FOS Exposure Limits

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Abstract

FOS Digicon detector exposure safety limits are investigated, with consideration given to both instantaneous and cumulative damage thresholds. Recommendations are developed concerning the use of the internal calibration lamps, external target brightness restrictions, and the 'overlight' protection.

I. Introduction

The scheduling and commanding system at the STScI must operate the FOS in a manner that ensures its safety and longevity as well as its efficient collection of scientific and calibration data. The 'overlight sum' protective device in the FOS, which will cause the instrument to 'safe' if the total counts (over all enabled channels) exceeds the overlight limit for two consecutive major frame (60 s) periods, is one means of ensuring detector safety. Its protection is limited, however; if the overlight limit is not carefully chosen, this protection will be either lost, or the FOS may be unnecessarily safed, having a very deleterious effect on observing efficiency. Another means of promoting safe FOS operation is to select only targets and FOS configurations that will result in count rates and accumulated count doses that do not exceed limits which are known from laboratory tests (and other considerations) below which detector degradation is unlikely.

Special care is required when specifying observations which utilize the camera mirror (target acquisition), the G160L grating, or the prism. The camera produces very compact, undispersed images of point sources, and G160L produces a high efficiency (approx. 40%) zero-order image on the detector. The very low dispersion produced by the prism at long wavelengths can also lead to high flux density on the detector photocathodes, especially dangerous on the red side of the FOS.

The internal calibration lamps are also problematic, especially on the red side, because of their relatively prodigious output into a forest of about two dozen neon lines at wavelengths above 5850 Å. While the cross-strapped lamp can be selected to diminish the line intensities, this can result in long exposure times for the UV gratings, impacting observing efficiency and lamp longevity.

The following analysis attempts to formulate a consistent set of target brightness and overlight limits, and cal lamp management rules that permit safe, long-term FOS operation without unduly degrading operational efficiency.

II. Exposure Limit Considerations

a) Instantaneous Flux Density Limits

We do not have any laboratory data from which an estimate can be made of the flux density of photo-electrons (pe) which causes damage to either the bi-alkalai or S-20 photocathodes. An SAI memo (Kepinski,1980) cites a cannonical limit of 1μ-amp/cm^2 for continuous exposure, corresponding to $6 \cdot 10^{12}$ pe/cm^2/s, for S-20. Presumably, the damage mechanism is some combination of ohmic heating and chemical poisoning (from ion implantation and/or surface reaction with material electron scrubbed off the anode). The bialkalai photocathode is much hardier, and is not sensitive to wavelengths longer than 5500 Å, where much of the flux from most potential FOS targets and the strong neon lines from the cal lamps reside.

The F8 S-20 digicon was accidentally exposed to a flux density of about $1.8 \cdot 10^6$ pe/s in the camera mirror image of the A4 apertures, illuminated by the direct internal cal lamp. This corresponds to a flux density of about 10^{12} pe/cm^2/s in the 15 micron diameter image. A special test was performed to determine if any damage resulted from this exposure: none was detected. Although F8 does not have a very high red response, its photocathode is very fragile, and we might have expected to see damage if 10^{12} pe/cm^2/s is close to the actual damage threshold. It would seem prudent to set an operational limit of 10^{11} pe/cm^2/s.

b) Cumulative Exposure Limits

Laboratory tests were made by Ed Beaver to determine the cumulative effects of continuous exposure at flux levels well below the limits discussed above (Harms, 1984). The EM3 test digicon, which had very good red response (comparable to that of F12), was first exposed to an accumulated dose of 10^{16} pe/cm^2, where the photocathode was illuminated over a small area (a slit image). No degradation of the QE (presumably measured in the area of the illumination) was observed. The tube was then illuminated over its entire faceplate to an accumulated dose of 10^{15} pe/cm^2 ($6 \cdot 10^{15}$ pe, integrated over the photocathode); again, no degradation was measurable. The exposure was continued to $5 \cdot 10^{15}$ pe/cm^2, whereupon QE measurements showed a clear drop in the red response. Subsequent exposure at reduced voltage (600V) to the same accumulated dose produced an additional marked reduction of the red response tail.

From these tests we can infer that the FOS digicons can be safely operated to accumulated doses of about 10^{15} pe. However, during flight operation the illumination will almost always be over very small areas of the photocathode, in contrast to the broad illumination utilized for the latter parts of the lifetime test, so the tests do not provide us with clear guidelines. As mentioned above, damage may be caused by chemical reaction with material that is electron scrubbed off the anode, or by some process involving ions impinging on the photocathode. If the former is the dominant mechanism, we should concern ourselves only with the total accumulated dose; however, if ion implantation is the major source of degradation, the dosage into relatively small areas of the photocathode must be considered. This is because an ion strikes the cathode at a location very near to the creation point of the photoelectron which produced it.

{ The minimal area over which we need to consider the cumulative dose may be estimated from the Larmor radius (35 microns) of a 1eV photoelectron (presumed typical) in the 100 gauss digicon field; an ion created by the photoelectron will likely hit the cathode within a radius of 70 microns of the point of illumination. The dose of 10^{16} pe/cm^2 that was seen to produce no damage with slit illumination in the life tests corresponds to about $1.5 \cdot 10^{12}$ pe accumulated in an area of this size. Since the suggested flux limit of 10^{11} pe/cm^2/s corresponds to a rate of $2 \cdot 10^5$ pe/s into the smallest image which the FOS can produce (camera with point source), the accumulated dose limit will be reached after 2000 hrs of exposure at this maximum flux.}

An important result of the life test is that, while a dose of 10^{16} pe/cm^2 in a slit image apparently caused no damage, half that dose over the full faceplate produced a definite decline in red response. It is likely, therefore, that the ion implantation mechanism is not dominant. Reasonable choices of cumulative dose limits are: 10^{15} pe (integrated over photocathode) and 10^{16} pe/cm^2 over the *effective* image area, accounting the spread of ions for very small images.

c) Calibration and TA Accuracy Considerations

Another factor that influences the choice of operational exposure limits is the calibration accuracy that can be achieved at high count rates. Lindler and Bohlin (1988) have shown that the FOS linearity correction uncertainty is 5% at 10^5 true cts/s/diode, and deteriorates rapidly to 25% at $1.5 \cdot 10^5$. The individual channel responses also begin to diverge sharply at rates just above 10^5 cts/s/diode, so that the flat field uniformity degrades markedly. It is reasonable to limit the maximum flux density to 10^5 pe/s/diode, at least for most purposes. This may be waived for data which do not require accurate flux calibration, such as wavelength calibration spectra.

Mode 2 target acquisition, in the Binary Search mode (the only autonomous mode currently being supported), finds the Y position of the target by placing its image on the edge of the diode array, such that the observed count rate is exactly halved. Since no linearity correction is performed, this method may be subject to error at high count rates. The correction factor is 2 at true rates of 10^5 cts/s/diode. However, software simulation of the performance of the binary search algorithm has shown that at this rate the paired-pulse induced error in target position determination is small, due to the very narrow predicted point spread function (Ford, 1988).

d) Adopted Limits

In summary, we can adopt the following operational exposure limits with a high degree of confidence that detector safety and data integrity will be maintained:

- Count rate: $< 10^5$ pe/s/diode (where flux cal required)
- Flux density at photocathode: $< 10^{11}$ pe/cm^2/s
- Total accumulated events: $< 10^{15}$ pe
- Accumulated event density at any spot on photocathode: $< 10^{16}$ pe/cm^2

III. Operational Constraints

In this section, we examine the limitations on source brightness and FOS observing configuration that are mandated by the limits adopted above. Because the illumination of the photocathode varies greatly depending upon which filter grating wheel element is selected, and whether an external target or the internal cal lamps are used, these cases are discussed separately.

a) Target Acquisition

Camera mirror images of point sources are extremely compact at the detector photocathode, due to the excellent image quality provided by both the ST OTA and the FOS, and the FOS demagnification (m=.5). Performance prediction calculations have shown that the OTA/FOS will place about 35% of the visible energy from a point source into an image core whose FWHM is about 10 microns in diameter. The flux density limit of 10^{11} pe/cm^2/s corresponds to a count rate of $7.9 \cdot 10^4$ pe/s in the core, or, assuming all the pe are counted by a single diode, $2.2 \cdot 10^5$ pe/s/diode. This is slightly less stringent than the adopted count rate limit.

When applying the accumulated event density limit to the TA images, the expected spread in the ion 'image' must be considered, reducing to a limit of about $1.5 \cdot 10^{12}$ pe in the TA image. At the maximum permitted rate, about $1.5 \cdot 10^7$ s, or 4000 hours, of exposure is required to reach this dose; this is not restrictive.

b) Spectra of Continuum Sources

1. High Resolution Gratings Point source images produced with the high resolution gratings are approximately 30 microns tall (cross-dispersion direction). The permitted flux density corresponds to an event rate of $1.5 \cdot 10^6$ pe/s/diode, well in excess of the adopted maximum count rate. The ion spread will again ameliorate the accumulated exposure limitation by extending the width of the exposed area from the approximately 30 micron image width to about 150 microns. The limiting exposure, at the maximum permitted count rate, occurs after about $8 \cdot 10^6$ s, or over 2000 hrs; again, this is not restrictive. Approximately $5 \cdot 10^{14}$ pe events will occur during these 2000 hrs of exposure, so the adopted limit on total cumulative dose is less stringent.

The stellar magnitudes (visual, A5V star) at which the count rate limit is reached for each grating/detector combination are indicated in Table 1., based on FOS simulator results.

2. Low Resolution Gratings The zero order diffraction of grating G160L images about 40% of the visible flux from a point source into a feature approximately 80 microns in diameter on the detector photocathode. The flux density limit reduces to a true count rate limit of about $4 \cdot 10^6$ cts/s/diode. Since there is no need for flux calibration of the zero order feature, the normal count rate limit is not applicable there. FOS simulator results indicate that the flux density limit in the zero order image will be reached at a normal star (A5V) visual magnitude of about 7.4 on the red side; the spectrum will peak at about 2600 cts/s/diode at this magnitude, nearly a factor of 40 less than the adopted count rate limit. On the blue side, the limiting magnitude is 6.3, at which the spectrum peaks at about 4000 cts/s/diode.

The zero order feature of the G650L grating, imaged onto the detector like that of G160L, is relatively inefficient (about 5%). The count rate limit is reached in the spectrum, with both blue and red detectors, at lower target brightness (by about 1 stellar magnitude) than required to breach the flux density limit in the zero order image.

The cumulative event density and total count limits are not restrictive for either of the low resolution gratings.

c) Internal Cal Lamp Exposures

In order to guage the exposure levels produced by the cal lamps in each relevant FOS configuration, calculations have been made, based on spectra obtained through the smallest (A4, 0.1 arcsec) apertures, of the peak flux density and total true count rates. Linearity corrections were applied and the imaging characteristics of the FOS were taken into account. The results are contained in Tables 2–4. The flux density limit was found to be exceeded for several configurations on the FOS red side.

The internal cal lamps produce a bright line spectrum that illuminates the entrance apertures in an approximately uniform manner. The flux in the neon lines longward of 5850Å is particularly strong, so that very high count rates occur on the red detector and special constraints on cal lamp use apply. Since the blue detector is insensitive to the neon lines, cal lamp operation on that side is not restrictive for any disperser/science-aperture combination.

The cal lamps can be used in either the direct or 'cross-strapped' mode (a beam-splitter arrangement permits either of the two lamps to be used on either side of the spectrograph). Utilization of the cross-strapped lamp results in a flux reduction of 20 to 30 in the region of the bright neon lines. The flux density limit is not violated by any side/disperser/aperture combination with the cross-strapped cal lamp.

The following discussion refers to direct cal lamp spectra obtained on the FOS red side, except where explicitly stated otherwise.

1. G570H (H57) The estimated direct lamp flux density for the neon line images in the G570H spectrum reaches a maximum (for the line at 5852Å) at about $1.5 \cdot 10^{11}$ pe/cm^2/s, through the A1 (TA) aperture. The flux density is only weakly dependent on aperture size, falling to about $4 \cdot 10^{10}$ through the A4 apertures, where the optical aberrations increase the effective image area. To meet the flux density limit criterion, direct cal lamp usage with G570H should be limited to aperture sizes less than or equal to 1 arcsec (thus eliminating the A1 and C3 apertures). The count rate limit will be clearly violated in the line peaks even for the smallest apertures. However, since accurate linearity correction is not a requirement for the wavelength calibration when the lines are well enough isolated that blending is insignificant, the count rate limit can be waived for the small apertures (A4 and B2) that are used for the template wavelength cal spectra (Sirk and Bohlin, 1986). G570H spectra through apertures larger than 0.3 arcsec should be obtained with the cross-strapped cal lamp.

2. G780H (H78) The flux densities produced by G780H are very similar to those for the G570H grating, and the same restrictions apply.

3. G650L (L65) The optical quality of the G650L grating images is somewhat inferior to that of the the high resolution gratings, as is its efficiency; for small apertures these factors reduce the flux density somewhat, in comparison to G570H. However, for larger apertures, the lower dispersion of this grating leads to significant line blending, increasing the flux density relative to G570H and contributing to inaccuracy in the calibration, due to poor linearity correction. The flux density limit is reached for apertures greater than 0.5 arcsec with the direct cal lamp; apertures A1, B3, C1, C3 and C4 should not be used with this lamp and grating.

4. G160L (L15) The zero order diffraction of grating G160L images about 40% of the visible flux from a point source into a feature approximately 80 microns in diameter on the detector photocathode. The flux density limit is exceeded for aperture sizes greater than .3 arcsec with the direct cal lamp; i.e., all apertures *except* A3, A4, and B2 should be avoided.

5. PRISM (PRI) The very low dispersion of the prism at the long wavelengths of the neon lines causes the flux density limit to be exceeded for all but the smallest (A4) apertures. Even with the A4 aperture, the line blending and linearity correction are severe.

The flux density limit is also violated with the direct cal lamp and the A1 (TA) aperture on the blue side; smaller (science) apertures do not exceed the limit.

6. Lamp and detector lifetime considerations Safe flux densities can be achieved for all FOS disperser/aperture configurations by selection of the cross-strapped cal lamp, rather than the direct lamp. However, this strategy should be utilized only when necessary. The exposure times required for each calibration spectrum are dictated by the integrated observed count levels reached in the spectral lines, so cross-strapped lamp exposures must generally be longer than those with the direct lamp, costing both spacecraft observing time and lamp operation time, with no savings of integrated tube dose. This argument breaks down when the true count rates are so great that very large deadtime losses occur and the exposure times for direct and cross-strapped cal lamps become both very short and similar. This is the case for large apertures with long wavelength dispersers on the red side, for which use of the cross-strapped lamp incurs little additional operation time and permits a (slight) reduction of the integrated dose. The same is *not* true of G160L calibration, since the far UV lines are weak, and long exposure times are required for even the direct lamp. It is particularly important to conserve the life of the direct blue (red cross-strapped) lamp, since the lines are very weak below 1500Å and the cross-strapped lamp requires extreme exposure times at these short wavelengths.

A life test was performed in 1981 at JHU on a Pt/Cr-Ne hollow cathode lamp similar to those used in the FOS. This test showed that, when operated at a duty cycle of about 23% (30 s on, 100 s off) at 10 mA (as in the FOS), the lamp produced reasonable spectral line output for 1100 operating hours, at which point its output dropped dramatically. The failure mechanism is presumed to be the accumulation of a conductive path of material sputtered from the cathode onto the tube wall that prevents the discharge from occuring in the cathode hollow. The calibration requirements of the FOS have been estimated at about 24000 cycles of 25 s lamp operation time, or less than 200 hrs cumulative exposure.

The flux density limit for all cal lamp configurations is considerably more restrictive than the cumulative dose limit: approximately 3000 hrs of operation are required to reach this limit for the permitted configuration producing the highest total event rate, i.e. the G650L grating with the A2 aperture pair and direct cal lamp on the red side. This is about 3 times the expected lamp lifetime.

The cumulative event density is considerably more restrictive, however. Again, the G650L grating, A2 apertures and direct cal lamp configuration provides the highest effective flux density; about 100 hours of exposure are required to reach 10^{16} pe/cm^2. Since the required exposure times for wavelength calibration are only a few seconds, and calibrations are expected to be performed only rarely for this configuration, this is several orders of magnitude longer than is likely to be needed during the FOS lifetime.

7. Summary of cal lamp restrictions The direct cal lamps should be used when the flux density limit is not violated, except where deadtime correction inaccuracies impair the calibration. The flux density limit is violated for the G570H, G780H, G150L, G650L, and PRISM dispersers, on the red side only, when these are used with all but the smallest apertures and the direct cal lamp. Although the (small aperture) template wavelength cal spectra could be obtained with the direct lamp for these dispersers, it is recommended that, excepting the G160L grating, the cross-strapped lamp be used for all apertures with these dispersers. This may result in slightly greater calibration accuracy, since there are non-linear offsets between calibrations obtained with the two lamps, and the linearity corrections will be more accurate, thus enhancing the calibration accuracy near line blends. Because of the long exposure time required for the G160L grating and its relatively lax wavelength calibration accuracy requirement, the direct lamp should be used for the A4, A3 and B2 aperture calibrations, and the cross-strapped lamp invoked for calibration with the larger apertures on the red side. No violations of the flux density limit will occur with the cross-strapped lamp.

The only restriction required for cal lamp operation on the blue side is that the PRISM, A1 (TA) aperture, and direct cal lamp combination should not be used; this configuration should never be required.

IV. Overlight Protection

The safe overlight sum depends dramatically on the manner in which the photocathode is illuminated. For point source TA, the permitted 10^5 pe/s/diode count rate is contained within a single diode width, so that the observed (paired-pulse corrected) total count rate is about $5 \cdot 10^4$ cts/s, per stellar object in the 4.3 arcsec field. Assuming a maximum of two such objects, this corresponds to an overlight sum limit of $6 \cdot 10^6$ cts. The same, safe count rate limit, when applied to a continuum spectrum, requires an overlight sum about 250 times this level, at $1.5 \cdot 10^9$ cts., very near the maximum possible value of $2.1 \cdot 10^9$ cts (all channels saturated at about $7 \cdot 10^4$ cts/s). The overlight sum required for continuous cal lamp operation for each aperture/disperser combination is shown in the last column in Tables 2-4. The largest value for a valid, safe configuration (G270H, C3, direct cal lamp, blue side) is $9.5 \cdot 10^8$ cts., while the lowest overlight sum for continuous operation in an *unsafe* configuration (G160L, B1, direct cal lamp, red side) is $3.9 \cdot 10^7$ cts.

It is clear that no single value of the overlight sum can permit operation of the FOS over its full, safe range of exposure, while simultaneously providing protection from damaging flux levels in some configurations. An obvious solution is to adjust the overlight limit according to the expected total count rate. This capability is not currently implemented in the command flows and would require considerable effort to assure that proper limits would always be set. A simplified version of this approach might be most appropriate: the overlight limit being set to $6 \cdot 10^6$ cts for all TA observations, and a much higher level for all other observations. The limit calculated above to correspond to the maximum count rate neglects the dead time, which is likely to be relatively large for observations of such a bright source, and requires that all diodes count at the maximum permitted rate – an unlikely spectral shape! An overlight limit of 10^9 cts would certainly accomodate all likely safe observations, including cal lamp exposures. A lower overlight limit would be inconsistent with the estimates of detector safety limits derived above (and the published count rate and target brightness limits in the CARD, OLD and Proposal Instructions).

Improper use of the cal lamps should be prevented by implementation of a set of standard exposures, specifying use of the cross-strapped lamp where the direct lamp fluxes are excessive, and limiting the lamp operating time to the minimum required for accurate calibration. Appropriate exposures are detailed by Hartig (1988), following the general wavelength calibration strategy outlined by Sirk and Bohlin (1986). These cal lamp management rules should be an extension of the restrictions inserted in the CARD, which should constrain cal lamp configurations to those which are safe. The overlight protection should not serve as a means of limiting cal lamp operation time; autonomous safing of the FOS, with its concomitant loss of FOS observing time and scheduling ramifications, is too costly for the cal lamp lifetime that might be saved during an inadvertantly long cal lamp exposure.

V. Conclusions

A reasonable limit to the true count rate (pe event rate) for most purposes is 10^5 cts/s/diode. This rate is generally 3 orders of magnitude below the cannonical flux density limit for continuous exposure of an S-20 photocathode, and two orders of magnitude below levels to which we have exposed such detectors without evidence of damage. Somewhat higher local count rates may be tolerated in special cases where absolute flux calibration is not required, especially for wavelength calibration spectra of the internal Pt/Cr-Ne lamps. In these cases, the adopted flux density limit (10^{11} pe/cm^2/s) must not be violated; this results in restrictions on use of the red side direct cal lamp with dispersers which cover the spectral region above 5800 Å, and the G160L grating (due to its efficient zero order diffraction). In no case were cumulative event limits, based on life testing of the EM3 S-20 digicon, found to be more restrictive than the adopted instantaneous flux density limits.

Because of the large disparity in the ratio of flux density to total count rate (integrated over the diode array) for non-dispersed (target acquisition) and normal spectral observations, the overlight sum limit should be set to different values for these two applications. To be consistent with the adopted exposure limits, overlight sum limits of $6 \cdot 10^6$ and 10^9 cts are required for TA and dispersed observations, respectively. The commanding software required to support this adjustment should be developed as soon as possible.

References

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Table 1. FOS Bright Limiting V Magnitudes

(A5V star, unreddened)

Disperser/Mirror	Red Side Limit	Blue Side Limit
G130H (H13)	—	-2.5
G190H (H19)	2.6	2.0
G270H (H27)	3.6	3.4
G400H (H40)	5.2	4.6
G570H (H57)	5.2	3.9
G780H (H78)	4.1	—
G160L (L15)	7.4	6.3
G650L (L65)	6.9	6.1
PRISM (PRI)	8.9	8.3
MIRROR (CAM)	12.3	11.2

Table 1 (cont'd). FOS Red Side Direct Cal Lamp Exposure Estimates

H78

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	2.324E+06	4.400E-05	5.281E+10	2.072E+07	1.882E+08
B2	1.023E+06	2.664E-05	3.840E+10	6.776E+06	1.136E+08
B3	6.062E+06	7.900E-05	7.674E+10	8.951E+07	3.543E+08
A1	1.704E+07	1.000E-04	1.704E+11	7.756E+08	9.784E+08
A2	3.156E+06	4.400E-05	7.172E+10	2.814E+07	2.096E+08
A3	9.264E+05	2.125E-05	4.359E+10	6.137E+06	1.091E+08
A4	2.283E+05	1.125E-05	2.029E+10	1.277E+06	4.628E+07
C1	6.571E+06	7.900E-05	8.318E+10	1.176E+08	4.061E+08
C2	5.983E+06	7.900E-05	7.573E+10	3.964E+07	2.227E+08
C3	1.185E+07	8.900E-05	1.331E+11	2.760E+08	6.154E+08
C4	6.409E+06	8.900E-05	7.201E+10	9.462E+07	3.612E+08

L15 (Zeroth Order)

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	5.591E+06	7.100E-05	7.875E+10	9.685E+06	3.938E+07
B2	2.170E+06	5.364E-05	4.045E+10	3.168E+06	2.175E+07
B3	1.690E+07	1.000E-04	1.690E+11	4.184E+07	1.027E+08
A1	2.922E+07	1.000E-04	2.922E+11	3.684E+08	5.080E+08
A2	7.593E+06	7.100E-05	1.069E+11	1.315E+07	4.713E+07
A3	1.965E+06	4.825E-05	4.072E+10	2.870E+06	2.081E+07
A4	4.814E+05	3.825E-05	1.258E+10	5.978E+05	1.088E+07
C1	1.882E+07	1.000E-04	1.882E+11	5.500E+07	1.254E+08
C2	1.269E+07	1.000E-04	1.269E+11	1.853E+07	5.781E+07
C3	2.369E+07	1.000E-04	2.369E+11	1.291E+08	2.369E+08
C4	1.786E+07	1.000E-04	1.786E+11	4.424E+07	1.068E+08

L65

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	3.006E+06	6.000E-05	5.010E+10	3.663E+07	3.134E+08
B2	1.141E+06	4.264E-05	2.675E+10	1.198E+07	1.983E+08
B3	8.938E+06	9.500E-05	9.409E+10	1.583E+08	5.402E+08
A1	3.686E+07	1.000E-04	3.686E+11	1.393E+09	1.098E+09
A2	4.082E+06	6.000E-05	6.804E+10	4.975E+07	3.488E+08
A3	1.033E+06	3.725E-05	2.774E+10	1.085E+07	1.906E+08
A4	2.565E+05	2.725E-05	9.413E+09	2.261E+06	8.230E+07
C1	9.821E+06	9.500E-05	1.034E+11	2.080E+08	5.984E+08
C2	6.672E+06	9.500E-05	7.024E+10	7.010E+07	3.827E+08
C3	1.821E+07	1.000E-04	1.821E+11	4.882E+08	8.097E+08
C4	9.449E+06	1.000E-04	9.449E+10	1.673E+08	5.501E+08

PRI

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	9.724E+06	4.400E-05	2.210E+11	3.560E+07	1.656E+08
B2	3.677E+06	2.664E-05	1.380E+11	1.165E+07	9.837E+07
B3	3.440E+07	7.900E-05	4.355E+11	1.538E+08	2.820E+08
A1	9.431E+07	1.000E-04	9.431E+11	1.354E+09	5.447E+08
A2	1.321E+07	4.400E-05	3.001E+11	4.834E+07	1.867E+08
A3	3.330E+06	2.125E-05	1.567E+11	1.055E+07	9.376E+07
A4	7.908E+05	1.125E-05	7.029E+10	2.197E+06	4.247E+07
C1	4.110E+07	7.900E-05	5.203E+11	2.021E+08	3.071E+08
C2	2.151E+07	7.900E-05	2.722E+11	6.812E+07	2.082E+08
C3	7.057E+07	8.900E-05	7.929E+11	4.746E+08	3.918E+08
C4	3.637E+07	8.900E-05	4.086E+11	1.626E+08	2.867E+08

Table 2. FOS Red Side Direct Cal Lamp Exposure Estimates

H19

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	6.278E+03	3.900E-05	1.610E+08	1.259E+05	7.443E+06
B2	2.490E+03	2.164E-05	1.151E+08	4.118E+04	2.457E+06
B3	1.698E+04	7.400E-05	2.295E+08	5.439E+05	3.116E+07
A1	4.345E+04	1.000E-04	4.345E+08	4.773E+06	2.392E+08
A2	8.526E+03	3.900E-05	2.186E+08	1.710E+05	1.006E+07
A3	2.255E+03	1.625E-05	1.388E+08	3.729E+04	2.226E+06
A4	514.	6.250E-06	8.225E+07	7.768E+03	4.655E+05
C1	1.858E+04	7.400E-05	2.510E+08	7.149E+05	4.062E+07
C2	1.456E+04	7.400E-05	1.968E+08	2.409E+05	1.400E+07
C3	2.576E+04	8.400E-05	3.066E+08	1.678E+06	9.192E+07
C4	1.795E+04	8.400E-05	2.137E+08	5.750E+05	3.286E+07

H27

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	3.003E+04	3.900E-05	7.699E+08	7.878E+05	4.454E+07
B2	1.241E+04	2.164E-05	5.737E+08	2.578E+05	1.510E+07
B3	7.897E+04	7.400E-05	1.067E+09	3.404E+06	1.715E+08
A1	2.949E+05	1.000E-04	2.949E+09	2.995E+07	9.383E+08
A2	4.078E+04	3.900E-05	1.046E+09	1.070E+06	5.935E+07
A3	1.124E+04	1.625E-05	6.919E+08	2.334E+05	1.371E+07
A4	2.600E+03	6.250E-06	4.161E+08	4.863E+04	2.903E+06
C1	8.780E+04	7.400E-05	1.186E+09	4.475E+06	2.186E+08
C2	7.261E+04	7.400E-05	9.813E+08	1.508E+06	8.031E+07
C3	1.441E+05	8.400E-05	1.716E+09	1.050E+07	4.496E+08
C4	8.349E+04	8.400E-05	9.939E+08	3.599E+06	1.798E+08

H40

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	1.630E+05	3.900E-05	4.179E+09	2.824E+06	1.246E+08
B2	6.510E+04	2.164E-05	3.008E+09	9.238E+05	4.784E+07
B3	4.434E+05	7.400E-05	5.992E+09	1.221E+07	3.718E+08
A1	1.862E+06	1.000E-04	1.862E+10	1.074E+08	1.307E+09
A2	2.213E+05	3.900E-05	5.675E+09	3.835E+06	1.570E+08
A3	5.896E+04	1.625E-05	3.628E+09	8.367E+05	4.382E+07
A4	1.417E+04	6.250E-06	2.267E+09	1.743E+05	1.008E+07
C1	4.841E+05	7.400E-05	6.542E+09	1.604E+07	4.516E+08
C2	3.808E+05	7.400E-05	5.146E+09	5.403E+06	1.938E+08
C3	9.349E+05	8.400E-05	1.113E+10	3.765E+07	7.757E+08
C4	4.687E+05	8.400E-05	5.580E+09	1.291E+07	3.848E+08

H57

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	2.546E+06	3.900E-05	6.528E+10	3.007E+07	3.377E+08
B2	1.092E+06	2.164E-05	5.046E+10	9.838E+06	1.887E+08
B3	6.663E+06	7.400E-05	9.004E+10	1.299E+08	6.858E+08
A1	1.539E+07	1.000E-04	1.539E+11	1.143E+09	1.567E+09
A2	3.458E+06	3.900E-05	8.866E+10	4.084E+07	3.874E+08
A3	9.890E+05	1.625E-05	6.086E+10	8.910E+06	1.799E+08
A4	2.359E+05	6.250E-06	3.775E+10	1.856E+06	6.982E+07
C1	7.257E+06	7.400E-05	9.806E+10	1.708E+08	7.814E+08
C2	6.387E+06	7.400E-05	8.632E+10	5.755E+07	4.363E+08
C3	1.112E+07	8.400E-05	1.324E+11	4.009E+08	1.121E+09
C4	7.043E+06	8.400E-05	8.385E+10	1.374E+08	7.014E+08

Table 2 (cont'd). FOS Blue Side Direct Cal Lamp Exposure Estimates

L15

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	1.366E+06	7.100E-05	1.923E+10	2.168E+06	3.308E+07
B2	5.555E+05	5.364E-05	1.036E+10	7.092E+05	1.450E+07
B3	3.325E+06	1.000E-04	3.325E+10	9.364E+06	1.021E+08
A1	5.597E+06	1.000E-04	5.597E+10	8.270E+07	4.182E+08
A2	1.854E+06	7.100E-05	2.612E+10	2.944E+06	4.136E+07
A3	5.031E+05	4.825E-05	1.043E+10	6.423E+05	1.364E+07
A4	5.990E+04	3.825E-05	1.566E+09	7.645E+04	3.270E+06
C1	3.608E+06	1.000E-04	3.608E+10	1.230E+07	1.257E+08
C2	3.249E+06	1.000E-04	3.249E+10	4.148E+06	5.193E+07
C3	4.523E+06	1.000E-04	4.523E+10	2.883E+07	2.301E+08
C4	3.515E+06	1.000E-04	3.515E+10	9.899E+06	1.063E+08

L65

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	2.107E+05	6.000E-05	3.512E+09	1.761E+06	7.278E+07
B2	7.058E+04	4.264E-05	1.655E+09	5.761E+05	2.911E+07
B3	8.033E+05	9.500E-05	8.456E+09	7.607E+06	2.011E+08
A1	2.096E+06	1.000E-04	2.096E+10	6.691E+07	6.404E+08
A2	2.862E+05	6.000E-05	4.769E+09	2.391E+06	9.108E+07
A3	6.392E+04	3.725E-05	1.716E+09	5.218E+05	2.671E+07
A4	8.529E+03	2.725E-05	3.130E+08	6.212E+04	3.637E+06
C1	9.138E+05	9.500E-05	9.619E+09	9.998E+06	2.399E+08
C2	4.128E+05	9.500E-05	4.345E+09	3.370E+06	1.130E+08
C3	1.554E+06	1.000E-04	1.554E+10	2.349E+07	3.972E+08
C4	8.492E+05	1.000E-04	8.492E+09	8.042E+06	2.078E+08

PRI

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	1.531E+06	4.400E-05	3.480E+10	1.064E+07	1.739E+08
B2	6.106E+05	2.664E-05	2.292E+10	3.482E+06	9.901E+07
B3	4.304E+06	7.900E-05	5.449E+10	4.599E+07	2.874E+08
A1	1.614E+07	1.000E-04	1.614E+11	4.047E+08	5.121E+08
A2	2.080E+06	4.400E-05	4.726E+10	1.445E+07	1.966E+08
A3	5.530E+05	2.125E-05	2.602E+10	3.154E+06	9.356E+07
A4	7.450E+04	1.125E-05	6.622E+09	3.754E+05	1.917E+07
C1	5.006E+06	7.900E-05	6.337E+10	6.045E+07	3.113E+08
C2	3.572E+06	7.900E-05	4.521E+10	2.037E+07	2.190E+08
C3	8.421E+06	8.900E-05	9.462E+10	1.419E+08	3.938E+08
C4	4.550E+06	8.900E-05	5.113E+10	4.862E+07	2.917E+08

Table 3. FOS Blue Side Direct Cal Lamp Exposure Estimates

H19

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	1.308E+04	3.900E-05	3.354E+08	2.845E+05	1.655E+07
B2	5.426E+03	2.164E-05	2.507E+08	9.309E+04	5.517E+06
B3	3.397E+04	7.400E-05	4.591E+08	1.229E+06	6.714E+07
A1	9.680E+04	1.000E-04	9.680E+08	1.072E+07	4.508E+08
A2	1.776E+04	3.900E-05	4.554E+08	3.864E+05	2.224E+07
A3	4.914E+03	1.625E-05	3.024E+08	8.431E+04	5.002E+06
A4	658.	6.250E-06	1.053E+08	1.004E+04	6.013E+05
C1	3.693E+04	7.400E-05	4.990E+08	1.615E+06	8.686E+07
C2	3.174E+04	7.400E-05	4.289E+08	5.445E+05	3.056E+07
C3	4.747E+04	8.400E-05	5.651E+08	3.798E+06	1.900E+08
C4	3.591E+04	8.400E-05	4.276E+08	1.299E+06	7.063E+07

H27

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	9.063E+04	3.900E-05	2.324E+09	2.583E+06	1.317E+08
B2	3.866E+04	2.164E-05	1.787E+09	8.450E+05	4.722E+07
B3	2.422E+05	7.400E-05	3.273E+09	1.115E+07	4.358E+08
A1	9.451E+05	1.000E-04	9.451E+09	9.829E+07	1.539E+09
A2	1.231E+05	3.900E-05	3.156E+09	3.507E+06	1.709E+08
A3	3.502E+04	1.625E-05	2.155E+09	7.653E+05	4.303E+07
A4	4.613E+03	6.250E-06	7.380E+08	9.110E+04	5.414E+06
C1	2.726E+05	7.400E-05	3.683E+09	1.465E+07	5.350E+08
C2	2.261E+05	7.400E-05	3.056E+09	4.942E+06	2.203E+08
C3	4.501E+05	8.400E-05	5.358E+09	3.445E+07	9.493E+08
C4	2.561E+05	8.400E-05	3.048E+09	1.178E+07	4.529E+08

H40

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	3.584E+05	3.900E-05	9.189E+09	4.793E+06	1.790E+08
B2	1.489E+05	2.164E-05	6.879E+09	1.568E+06	7.373E+07
B3	9.562E+05	7.400E-05	1.292E+10	2.071E+07	4.814E+08
A1	4.055E+06	1.000E-04	4.055E+10	1.823E+08	1.377E+09
A2	4.867E+05	3.900E-05	1.248E+10	6.510E+06	2.207E+08
A3	1.348E+05	1.625E-05	8.296E+09	1.420E+06	6.796E+07
A4	1.822E+04	6.250E-06	2.915E+09	1.690E+05	9.734E+06
C1	1.043E+06	7.400E-05	1.410E+10	2.722E+07	5.699E+08
C2	8.706E+05	7.400E-05	1.177E+10	9.171E+06	2.644E+08
C3	2.067E+06	8.400E-05	2.460E+10	6.392E+07	8.981E+08
C4	1.011E+06	8.400E-05	1.203E+10	2.189E+07	4.957E+08

H57

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	3.740E+04	3.900E-05	9.589E+08	1.842E+05	1.013E+07
B2	1.367E+04	2.164E-05	6.315E+08	6.026E+04	3.490E+06
B3	1.116E+05	7.400E-05	1.508E+09	7.942E+05	3.809E+07
A1	2.250E+05	1.000E-04	2.250E+09	6.959E+06	2.362E+08
A2	5.079E+04	3.900E-05	1.302E+09	2.501E+05	1.342E+07
A3	1.238E+04	1.625E-05	7.617E+08	5.458E+04	3.170E+06
A4	1.612E+03	6.250E-06	2.578E+08	6.497E+03	3.881E+05
C1	1.221E+05	7.400E-05	1.650E+09	1.045E+06	4.863E+07
C2	7.994E+04	7.400E-05	1.080E+09	3.525E+05	1.802E+07
C3	1.554E+05	8.400E-05	1.850E+09	2.458E+06	1.022E+08
C4	1.180E+05	8.400E-05	1.405E+09	8.396E+05	3.988E+07

Table 4. Selected FOS Red Side Cross-strapped Cal Lamp Exposure Estimates

H57

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	1.122E+05	3.900E-05	2.878E+09	1.387E+06	6.465E+07
B2	4.496E+04	2.164E-05	2.077E+09	4.538E+05	2.431E+07
B3	3.132E+05	7.400E-05	4.232E+09	5.993E+06	1.976E+08
A1	6.832E+05	1.000E-04	6.832E+09	5.274E+07	8.366E+08
A2	1.524E+05	3.900E-05	3.908E+09	1.884E+06	8.198E+07
A3	4.071E+04	1.625E-05	2.506E+09	4.109E+05	2.222E+07
A4	9.716E+03	6.250E-06	1.555E+09	8.561E+04	5.002E+06
C1	3.432E+05	7.400E-05	4.638E+09	7.876E+06	2.430E+08
C2	2.629E+05	7.400E-05	3.553E+09	2.654E+06	1.003E+08
C3	4.390E+05	8.400E-05	5.226E+09	1.849E+07	4.512E+08
C4	3.311E+05	8.400E-05	3.942E+09	6.335E+06	2.040E+08

H78

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	8.748E+04	4.400E-05	1.988E+09	8.373E+05	3.820E+07
B2	3.627E+04	2.664E-05	1.361E+09	2.739E+05	1.451E+07
B3	2.286E+05	7.900E-05	2.893E+09	3.618E+06	1.142E+08
A1	8.216E+05	1.000E-04	8.216E+09	3.137E+07	4.989E+08
A2	1.188E+05	4.400E-05	2.700E+09	1.137E+06	4.812E+07
A3	3.285E+04	2.125E-05	1.546E+09	2.481E+05	1.328E+07
A4	7.677E+03	1.125E-05	6.824E+08	5.165E+04	3.008E+06
C1	2.478E+05	7.900E-05	3.137E+09	4.754E+06	1.404E+08
C2	2.121E+05	7.900E-05	2.685E+09	1.602E+06	5.681E+07
C3	4.690E+05	8.900E-05	5.269E+09	1.116E+07	2.594E+08
C4	2.416E+05	8.900E-05	2.715E+09	3.824E+06	1.175E+08

L15 (Zeroth Order)

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	5.438E+05	7.100E-05	7.659E+09	9.797E+05	1.649E+07
B2	2.110E+05	5.364E-05	3.934E+09	3.205E+05	9.250E+06
B3	1.643E+06	1.000E-04	1.643E+10	4.233E+06	3.709E+07
A1	2.842E+06	1.000E-04	2.842E+10	3.730E+07	1.897E+08
A2	7.385E+05	7.100E-05	1.040E+10	1.330E+06	1.897E+07
A3	1.911E+05	4.825E-05	3.961E+09	2.903E+05	8.789E+06
A4	4.682E+04	3.825E-05	1.224E+09	6.047E+04	2.917E+06
C1	1.831E+06	1.000E-04	1.831E+10	5.563E+06	4.470E+07
C2	1.234E+06	1.000E-04	1.234E+10	1.875E+06	2.141E+07
C3	2.304E+06	1.000E-04	2.304E+10	1.306E+07	8.351E+07
C4	1.737E+06	1.000E-04	1.737E+10	4.474E+06	3.824E+07

L65

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	1.062E+05	6.000E-05	1.769E+09	1.737E+06	7.805E+07
B2	4.173E+04	4.264E-05	9.787E+08	5.683E+05	3.014E+07
B3	3.409E+05	9.500E-05	3.588E+09	7.508E+06	2.117E+08
A1	1.581E+06	1.000E-04	1.581E+10	6.614E+07	6.135E+08
A2	1.442E+05	6.000E-05	2.403E+09	2.359E+06	9.800E+07
A3	3.779E+04	3.725E-05	1.015E+09	5.147E+05	2.758E+07
A4	8.745E+03	2.725E-05	3.209E+08	1.072E+05	6.257E+06
C1	3.793E+05	9.500E-05	3.993E+09	9.867E+06	2.480E+08
C2	2.441E+05	9.500E-05	2.569E+09	3.324E+06	1.200E+08
C3	7.350E+05	1.000E-04	7.350E+09	2.314E+07	3.807E+08
C4	3.603E+05	1.000E-04	3.603E+09	7.937E+06	2.176E+08

Table 4 (cont'd). Selected FOS Red Side X-strapped Cal Lamp Exposure Estimates

PRI

Ap	True Pk Rate	Eff Img Area	Pk Flux Dens	True Tot Rate	Cont O/L Lim
B1	4.407E+05	4.400E-05	1.002E+10	2.848E+06	7.612E+07
B2	1.508E+05	2.664E-05	5.663E+09	9.319E+05	3.682E+07
B3	1.751E+06	7.900E-05	2.217E+10	1.231E+07	1.712E+08
A1	5.435E+06	1.000E-04	5.435E+10	1.083E+08	3.876E+08
A2	5.985E+05	4.400E-05	1.360E+10	3.868E+06	9.082E+07
A3	1.366E+05	2.125E-05	6.429E+09	8.440E+05	3.435E+07
A4	2.955E+04	1.125E-05	2.627E+09	1.758E+05	9.420E+06
C1	2.238E+06	7.900E-05	2.833E+10	1.618E+07	1.960E+08
C2	8.823E+05	7.900E-05	1.117E+10	5.451E+06	1.076E+08
C3	4.038E+06	8.900E-05	4.537E+10	3.798E+07	2.813E+08
C4	1.851E+06	8.900E-05	2.080E+10	1.301E+07	1.755E+08