their survival. The sudden change in illumination on an otherwise dark night may cause abnormal behavioral patterns.

IV. ESTIMATION OF POTENTIAL EFFECTS OF REFLECTED LIGHT

The above considerations raise the possibility that reflected light may have multiple effects on the biology of animals. Information required to evaluate the effects of this light include the following:

1. Intensity of light: Illumination must exceed threshold levels required to stimulate appropriate photoreceptors (note: these receptors are known to be extra-ocular in the case of photoperiodism, and hence have

different sensitivities from that of normal vision).

2. Spectral quality of light: Photoperiodic responses, in particular, have different action spectra from visual receptors in the eyes. In most vertebrates active spectra peak at red wavelenghts.

3. Duration of light pulse: The requirement for the minimal length of time that an animal must be exposed to light during the night to elicit an abnormal photoperiodic response has not been established for most species. However, available evidence indicates that, at least for some (especially insects, and some birds), even a few minutes illumination can be significant if they coincide with the peak of the photosensitive phase of the daily photosensitivity rhythm.

4. Phase realtionship between reflected light and normal daily solar and lunar lighting.

5. Regularity or predictability of light pulses in terms of both the time of day and from day to day: As already mentioned, a single nighttime interruption can have measurable effects, but the significance of the consequences would normally depend on more prolonged interruptions.

The data provided in the Boeing Report (especially Table 5) do not detail all of these characteristics of the reflected light, but some may be inferred from the description of phenomena involved in the reflectance. For example, while the description of spectral quality of the reflected light can only be approximated, it may be assumed that it will represent a relatively broad spectrum of wavelengths in the visible range, and hence will contain those wavelengths required to stimulate appropriate photoreceptors. Thus, this aspect of the reflected light is not considered critical for evaluating its effect. However, if the composition of this light should prove to be especially enriched or impoverished in specific wavelengths known to be most effective for photoperiodism, then the interpretation of irradiance may be in error.

The first and most important quality of the reflected light is its intensity as measured by illuminance in the general habitat. If intensity is considered to be below significant threshold levels for stimulation, then the remaining characteristics (duration, timing and regularity) need not be considered in detail. Unfortunately, the photosensitivity thresholds for animals vary widely between species and among the various physiological processes discussed. For example, nocturnal animals would be considerably more sensitive to light than would diurnal forms, and visual processes have different sensitivities from photoperiodic processes. In all cases, however, it is the reflected light that falls during the night that is considered to be most significant here, since daytime levels of illumination resulting from reflected light are trivial compared with normal ambient illumination. Table 5 of the Boeing Report lists six cases in which reflected light would occur at night, and attention is thus focused upon these cases. These cases differ in respect to both intensity and predictability.

Presumably the most regular, and hence potentially detrimental light comes from the diffuse light in controlled orientation. The worst case geometry yields calculations for two such cases (Cases 2 and 4) for night-time irradiance on the order of 10^{-6} to 10^{-9} W/m^2. These values represent extremely low levels that may reasonably be disregarded as being essentially nondetectable by the vast majority of animals since they would fall within normal ambient levels of illumination.

Specular irradiance is considerably greater than the diffuse, but even these values (0.01 to 0.03 W/m^2) are relatively low. Moreover, the calculation that a given spot would be exposed to such light for only 1 minute (Case 2, Boeing Report) or 2 minutes (Case S3) would make it unlikely that even animals fully exposed to this low light would show significant reponses.

The most extreme levels of irradiance are indicated by the out-of-control orientation described by Case S7. These levels of irradiance which are at least an order of magnitude greater than moonlight are certainly sufficiently high to be of potential significance to the photobiology of animals. The report does not explicitly calculate the probable duration or timing of exposures of such light, but I have been informed (personal communication, Dr. Harold Liemohn, Boeing Co.) that such unusual situations would involve extremely short pulses (seconds or minutes) of an unpredictable or irregular nature. Hence, any given habitat would be unlikely to experience such added illumination for sufficiently long or frequently enough to show appreciable responses. However, certain critical processes in insects may be triggered by a relatively short period of a single light pulse. If the light were to fall at such critical moments in an animal's life, it would trigger longer term actions. The erratic nature of this out-of-control situation precludes further estimation of the likelihood of such an event.

The potential effects of nocturnal illumination from reflectance on the two aspects of behavior mentioned above, namely, celestial navigation and nocturnal hunting and foraging activity, are among the most difficult to evaluate because of the paucity of a quantitative data base. It is not unlikely that an occasional disruption or modification of normal ecological relationships such as in the situation involving the interaction between predator and prey will result from an unexpected increase in habitat illumination, especially when this light is equivalent to full moonlight. However, it is difficult to see how such an event would have long lasting effects on the ecology of any species.

Celestial navigation, as in the case of nocturnally migrating birds, may well be sensitive to low levels of illumination equivalent to some of the intermediate cases of reflectance that are predicted. The possibility must be considered that the addition of a point source of reflected light that is equivalent to a bright new star in the night sky could lead to navigational errors. However, available experimental evidence suggest that birds utilizing this form of navigation probably depend more on star "patterns" rather than on single star for orientation. Hence, it seems unlikely that the presence of a new source of illumination, even though it might be equivalent to a star, would have a major impact on migratory behavior.

AN ANALYSIS OF THE EFFECTS OF REFLECTED LIGHT FROM SOLAR POWER SYSTEMS ON PLANT GROWTH AND DEVELOPMENT

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SUMMARY

Using the data supplied in the Final Report on Space Power System Brightness (1), we have assessed the potential impact of reflected light on the growth and development of plants. During daylight hours when the phytochrome pigment system has reached a photostationary state during the first few minutes of daylight, the effects of diffuse or specular reflection on plant development can be discounted. Furthermore, since leaves are normally oriented to full sunlight, the additional specular reflectance from SPS is unlikely to influence any aspect of the light harvesting process. At nighttime, plants are sensitive to low level illumination and the flowering process is the developmental event most likely to be influenced by low level irradiation. Even the worst case geometry levels of radiation however are not thought to be either of sufficient intensity or duration to influence flowering or other developmental processes.

INTRODUCTION

An assessment of the impact which reflected light from large Satellite Power Systems (SPS) would have on the biosphere includes an analysis of the effect of reflected light on plants. Because of the very large size of both the solar cells (55 km^2) and microwave antenna (1 km^2) as well as the other components of the Baseline System and the relatively low altitude of some components of the Baseline System, the reflections will be very bright (1).

During daytime, the specular reflection from Orbit Transfer Vehicles (OTV) can reach an irradiance of 2 W/m^2 in a spot 25 km across moving at a speed of 8 km/sec (1). The brightest nighttime reflection will come from the SPS antenna with an irradiance of 0.01 W/m^2 in a spot 350 km^2 moving at a speed of 150 km/sec.

We have assessed the impact of this radiation on plant growth and development by conducting a thorough review of the literature and by consultation with other experts in the field of plant photobiology. For convenience of analysis we have dealt separately with the effects of reflected light which affect processes occurring in plants during daylight hours and include effects on both plant development and photosynthesis and those which occur at night and affect the development of the plant.

BACKGROUND

The effects of light on plants can be divided into three broad categories:

a. Photosynthesis: The process whereby light energy is captured and converted into chemical energy. The action spectrum for photosynthesis has absorption maxima in the red and blue region of the spectrum and the principle pigments are the chlorophylls.

b. Phototropism: The bending growth of plants to unilateral illumination having an action spectrum in the blue region of the spectrum. For this response, the photoreceptor is not known.

c. Photomorphogenesis: The effects of light on the growth and development of plants. The number and variety of responses elicited by plants in light are listed in Table I. All of the responses listed in this table possess an action spectrum in either the red (660 nm) or far-red (730 nm) regions of the spectrum and they are mediated via the phytochrome pigment system.

The range of intensities of light to which plants respond is shown in Fig. 1. In plants the variation is great ranging from 10^4 $\mu W/cm^2$ for photosynthesis to 10^{-8} $\mu W/cm^2$ for photomorphogenesis in grass seedlings. It should be noted that the responses of plants in the lower range of intensities listed in Figure 1 were obtained from plants grown under strictly dark conditions. Since etiolated plants are not found in natural environments the importance of these responses must be interpreted with caution. Furthermore, the responses of plants to very low light intensities are measured over long time periods. Thus, for some of the responses listed in Fig. 1, exposure times vary from 12 days for photomorphogenesis in _Avena_

Table I. Plant Growth Responses Under the Control of Phytochrome
From F.B. Salisbury (2)

I. Time-independent responses, the degree of response usually related to the amount of P_{FR}.

A. Elongation or Enlargement Responses

1. Stem elongation of vascular plants
2. Petiole elongation
3. Root growth
4. Leaf enlargement
5. Plunular hook unfolding

B. Pigment Formation

1. Anthocyanin formation in various systems, e.g., apple or turnip skin, cabbage leaves, etc.
2. Carotene formation in tomato skins
3. Activation of chlorophyll synthesis

C. Process Initiation

1. Germination of many seeds and spores
2. Dark growth of fern gametophytes and Lemna
3. Chloroplast orientation toward light
4. Gametophyte formation from sporophyte in some mosses
5. Initiation of timing in certain circadian rhythms

II. Time-dependent Responses: Photoperiodism

1. Flower initiation in long-day and short-day plants
2. Flower development
3. Morphological responses of vegetative plant to daylength
4. Development of reproductive structures in Bryophytes
5. Germination of certain seeds
6. Onset of dormancy
7. Carbon fixation in succulents

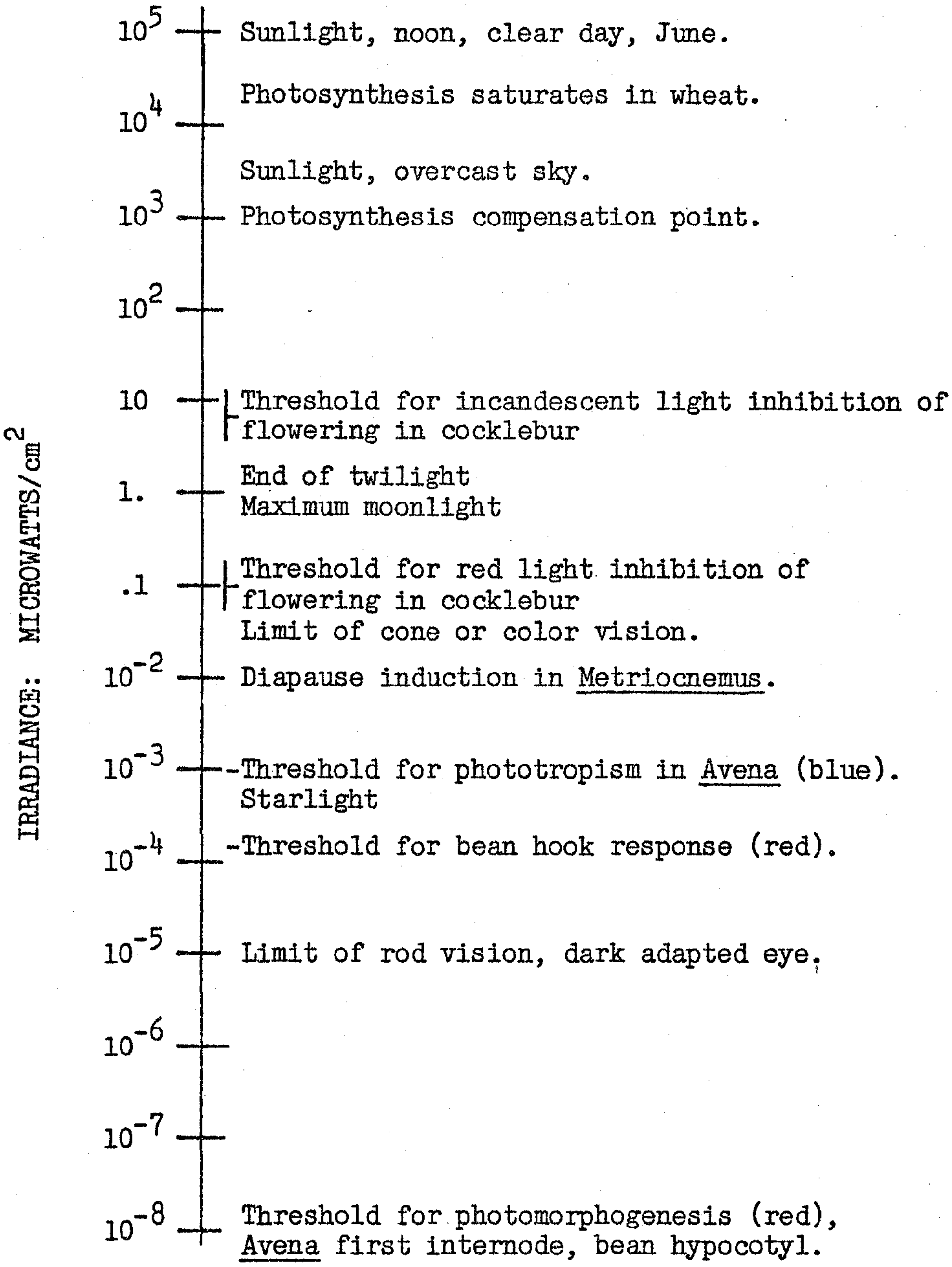

Figure 1. The range of light intensities for biological responses. Redrawn from F. B. Salisbury (2).

and 7 days in the bean hypocotyl (2). It is clear that the total amount of energy required to initiate these responses at low light intensities is higher than that required by the human eye since the response of the eye to low light intensities takes a fraction of a second.

The photoreceptor for photomorphogenesis in plants is the chromoprotein phytochrome (P). The phytochrome pigment system exists in 2 forms — P_{FR} — the far-red-light-absorbing form which exists after irradiation with red light and P_R- the red-light-absorbing-form. The relationship between these two forms of phytochrome is shown in Fig. 2.

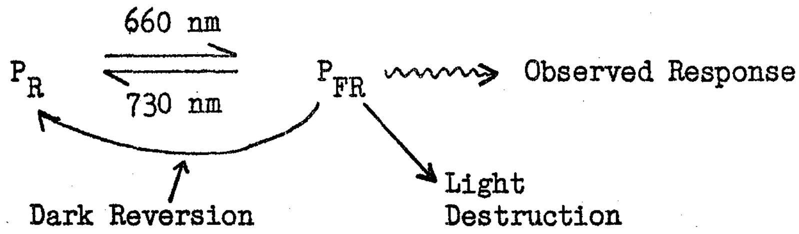

Figure 2. The relationship between phytochrome and red-light or far-red-light illumination. Note that destruction of P_{FR} to an unknown occurs in light. Plants respond to P_{FR}.

Developmental responses in plants are regulated by the levels of P_{FR}; as far as is known, P_R does not play a regulatory role in development (3). The way in which phytochrome acts to influence developmental events in plants is not known; however, a considerable amount is known about the relationship between P_{FR} formation and the initiation of the developmental event.

It is generally agreed that there is a roughly logarithmic relationship between P_{FR} and the developmental response (4,5). Furthermore, for most responses, saturation occurs when 50% of the phytochrome is as P_{FR} (4,5). Mandoli and Briggs (6,7) however, reported that a low irradiance response in etiolated wheat was saturated when there was less than 3% P_{FR}. This low irradiance response was only observed when plants were grown in total darkness. When plants grown in darkness but exposed to low intensity green "safe lights" were used they did not show the low intensity response. Rather, these plants showed a second response to red light which saturated when there was approximately 50% P_{FR} (6,7). It is clear therefore that in addition to demonstrating sensitivity to low light intensities (see Figure 1) plants which are grown under strictly dark conditions can also exhibit enhanced sensitivity to P_{FR}. It cannot be overemphasized in the context of this analysis that these etiolated plants do not represent plants which would be found in a normal environment.

The kinetics of phytochrome conversion both in vitro and in vivo have been well worked out (Fig. 3) (8).

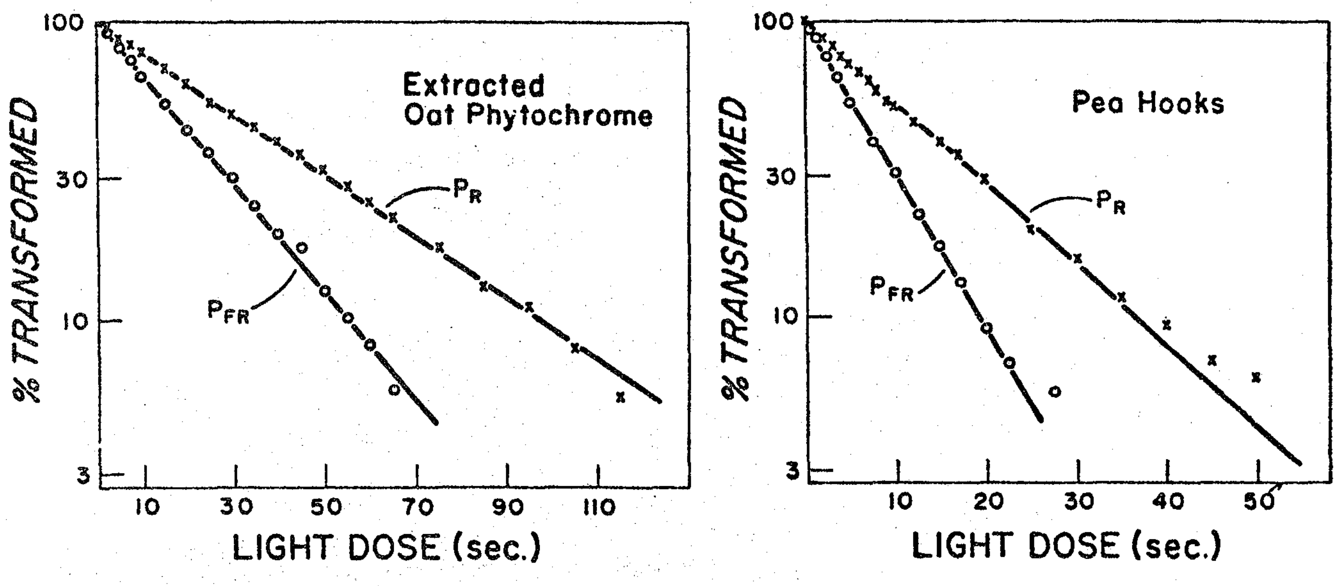

Figure 3. Dose-response curves for phototransformation of oat phytochrome in vitro and pea hook phytochrome in vivo. Actinic beam energy for P_R transformation: 8.2×10^{-2} erg cm^{-2} sec^{-1}; for P_{FR} transformation: 2.9×10^{4} erg cm^{-2} sec^{-1}. From Everett et al. (8).

From Figure 3 it can be seen that for phototransformation of 50% P_{FR} *in vivo* requires approximately 6×10^3 erg/cm^2 and for *in vitro* transformation of 50% of P_{FR} requires approximately 10^4 erg/cm^2 (10^{-3} W/cm^2).

ANALYSIS OF EFFECTS OF REFLECTED LIGHT

Effects of Reflected Light in Daylight Hours.

The irradiances produced from the various components of the SPS during daylight hours are given in Table 2.

Table 2. Ground Irradiance — Daylight Hours[a]

Reflection	Condition	Midday (M) Dawn/Dusk (D)	Irradiance W/m^2
Controlled Orientation — Worst Case Geometry			
Diffuse	OTV/SB in LEO	M	3×10^{-4}
Diffuse	OTV powered near LEO	D	4×10^{-6}
Diffuse	OTV between LEO and GEO	D	2×10^{-7}
Specular	OTV/SB in LEO (solstice)	M	
Specular	Front solar panels	M	1.2
Specular	Aluminum back	M	19.0
Specular	Misaligned front	M	0.1
Specular	Misaligned back	M	2.0
Specular	OTV powered near LEO	D	0.19
Specular	OTV between LEO and GEO	D	0.01
Out of Control Orientation — Worst Case Geometry			
Specular	OTV in LEO	D	56

[a]From Space Power System Brightness Report (1).

The most extreme case is illustrated by the out of control orientation of OTV in LEO where irradiances of 56 W/m^2 for short periods (1 or 2 seconds) can be obtained. Even this most extreme case will not affect either photosynthesis or plant development. Plants do not exhibit sensitivity to direct insolation. Indeed most plants characterized as "sun-plants" (plants which grow in conditions of direct exposure to sunlight as opposed to "shade-plants" which grow in shaded environments, e.g., forest floors) orient their leaves perpendicular to the sun's rays to maximize interception of sunlight. Ground irradiance from OTV in LEO would not be expected to affect those plant parts oriented toward sunlight since the increase in irradiance would only amount to 4% of full sunlight. There is no evidence to suggest that even very large changes in irradiance affect plants (by comparison with effects on the human eye). Rather, over a wide range of irradiances, the rate of photosynthesis would change and saturation would occur at 20% of full sunlight (Fig. 1). Above saturation there is no evidence suggesting deleterious effects of full sunlight on the photosynthetic process.

Similarly, during full sunlight there is no evidence that the development of sun-plants would be affected by irradiation from OTV in LEO. In full sunlight phytochrome levels will have reached a photostationary state (3,4) and indeed the photostationary state would be saturated by a fraction of the energy of full sunlight. The development of plants exposed to sunlight will reflect the fact that phytochrome is predominantly (greater than 60%) in the P_{FR} form. Since all developmental responses to red-light are known to be saturated when P_{FR} exceeds 50% of total phytochrome, small deviations from maximum full sunlight can have no affect on developmental responses controlled by phytochrome.

Effect of Reflected Light at Nighttime.

The irradiances from SPS at nighttime are shown in Table 3.

Table 3. Ground Irradiance — Nighttime[a]

Reflection	Condition	Irradiance (W/m^2)
Controlled Orientation — Worst Case Geometry		
Diffuse	SPS in GEO	1×10^{-5}
Diffuse	OTV between LEO and GEO	
Specular	SPS solar panel in GEO (Equinox)	
Specular	Flat surface	0.03
Specular	Misaligned surface	3×10^{-4}
Specular	SPS antenna in GEO (equinox)	0.01
Specular	OTV between LEO and GEO	2×10^{-3}
Out of Control Orientation — Worst Case Geometry		
Specular	SPS in GEO	0.4

[a]From Space Power System Brightness Report (1)

With the exception of the worst case geometry with the OTV in LEO the maximum nighttime irradiance is 0.01 W/m^2 for 2-3 seconds. From the data of Everett et al. (8) shown in Fig. 3, it can be calculated that with this level of irradiation, approximately 0.5% of P_{FR} would be formed. Assuming that not all of the light is absorbed, this value of 0.5% represents far more P_{FR} than could be expected following 2-3 seconds of irradiation at 0.01 W/m^2.

Although low levels of light might cause subtle changes in the growth of plants via the phytochrome system, these changes are likely to be so small as to be undetectable. The potential effects of nighttime light on the flowering process, however, might have more far-reaching consequences. Plants are classified as being day neutral (relatively unresponsive to day length), long-day (flower when days exceed a certain minimum) or short-day (flower when days are shorter than a certain minimum). The flowering of short-day or long-day plants can be influenced by light-breaks which occur at nighttime. In short-day plants, light breaks during the long-night will nullify the flower promoting effects of the long night. Conversely, in long-day plants, a light break during a long night will nullify the inhibitory effects of the long night. Ground irradiance at night has the potential to affect the flowering of important crops which flower according to prescribed daylength requirements. Among crop plants which are short-day or long-day plants are soybean (<u>Glycine max</u>), rye grass (<u>Lolium temulentum</u>), and barley (<u>Hordeum vulgare</u>) (Table 4). It is clear from the data in Table 4 that although both short- and long-day plants are sensitive to low levels of irradiation this irradiation must be supplied continuously throughout the night. It is clear that the total energy from these low irradiances greatly exceeds the energy levels from the SPS in any configuration.

Another means of comparing the potential effects of irradiation from SPS comes from an evaluation of the effects of moonlight on the flowering process. Moonlight has been estimated at the order of 10^{-3} W/m^2 but even in the most sensitive of all flowering plants (<u>Xanthium strumarium</u>), the effects of <u>continuous</u> nighttime irradiation with moonlight are marginal (9). It is agreed that very few plants are as sensitive to light-breaks as <u>Xanthium</u>. For example, Table 4 shows that <u>Cannabis</u>, <u>Poinsettia</u>

Table 4. Approximate Threshold Light Values for the Suppression or Induction of Floral Initiation in Some Long- and Short-Day Plants. Adapted from (9).

SHORT-DAY PLANTS	Threshold light value[a] for the inhibition of flowering (lx)
Chrysanthemum morifolium	21.5
Kalanchoe blossfeldiana	21.5
Euphorbia pulcherrima (poinsettia)	5.0
Pharbitis nil	1–10.0
Cannabis sativa cv Kentucky	0.3
Glycine max	0.1
Xanthium strumarium	0.1

LONG-DAY PLANTS	Threshold light value[a] for the promotion of flowering (lx)
Brassica campestris	1075.0
Lolium temulentum cv Ceres	10.5
Silene armeria	7.5–21.5
Hordeum vulgare	2.5–5.0
Callistephus chinensis	1.0–3.0

[a]Using tungsten-filament lamps continuously throughout the night or for the greater part of the night. 1 lx = 4.2×10^{-3} J m^{-2} s^{-1}.

and *Kalanchoe* are from 3 to 200 times less sensitive to nighttime light than *Xanthium*.

It is known that brief flashes of light applied during the dark period will affect the flowering process. In *Xanthium* flashes of very high intensity light of less than 1 second can inhibit flowering; however, the available evidence shows that even the irradiance in the worst case geometry (o.4 W/m^2) is insufficient to influence flowering.

CONCLUSIONS

The available evidence indicates that ground irradiance from SPS will not affect the growth or development of plants. During daylight hours, the effect of specular radiation is unlikely to influence the aerial parts of plants since these show no sensitivity to insolation. Developmental effects of either specular or diffuse radiation are unlikely to occur either during day- or nighttime irradiation. Although plants are sensitive to low intensity radiation, the duration of the irradiation provided by reflection from SPS are insufficient to cause developmental changes.

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Appendix I. Glossary

action spectrum: a graph of the magnitude of a reaction or a response plotted as a function of wavelength of light.

anthocyanin: a soluble, reddish-blue pigment in plants.

carotenes: red or orange colored pigments found in carrots and certain other vegetables.

carbon fixation: the incorporation of carbon dioxide into other organic compounds. Photosynthesis the most common form of carbon dioxide.

chlorophyll: the green pigment found in the chloroplasts of plant cells; occurs in two forms (chlorophylls a and b) and is involved in photosynthesis.

chloroplast: a membrane-bound, chlorophyll-containing organelle in plant cells that is the site of photosynthesis.

chromoprotein: a conjugated protein containing a pigment.

circadian rhythm: behavioral or physiological rhythm associated with the 24-hour cycles of earth's rotation.

cones: flask-shaped cells in the retina of the vertebrate eye that are sensitive to bright light and color; concerned with perception of color and discrimination of detail.

cotyledon: a leaf-like structure of the embryo of a seed plant; contains stored food used during germination.

diapause: a period of delayed development or growth accompanied by reduced metabolism and inactivity especially in certain insects and snails.

etiolated: the pale or bleached appearance of a plant grown in the dark.

gametophyte: the haploid (i.e., having one set of chromosomes) generation of the plant life cycle; the gametophyte produces the gametes.

hypocotyl: the stem between the cotyledons and the root in seedlings like lettuce and bean.

long-day plant: photoperiodic plant that flowers only when daylight exceeds a critical length.

morphogenesis: changes in structure, form, or size of an organism or its cells or tissues, occurring during growth and development.

petiole: the stalk of a leaf.

photoperiodism: the control of flowering and other physiological processes by the intensity, length, timing and quality of light and dark periods.

phototropism: the movement or growth of an organism toward or away from a unilateral source of light.

phytochrome: a photoreversible, bluish-green pigment that, in response to variations in red light, controls many phases of plant growth and development; occurs in two forms, a far-red light absorbing form that is formed in response to red irradiation and a red light absorbing form formed in response to far red irradiation.

plumule: the growing stem tip of the embryo of a seed above the place of attachment of the cotyledons.

rods: rod-shaped cells of the retina of the vertebrate eye that are sensitive to dim light; concerned with vision in dim light.

short-day plant: photoperiodic plant that flowers when the light period does not exceed a critical length.

sporophyte: the spore-bearing generation of a plant's life cycle that is diploid and reproduces by spores; the sporophyte generation begins with the fertilized egg and ends with meiosis.

vascular plants: plants with specialized tissues, xylem and phloem, for support and conducting water and nutrients.

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