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Concentration of Off-Axis Radiation by Solar Concentrators for Space Power

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CONCENTRATION OF OFF-AXIS RADIATION BY SOLAR CONCENTRATORS FOR SPACE POWER

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E-4804

ABSTRACT

Off-axis radiation is sunlight or, in general, any radiation from any direction not parallel to the axis of the solar concentrator. It will be reflected to regions other than the focus of the parabolic concentrator and possibly concentrated there. Four types of off-axis radiation are discussed. These are (1) small off-axis angles during walk-off, (2) large off-axis angles, (3) an extended off-axis source such as Earth albedo, and (4) miscellaneous off-axis sources including radio frequency sources and local point sources. A previous analytical study used a computer code named PIXEL to predict concentration of off-axis radiation and a previous experimental study used an 11 m diameter multifaceted dish concentrator to validate the PIXEL analysis. The PIXEL code was limited in that it represented concentration by an ideal parabolic reflector of light from a point source. Another code named OFFSET has been developed to represent the solar concentrator being developed for Space Station Freedom. It is a detailed, ray tracing model which represents 50 ray originating points on the Sun and reflections from 10 points on each of the 456 concentrator facets. Results of this code are generally similar to the PIXEL results although there are small differences due to the more detailed representations of the Sun and concentrator that were used in the OFFSET code.

INTRODUCTION

A solar dynamic power system is baselined to provide increased electrical power generating capability for Space Station Freedom. The solar dynamic system uses a parabolic reflective concentrator to collect solar energy. This solar energy is input to a heat engine, which turns a rotor in an alternator to produce electrical power.

The current space station baseline uses an offset concentrator configuration which is one in which the parabolic vertex, instead of being located at the center of the concentrator, is offset to a point near the outer edge of the collector. To successfully develop the power system, it is necessary to understand the reflector flux distribution at various locations, including those due to off-axis incident radiation.

Off-axis radiation is intended as a broad category to include any energy reflected by the concentrator that doesn't enter the receiver aperture which is at the parabolic focal point. Four types of off-axis radiation are discussed in this paper:

(1) Solar walk-off in the immediate vicinity of the focal point caused by stoppage of the concentrator pointing gimbals. This was a significant problem in the terrestrial energy program. Methods of dealing with walk-off for terrestrial concentrators are discussed by L.D. Jaffe et al. [1].

(2) Concentrations of parallel light rays that deviate significantly (10° to 90°) from the desired on-axis direction. The boundary within which concentration ratios greater than one can occur needs to be determined for the solar concentrator. For reflections from the space shuttle radiator this boundary was determined using a scale model experiment. Results from this experiment and supporting analysis are discussed by Harold R. Howell and J. Gary Rankin [2]. Possible concentration ratios within this boundary also need to be determined. An analytical code named PIXEL was developed for this purpose. Results of the PIXEL code were validated by comparison to experimental results using an 11 m diameter, multifaceted dish concentrator. These experimental and analytical results were reported by S. Holly et al. [3].

(3) Concentration of an extended light source, such as reflections to a solar concentrator in low Earth orbit from the Earth and the ocean.

(4) Possible concentration of other sources of radiation. This category includes point sources of light near the concentrator and radio frequency sources either on Freedom or directed from Earth towards Freedom.

A feature of parabolic reflectors is that off-axis radiation will be reflected to regions other than the focus of the parabola. Off-axis solar radiation can result if the concentrator is misoriented. Off-axis radiation can also result from other energy sources which irradiate the solar concentrator.

SOLAR WALK-OFF

The primary off-axis concern in the terrestrial energy program was damage to structure and equipment in the vicinity of the focal point during walk-off. Walk-off caused by loss of power to the concentrator gimbals should be distinguished from normal acquisition and deacquisition during which the spot moves across the aperture plate at 30° to 120° per minute. For walk-off due to gimbal failure, the apparent motion of the Sun is a key parameter in the rate the concentrated flux moves across the aperture plate. In a terrestrial system, the

Sun appears to move across the sky at the rate of the Earth's daily rotation, 360° per 24 hr, or 1° every 4 min. The concentrated beam walks across the front of the receiver at this same rate. The duration of direct exposure, for components near the focal plane, is typically 5 to 15 min. If no cooling is provided local temperature may rise to radiative equilibrium. This may be as high as 4000 °C (7000 °F) for highly concentrating terrestrial systems. Methods of dealing with walk-off for terrestrial systems are discussed by Jaffe [1]. Aperture plate temperature sensors were recommended to sense a walk-off emergency. Three generic approaches for preventing damage from walk-off that were discussed are: (1) receiver design to passively withstand the solar input, (2) forced cooling of the receiver, and (3) emergency systems to detrack or defocus.

As with the terrestrial programs, walk-off due to a pointing mechanism failure is also an important concern for the Freedom solar dynamic power system. However, the rate of walk-off in low Earth orbit is considerably faster, because with a 96 min orbit period, the Sun appears to move nearly 4° per minute. Thus the duration of direct exposure is typically less than 1 min. Still, special materials and/or other precautions will be required to protect the receiver from walk-off.

The OFFSET computer code model of the Freedom solar concentrator is being used to determine the solar flux intensities during walkoff. This code is a detailed ray tracing model of the Freedom concentrator, which represents 50 ray originating points on the Sun and reflections from 10 points on each of the 456 concentrator facets. This code was described and on-axis results were presented at the 23rd IECEC [4]. Results from OFFSET are shown in

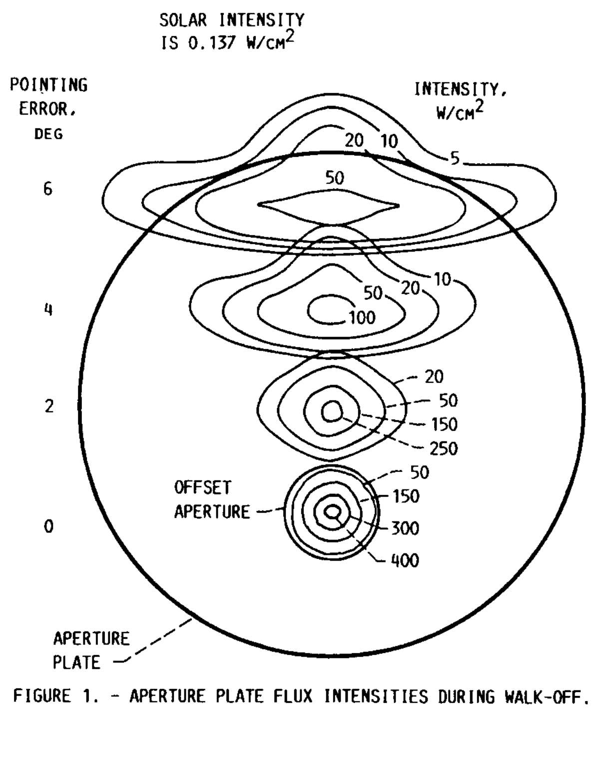

FIGURE 1. - APERTURE PLATE FLUX INTENSITIES DURING WALK-OFF.

Fig. 1 for walk-off positions of 0°, 2°, 4°, and 6°. This corresponds to the first 90 sec of walk-off. Note that the beam gets larger and less intense as it moves away from the focal point. The aperture is shown offset from the center of the receiver aperture plate in this figure, because an offset aperture is being considered to improve receiver flux distribution. There are two gimbals in the Freedom concentrator pointing system. The alpha gimbal rotates once every 96 min orbit and the beta gimbal moves much more slowly to adjust for seasonal variations in the angle between the orbit plane and the plane of the ecliptic. If only one gimbal failed, the other gimbal would be used to rapidly bring the concentrator off Sun. The walk-off shown in Fig. 1 would result from failure of both the alpha and beta gimbals. The path would be up or down from the aperture in Fig. 1 depending on whether the solar dynamic power system is above or below the transverse boom of Freedom. Computed flux intensities during walk-off will be used in the design of the receiver aperture plate to withstand the walk-off transient.

CONCENTRATION OF PARALLEL LIGHT AT LARGE OFF-AXIS ANGLES

In the terrestrial program it was often assumed that light converges from the concentrator to the focal point and that at a distance of two focal lengths from the vertex of the parabolic concentrator, the concentration ratio will be less than one. This concentration ratio boundary was considered to be either a two focal length radius sphere centered at the vertex or a plane perpendicular to the parabolic axis two focal lengths from the vertex. These boundaries are realistic for small off-axis angles, but at large off-axis angles there can be significant concentrations even on the two focal length plane.

Additional analyses and experiments have been done to better understand concentration of parallel light at large off-axis angles. These include: (1) a computer code analysis using the PIXEL code that was later validated by experimental testing, (2) testing and analysis for the space shuttle reflective radiator, and (3) optical analysis of concentration by individual facets.

PIXEL Results On Two Focal Length Plane

A computer code named PIXEL was developed to evaluate possible/concentration ratios on various planes perpendicular to the parabolic axis for various off-axis angles. This code assumed a point light source and an ideal parabolic concentrator that was either a symmetric parabola or an offset parabola. Results from the PIXEL code for the plane $Z = 2$ focal lengths are shown in Fig. 2. Concentration ratio increases to maximums of 4.5 for symmetric concentrators and 103 for offset concentrators at an off-axis angle of 65°. The relative positions and orientations of the concentrator, the plane $Z = 2$, the incoming light rays and the high flux point are shown in Fig. 3(a) for the symmetric parabola and Fig. 3(b) for the offset parabola. Note that the high flux point is significantly closer to the concentrator on Fig. 3(b) than the

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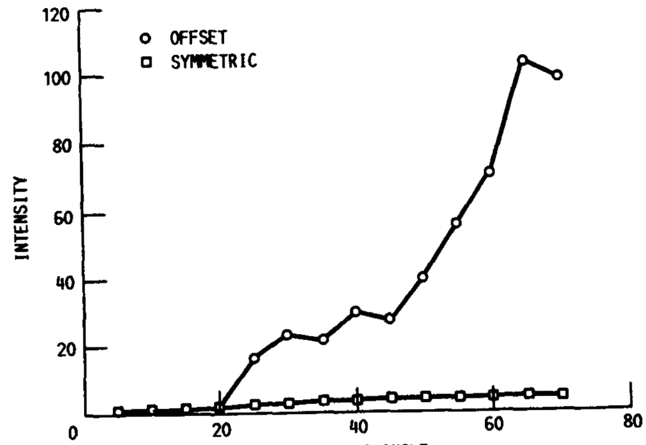
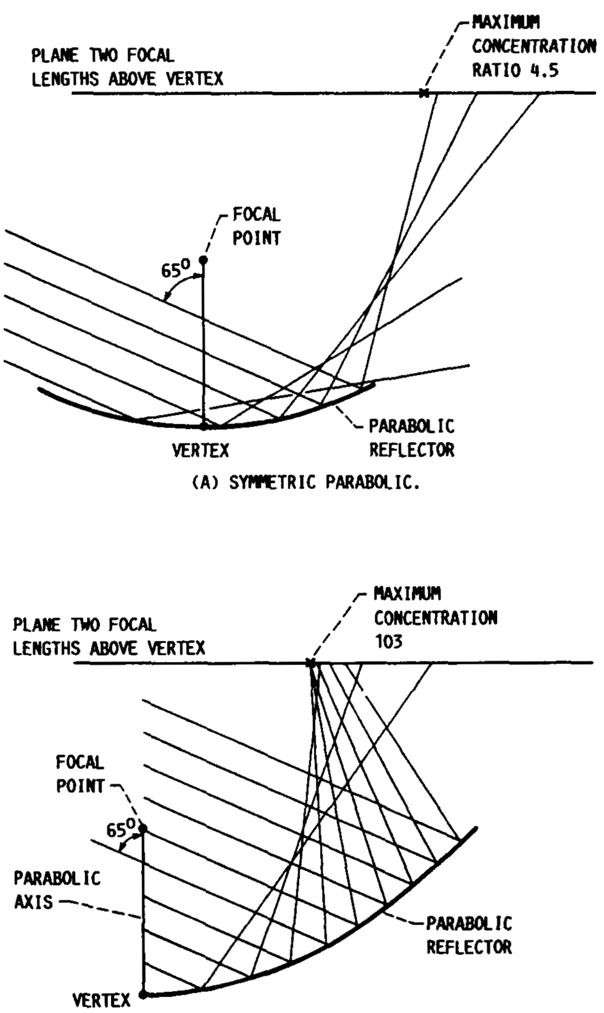


FIGURE 2. - CONCENTRATION RATIO ON PLANE z = 2.



(B) OFFSET PARABOLIC.

FIGURE 3. - LOCATION OF PEAK INTENSITY ON PLANE TWO FOCAL LENGTHS ABOVE REFLECTOR WITH 65° OFF-AXIS ILLUMINATION.

corresponding point is in Fig. 3(a). These high flux values show that the plane $Z = 2$ is not a realistic estimate of the boundary where concentration ratio is less than one. This is especially true for offset concentrators.

An experiment was conducted using the Vanguard concentrator from the terrestrial energy program to validate the PIXEL code. This concentrator is 11 m in diameter and has 336 spherically contoured, rectangular, reflective facets. Intensities were measured on a plane perpendicular to the parabolic axis and 1.5 focal lengths above the vertex. These intensities were normalized to the intensity of the incident light. The source, a high intensity landing light at a distance of 426 m (1400 ft), approximated a point source. The concentrator was aligned to an approximately 39° off-axis angle. The PIXEL code predicted the location and magnitude (a concentration ratio of 15) of the highest intensity region quite accurately. However, there were local variations in intensity shown in Fig. 4 which appeared to be due to the individual concentrator facets. Maximum intensity was measured to be a concentration ratio of approximately 100, whereas adjacent areas in some cases only a couple of inches away, had concentration ratios of 1 or 2. The experimental comparison to the PIXEL analysis is described in detail by S. Holly et al. [3].

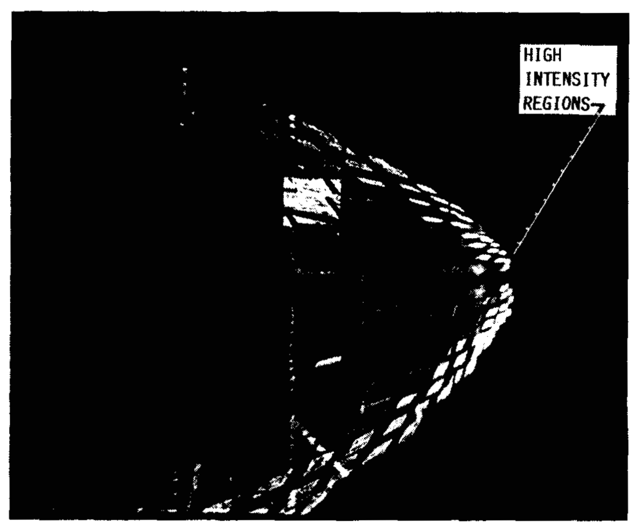


FIGURE 4. - TYPICAL LIGHT PATTERN SHOWING INTENSITY DISTRIBUTION DUE TO A 39 DEG ANGLE OF INCIDENCE OF INCOMING ILLUMINATION.

Safe Region For Space Shuttle Radiator

Although the space shuttle radiator is not a solar collector, its highly reflective panels caused the same concerns for the space shuttle program that the solar dynamic concentrator causes for the Freedom program. The shuttle orbiter has the radiator panels on both sides of and along the entire length of the payload bay. The shuttle radiator concerns were answered by a combination of analysis and experiment. Testing of a scale model of the space shuttle radiator is described in detail by Harold R. Howell and J. Gary Rankin [2].

The concave shape of the panels and their specular silver/Teflon coating causes focusing of the reflected solar energy which could have adverse heating effects on equipment or astronaut EVA. A limiting acceptable solar environment of one-sun from each of two different directions (direct and reflected) was originally established by NASA/JSC for EVA by the astronauts. Later information indicates higher solar environments can be tolerated. Ray trace analysis predicted the size and shape of the region with concentration greater than one. A one-tenth scale model of the radiator panels was illuminated by a xenon "sun-gun"/lamp and the intensity of the reflected light was measured. The test results agreed closely with the ray trace analysis.

Concentration by Facets

The concentrator experiment to validate the PIXEL code showed local high intensity regions due to individual facets (see Fig. 4). These facets are spherically contoured reflective surfaces. Basic optical principles for focussing of spherical mirrors are discussed by Max J. Riedl [5]. Focusing of parallel incoming light rays is illustrated in Fig. 5. The incoming beam is shown in two perpendicular planes. Rays in the plane containing incoming rays and the normal to the spherical mirror focus to a point called the sagittal focus. Rays in the plane perpendicular to this plane focus to the tangential focus. The best focus (called the circle of least confusion) is located between the sagittal and tangential foci at a distance of one-half the spherical radius of curvature from the spherical mirror. The intensity of the reflected light then decreases to a concentration ratio of one at the radius of curvature from the spherical mirror. Therefore to avoid concentration ratios greater than one, independent of the direction of the incoming radiation, a minimum distance of the facet radius of curvature is required from every facet of the solar concentrator. A greater distance may be required if facet images overlap. Toroidal facets which have different radii of curvature in two orthogonal directions are being considered for the Freedom concentrator. The toroidal facets bring the sagittal and tangential foci closer together for the design angle of incidence. Four groups of toroidal facets with different radii of curvature, shown in Fig. 6 are planned for the space station concentrator. With toroidal facets, the distance to reduce to a concentration ratio of one is the geometric mean of the facet's radii of curvature. The curve beyond which the concentration ratio is less than one for the Freedom concentrator is illustrated in Fig. 7.

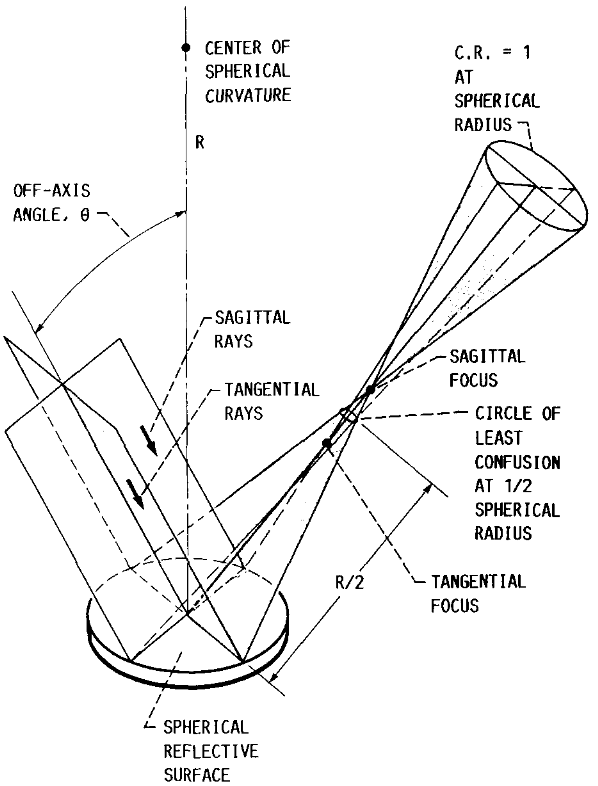


FIGURE 5. - SPHERICAL REFLECTIVE SURFACE REFLECTS PARALLEL "OFF-AXIS" RAYS TO CIRCLE OF LEAST CONFUSION AT HALF OF SPHERICAL RADIUS. RAYS SPREAD TO CONCENTRATION RATIO (C.R.) OF ONE AT SPHERICAL RADIUS.

FACET TYPE:	△	△	△	△
RADIUS ALONG LINES, CM:	1963	2438	3038	3830
RADIUS ACROSS LINES, CM:	1844	1996	2154	2314

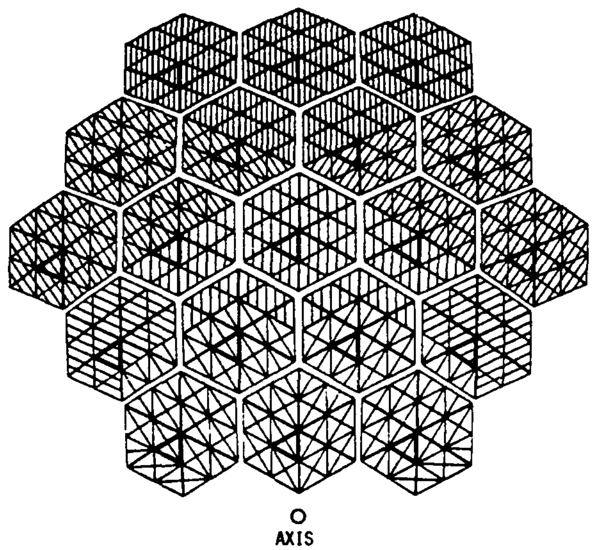


FIGURE 6. - OFFSET COLLECTOR WITH FOUR GROUPS OF TOROIDAL FACETS.

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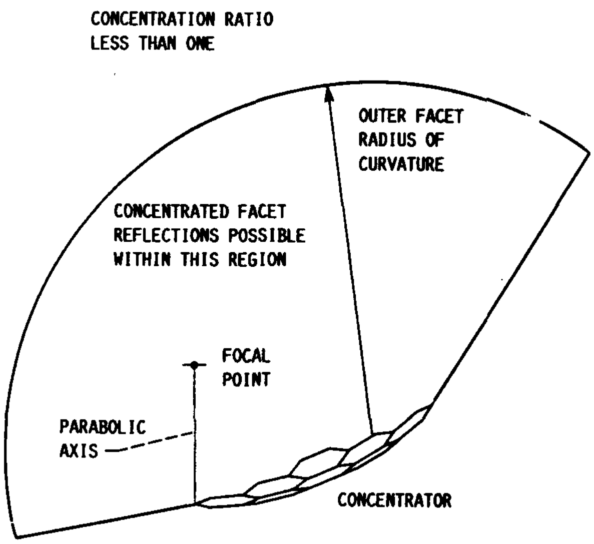

FIGURE 7. - MAXIMUM POSSIBLE EXTENT OF CONCENTRATED REFLECTIONS FROM INDIVIDUAL FACETS.

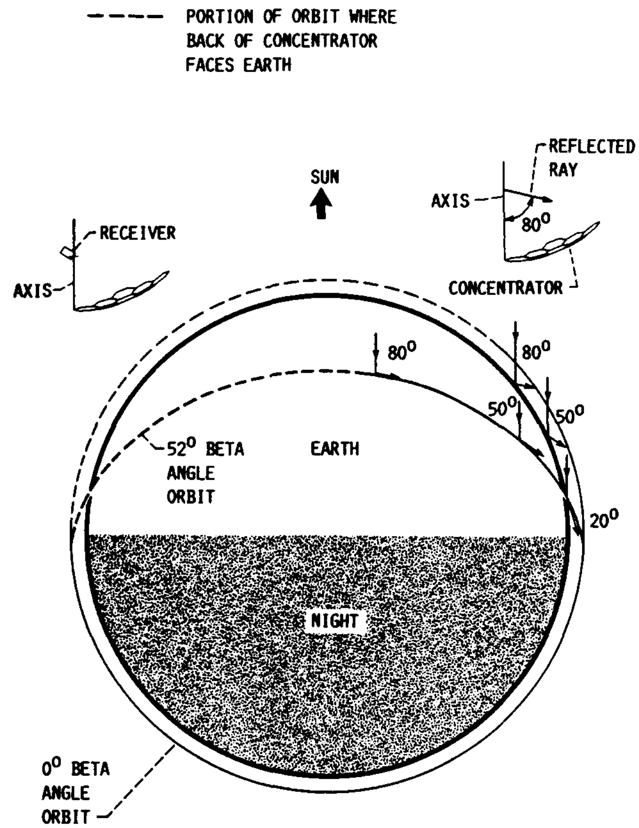

FIGURE 8. - EARTH ALBEDO REFLECTIONS TO SOLAR CONCENTRATOR IN 0° BETA ANGLE ORBIT AND 52° BETA ANGLE ORBIT. VIEW IS ORIENTED WITH SUN DIRECTLY ABOVE EARTH.

CONCENTRATION OF EARTH AND OCEAN REFLECTIONS

Earth albedo and reflections from the ocean can be reflected and to a limited degree concentrated by solar concentrators for space. Earth has an average visual albedo of 0.36, i.e., about one-third of the visible light incident on the Earth is reflected back into space. Although there is considerable scattering, the strongest reflections are in the direction of the principal ray, i.e., the direction of specular reflections. This enables some concentration. There is also a significant amount of infrared radiation from the Earth. This radiation has no preferred direction and will not be concentrated.

During normal operation, the solar concentrator is oriented with its axis pointing towards the Sun. As the space station orbits the Earth, the reflective surface of the solar concentrator receives significant reflections from the Earth called Earth albedo during a portion of each orbit. Earth orbits for Freedom are shown in Fig. 8. In this figure, the point on the Earth where the Sun is directly overhead is at the top. The orbit shown around the outline of the Earth is called the zero beta angle orbit because/it is in the ecliptic plane. There is a seasonal variation of the beta angle of the Freedom orbit to a maximum angle of 52° between the orbit plane and the ecliptic plane. The daylight portion of a 52° beta orbit is shown as an arc. The space station is on the night side of the Earth during approximately one-half of each orbit. There is a limited amount of Earth albedo reflected onto the concentrator at the beginning and end of the night portion of the orbit. Significant Earth albedo falls on the front of the concentrator during one-eighth of the zero beta orbit and during one-quarter of the 52° beta orbit. During the remainder of the daylight portion, the side edge or back of the concentrator is facing the Earth and little or no Earth albedo falls on the front of the concentrator. Points are labeled during the portions of each orbit with significant albedo on the front of the concentrator. These points are at 20°, 50°, and 80° for the zero beta orbit and at 20°, 40°, 60°, and 80° for the 52° beta orbit. The degrees represent the angle that the principal reflected ray of the Earth albedo makes with the axis of the solar concentrator.

The OFFSET code was used to evaluate concentration of Earth albedo. Reflections from the Earth and ocean could come from the entire portion of the Earth visible to the concentrator, but are more intense in the direction of the principal reflected ray. The relative intensity depends on whether the principal ray is reflected by the ocean and the smoothness of the water. Reflections were assumed to be limited to a circle of radius 50 miles at a distance from the space station of 200 miles. This increases the possible concentration ratio. Thus all the Earth albedo shining onto the concentrator was assumed to come from a cone around the principal reflected ray with an apparent radius of 250 mrad.

Based on PIXEL code results, it was expected that the greatest concentration would be on a plane one and one-half focal lengths in front of the concentrator. OFFSET code results on this plane are shown in Fig. 9 for the principal reflected ray angles of 20°, 50°, and 80°. Note in Fig. 9 that the area with concentrated Earth albedo is directly

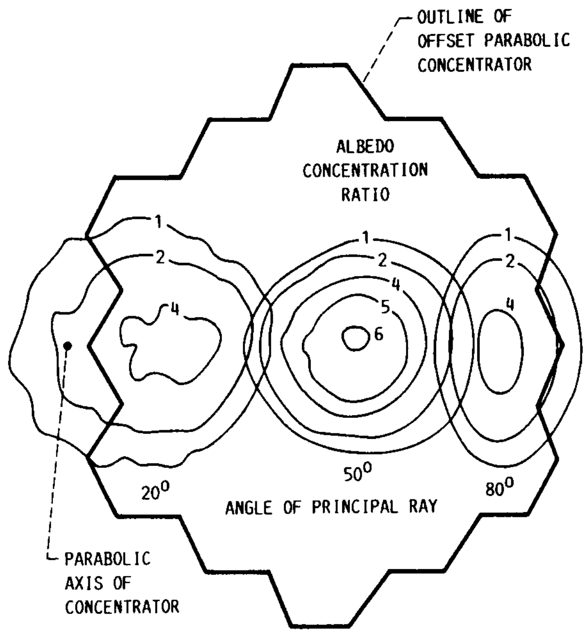

FIGURE 9. - CONCENTRATION OF EARTH ALBEDO ON PLANE 1.5 FOCAL LENGTHS ABOVE CONCENTRATOR WITH ORBIT IN ECLIPTIC PLANE.

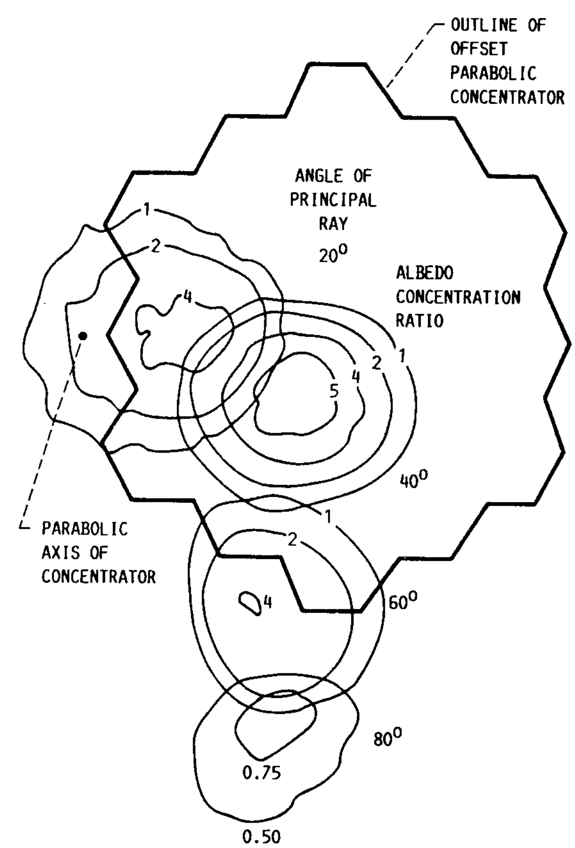

FIGURE 10. - CONCENTRATION OF EARTH ALBEDO ON PLANE 1.5 FOCAL LENGTHS ABOVE CONCENTRATOR WITH ORBIT PLANE INCLINED 52 DEG TO ECLIPTIC PLANE.

in front of the concentrator during the zero beta orbit. The concentration ratios are the flux of reflected Earth albedo in units of the incident Earth albedo. The peak intensity shown is a concentration ratio of 6 for the 50° case. The principal ray is attenuated because it passes through the atmosphere at an angle of 25° for this case. Thus the albedo will be less than the average value of 0.37 and the concentration ratio of 6 corresponds to a flux of little over one Sun.

OFFSET code results on the one and one-half focal length plane are shown in Fig. 10 for the principal reflected ray angles of 20°, 40°, 60°, and 80° for the orbit with 52° beta angle. The area with concentrated Earth albedo is in front of the concentrator for angles of the principal ray with the concentrator axis of 20° and 40°. The 60° area is over the edge of the concentrator and the 80° area is off to the side of the concentrator. Note that with an angle of 80°, the peak concentration ratio of Earth albedo is less than one.

CONCENTRATION OF POINT SOURCES AND RF SOURCES

This section is intended to complete the review of potential off-axis concerns. Previous sections discussed concerns due to the Sun (large and small off-axis angles) and to Earth albedo. The remaining concerns are point sources and RF sources.

For a source to become a concern, the concentrator must reflect sufficient energy from the source to cause damage to something in the vicinity of the concentrator. Extremely small light sources such as reflections of starlight which could disrupt star-tracking instrumentation can be safely accommodated with logic built into instrumentation to ignore any signals coming from the location of the concentrator. Reflections of RF signals may be a concern even if the energy level is small, because the RF instrumentation may not be able to determine that the energy was reflected by the concentrator. Thus the remaining concerns are (1) point sources of light which illuminate the concentrator with a significant amount of energy and (2) the nonvisible portions of the electromagnetic spectrum.

Point sources of light in the immediate vicinity of the concentrator will need to be evaluated on a case-by-case basis. Low power light sources can generally be ignored, because mirrors cannot reflect more power than the source produces. Reflections of light sources outside the facet radius of curvature boundary shown in Fig. 7 can only converge to areas inside this boundary. Thus the major remaining concern for point light sources are high power sources inside the facet radius of curvature boundary. This is a cautionary reminder rather than a serious concern because high power sources in this region are unlikely.

The major nonvisible sources are RF sources either located on Freedom or beamed from Earth towards Freedom. The concentrator facets have a graphite epoxy substrate which is reflective to RF, but the facets are staggered with steps of up to 4 in. between facets which will interfere with reflection and focusing of some RF frequencies.

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CONCLUDING REMARKS

Off-axis radiation is sunlight or, in general, any radiation from any direction not parallel to the parabolic axis of the solar concentrator. Four types of off-axis radiation include: (1) walk-off, (2) large off-axis angles, (3) extended off-axis sources, and (4) miscellaneous off-axis sources.

Walk-off was the primary off-axis concern in the terrestrial energy program. Walk-off is caused by failure of both concentrator gimbals, because if only one gimbal fails, the other gimbal will be used to rapidly bring the concentrator off sun. Walk-off due to a pointing system failure in low Earth orbit is considerably faster (4°/min) than terrestrially (1° every 4 min). Thus the duration of exposure to the concentrated beam is considerably shorter. Still, special materials and/or other precautions will be required to protect the Freedom receiver from walk-off.

Concentration of parallel light at large off-axis angles was evaluated using a combination of computer simulation, experiment, and optical analysis. Concentration on planes perpendicular to the parabolic axis was analysed using the PIXEL code which was validated by an experiment using an 11 m diameter multifaceted dish concentrator. High concentration ratios, up to 4.5 for symmetric concentrators and 103 for offset concentrators were found to exist even on the plane two focal lengths from the parabolic vertex. The concentration ratio from individual facets is less than one at distances of the facet contour radius of curvature from the facets. Continued analysis is planned to evaluate concentration of parallel light and to define precautions that may be required in the region where concentration is possible.

Concentration of extended light sources such as Earth and ocean reflections was analyzed using the OFFSET code which models the Freedom concentrator. As the space station orbits the Earth, the reflective surface of the solar concentrator receives Earth albedo during one-eighth to one-quarter of each orbit. The highest concentrations were expected on a plane one and one-half focal lengths in front of the concentrator. The peak intensity was located directly in front of the middle of the concentrator. The peak intensity was an Earth albedo concentration ratio of 6. This peak is approximately the intensity of unconcentrated sunlight.

In general, the potential off-axis concerns mentioned in this paper do not impact the overall Freedom project. They are design constraints for the design and safe operation of the solar dynamic system and the surrounding region. Walk-off flux will be taken care of by the design of the receiver aperture plate and surrounding structure. The boundary for concentration of parallel light has been defined and will define the region within which precautions may be required. Earth albedo concentrations were calculated to have a peak value equivalent to the intensity of unconcentrated sunlight and are not expected to cause any problems. High intensity sources are not planned for the vicinity of the concentrator and will be excluded from this region. As rf sources and communications become defined, evaluations of rf reflections by the concentrator will be made to ensure that there is no interference.

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16. Abstract

Off-axis radiation is sunlight or, in general, any radiation from any direction not parallel to the axis of the solar concentrator. It will be reflected to regions other than the focus of the parabolic concentrator and possibly concentrated there. Four types of off-axis radiation are discussed. These are (1) small off-axis angles during walk-off, (2) large off-axis angles, (3) an extended off-axis source such as Earth albedo, and (4) miscellaneous off-axis sources including radio frequency sources and local point sources. A previous analytical study used a computer code named PIXEL to predict concentration of off-axis radiation and a previous experimental study used an 11-m diameter multifaceted dish concentrator to validate the PIXEL analysis. The PIXEL code was limited in that it represented concentration by an ideal parabolic reflector of light from a point source. Another code named OFFSET has been developed to represent the solar concentrator being developed for Space Station Freedom. It is a detailed, ray tracing model which represents 50 ray originating points on the Sun and reflections from 10 points on each of the 456 concentrator facets. Results of this code are generally similar to the PIXEL results although there are small differences due to the more detailed representations of the Sun and concentrator that were used in the OFFSET code.

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