AN ASSESSMENT OF THE IMPACT OF POTENTIAL MINING OPERATIONS AT THE ROSEMONT COPPER MINE ON THE NIGHT SKY OF SOUTHERN ARIZONA

II. THE 2012 LIGHTING PLAN

DRAFT FINAL REPORT

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for
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EXECUTIVE SUMMARY

This study presents results from computer calculations of the sky brightness due to proposed operations in the Rosemont Copper Mine (RCM) when viewed from six observation points, three of which are astronomically sensitive sites. The revised lighting plan for the RCM calls for a total of 6.4 million lumens. Our analysis shows that there would be an increase in sky glow at all sites due to RCM operations. At the astronomical observatory sites, including Fred L Whipple Observatory (FLWO), Jarnac, and Empire Ranch, the increase in brightness of the zenith is 0.4%, 0.7% and 1.1% respectively. In the astronomically "useful" portions of the sky, which we consider here to be out to zenith angle of 70°, the maximum brightening at these sites due to the proposed RCM lighting will be larger, reaching 3%, 8% and 10.5%, respectively.

The impact on sky brightness over the FLWO of increased atmospheric dust produced by the mining operations appears to be very small, and detectable only at large zenith angles toward the mine site.

The spectral emission from the proposed LED lights covers a wider part of the spectrum than does conventional HPS lighting, though neither emit significant light in the blue part of the spectrum (shortward of 500nm wavelength).

Options that could produce reductions in these impacts are limited at this time; the existing lighting plan has reduced outdoor lighting compared to previous plans and uses shielding for most applications. Regular cleaning of lighting on equipment may reduce the uplight fraction for this component. Though restriction of mining operations to daylight hours may be unlikely, this restriction would be the only way to significantly decrease impacts on the night sky of Southern Arizona.

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I. INTRODUCTION

Protection of dark night skies is a vital issue in Southern Arizona due to the large investment in astronomical facilities in the region (AASTA, 2007). Pima County and the City of Tucson have long recognized the importance of night sky protection through the adoption and enforcement of outdoor lighting ordinances. Though such ordinances can reduce impacts, they cannot eliminate them; they further do not address issues of appropriate land uses or locations. Increasingly, proposed developments that could impact dark sky sites are now being required to address the potential impact of new outdoor lighting on dark skies as part of the environmental assessment process.

This study examines the sky glow that would arise from open pit copper mining operations in the Rosemont Copper Mine (RCM) in the Santa Rita Mountains of Southern Arizona. The proposed mine site is shown in Figure 1, along with nearby towns and astronomical facilities. The sky glow created by the lighting described in this report is evaluated using a model describing the interaction of light emitted near the ground with objects and surfaces near the ground, the atmosphere of molecules and aerosols over the mine site, and between the mine site and points of observation. This model is described in detail in published papers by Garstang (1986, 1989, 1991) and by Luginbuhl *et al.* (2009b), and has been incorporated into a computer program by Dark Sky Partners LLC (DSP).

This report, the second one to assess the impact of RCM lighting (see DSP 2011 for the first report), evaluates the revised RCM lighting plan devised and summarized by Monrad Engineering (Monrad 2012a, 2012b; hereafter M2012a, M2012b). This revised plan was commissioned by the RCM project during the comment period on the DEIS and uses a significantly lower lighting amount than proposed under the plan analyzed in the 2011 DSP report. This new lighting plan also replaced the previous low-pressure sodium (LPS) and high-pressure sodium (HPS) lighting with two varieties of light-emitting diode (LED) sources.

Following comments received on the DEIS, and to address sky glow implications of differing lamp types, improvements were made to the model to include the effects of terrain blocking around the mine site and the spectral power distribution of the proposed LED lights.

This assessment provides calculations of how the night sky brightness would be increased by proposed RCM operations on the clearest and darkest nights. The goal is to provide an assessment of the maximum impact on sky glow; compliance of the proposed lighting with the Pima County Outdoor Lighting Code is not evaluated.

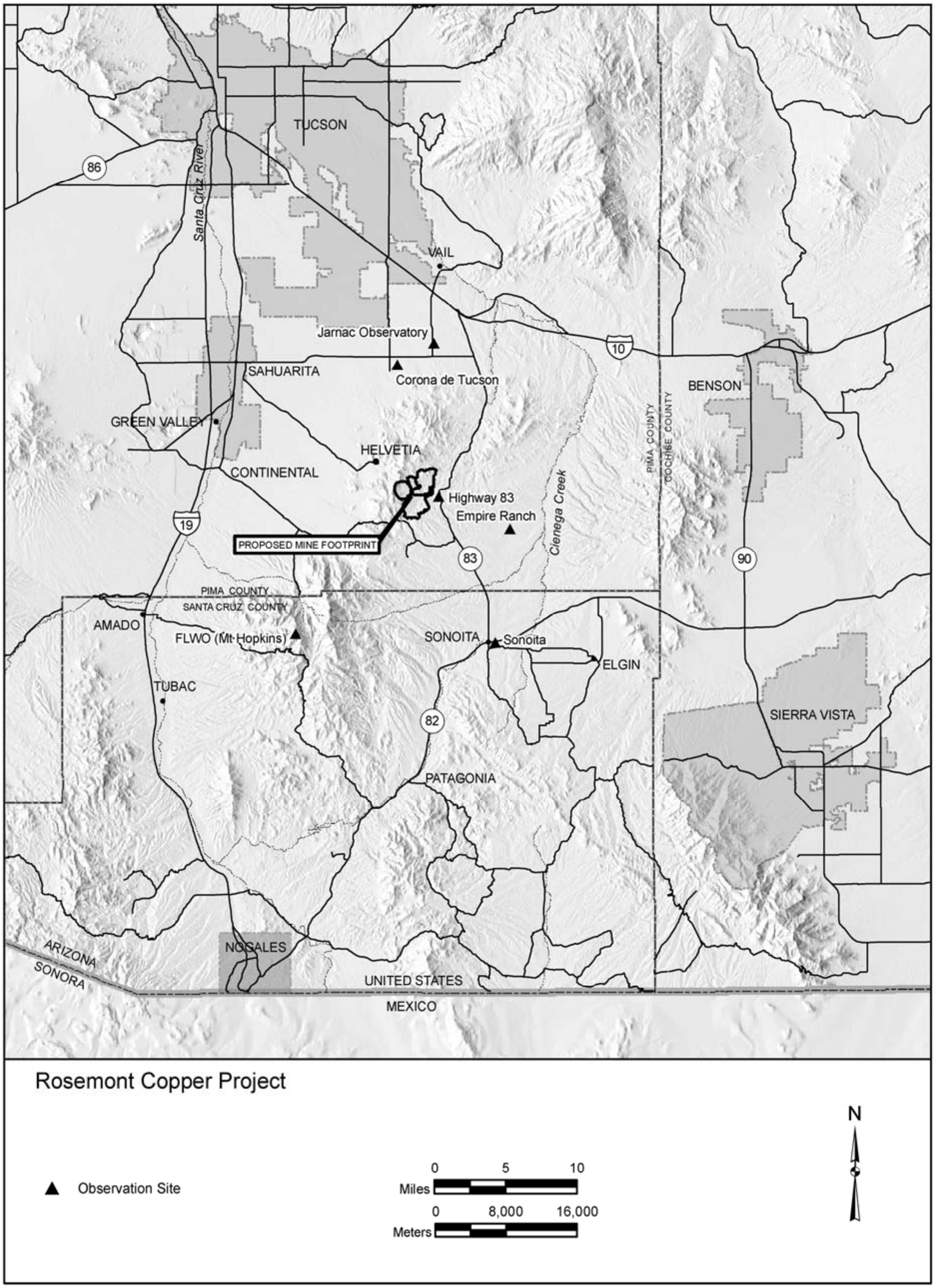

Figure 1. The location of the Rosemont Copper Mine, together with regional towns and cities included in sky glow models.

II. Study Methodology

A. The Numerical Model

R. Garstang (Garstang 1986, 1989, 1991) developed and published a model for calculating sky brightness arising from natural atmospheric emission and artificial outdoor lighting. This model has been recently improved by Luginbuhl et al. (2009b) to include effects on light propagation caused by blocking of the light emissions by objects near the ground, such as buildings, vegetation and terrain, an improvement essential to accurately connect light emissions measured at the light sources (lamps) with the resultant sky glow. A computer program based on this improved model, developed by Dark Sky Partners LLC, calculates the sky brightness observable from any location and toward any viewing direction due to natural atmospheric emission and light emitted from cities and towns or any specific light source or sources (i.e., fixtures). This program allows modeling of specific sources of artificial lighting such as shopping centers, housing developments or industrial projects, with the capability of specifying details such as amounts, spatial distribution, and shielding characteristics of lighting sources (Davis et al., 2006). This computer program was used to assess the impact of lighting at potential RCM mining operations on dark skies of the surrounding region.

The model was enhanced for the present analysis to accommodate 1) blocking by terrain near the RCM site and 2) different lamp types with different spectral distributions. The terrain blocking profile, *i.e.*, the terrain elevation as a function of azimuth, for locations where lighting is planned was generated by SWCA using a Digital Elevation Model. Figure 2 shows the blocking profiles for the three sites where lighting is proposed at the RCM.

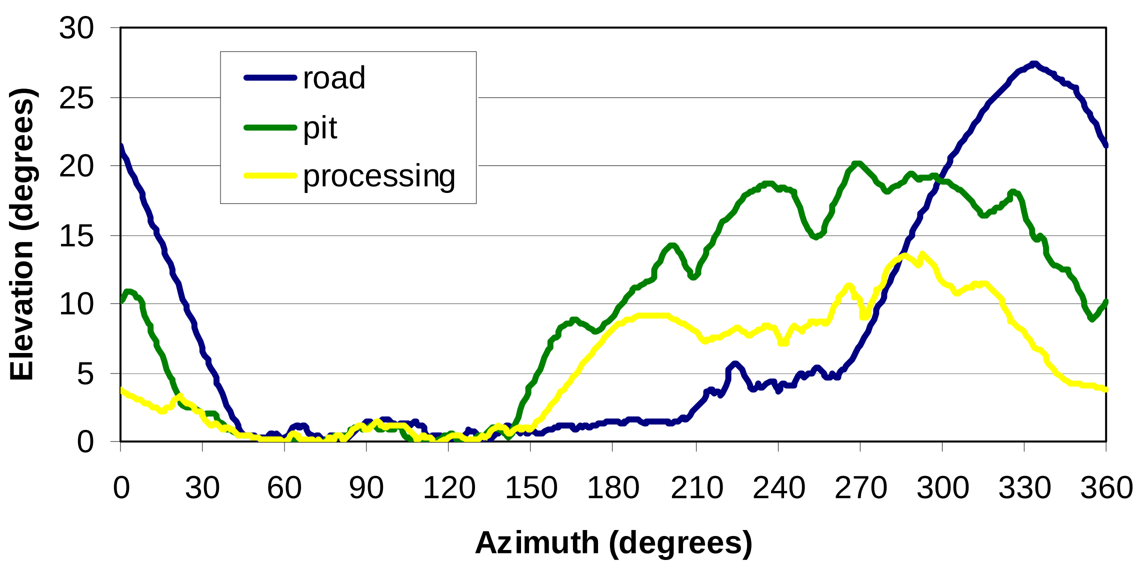

Figure 2. Terrain blocking profiles for the three illuminated sites at the RCM. The elevation angle of the surrounding terrain as viewed from the indicated sites within the RCM is shown for all azimuths.

The spectrum of each lamp type is specified as a table giving spectral radiant power as a function of wavelength. This spectrum is simplified by summing the emission within discrete wavelength bins, typically 20 nm wide, and the radiant sky glow arising from the lights within each bin is calculated using appropriate atmospheric scattering parameters at each wavelength. To determine the total sky glow resulting from the lamps the results are weighted by the radiant output of all lamps and the CIE V response, then summed to convert radiant sky glow to luminance (visual or approximately astronomical V-band) units (nanoLamberts[1] or nL). For sites with different lamp types, separate calculations are made for each type and then added to get the total sky glow contribution for the site. M2012 specifies two lamp types for the RCM project, filtered LED (FLED) lights and amber LED (ALED) lights. FLED lights are white LEDs with a blocking filter which removes most of the emission below 500nm, while ALED has most of its emission between about 560 nm and 610 nm. Figure 3 gives the spectral distribution for these two types of LEDS.

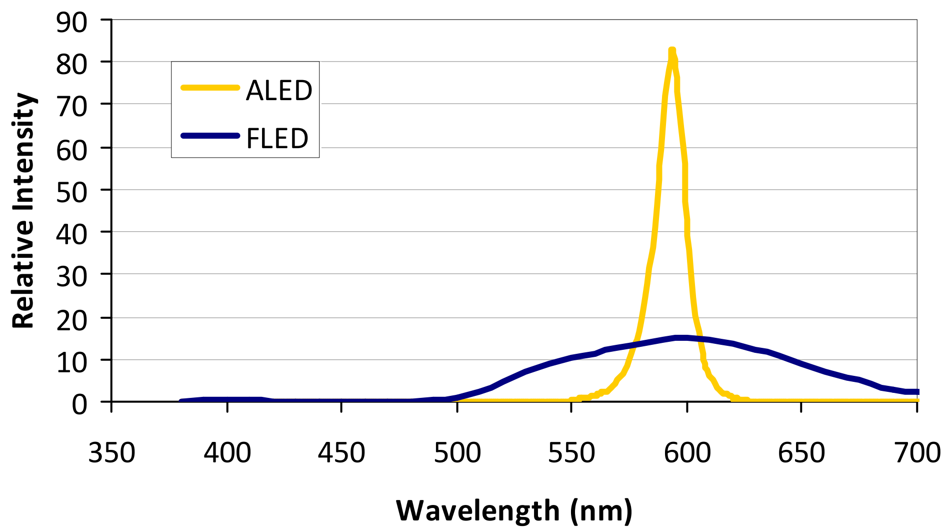

Figure 3. Spectral distribution of the FLED and ALED lights. Each source has equal luminous flux (lumens).

B. Data Input for the Model

The inputs for the computer model include parameters describing the atmosphere and ground reflectivity, the location and amounts of light emitted (measured in lumens), the fraction of this light that escapes directly upward into the night sky (the uplight fraction), and the locations from which the sky is observed.

Atmosphere and Ground

Table 1 shows the parameters characterizing the atmosphere and ground; these values were kept constant for all locations. The parameter that describes the amount of aerosol (particulates) or clarity of the atmosphere, K, was set to 0.10. This is lower than the value used by Garstang for typical western cities (K=0.5), but is based on observations made by the National Park Service (NPS) Night Sky Team at Saguaro National Monument and describes the 90th percentile (i.e.,

[1] A nanoLambert (nL) is a unit of luminance or surface brightness. 1 Lambert = 1/π lumen/sq cm for a uniformly diffusing surface. A naturally dark sky has a brightness of about 54 nL at the zenith, rising (due to natural causes) to approximately 100 nL 10° above the horizon (see the lowest curve in Figure 5).

the K value was observed to be larger than this 90% of the time). Such a low value is not entirely unexpected due to the clarity of the air in this region. (It is important to recognize the modeling does not account for increased aerosols that may result from some weather conditions, air pollution, or the dust produced by the mining operations themselves in general; see is discussed in Section IV for specific dust impacts.)

These atmospheric parameters describe very clear conditions and will lead to modeling results that show greater impacts at the observation points from potential lighting in the RCM as well as from nearby towns than will typically be the case. The purpose in using these clear conditions for the analysis is to show what the impacts would be during the "best" observation nights, when the air is clearest and the stars most visible. It is important to recognize that much of the time the air will be less clear, and the sky glow impacts smaller at distances evaluated here.

Light reflected from the ground and emitted directly upward from light fixtures is partially blocked by near-ground objects (vegetation, built structures, terrain). The DSP model treats this effect in two ways. In areas other than the mine site an analytical treatment described by Luginbuhl, *et al.* (2009b) is used, characterized by the two parameters E_b and β. The values indicated in Table 1 for these parameters are slightly adjusted from the values producing the best agreement between the model calculations and sky brightness measurements in the work described by Luginbuhl et al. (2009b). The values shown are chosen to better describe the relatively un-vegetated and open nature of the desert environment in this region.

For the mine site the modeling treated blocking through the terrain profiles shown in Figure 2. Though the lighting in the pit will eventually become subject to greater blocking due to the pit walls themselves, DSP feels that the most conservative approach should assume current terrain profiles since this represents conditions at the initial stages of the operation.

The ground reflectivity of 0.15 is typical of a wide variety of surfaces including terrain, vegetation, dirty concrete and aged asphalt hardtop, and has been found to adequately characterize ground reflectivity for all warm season light pollution modeling efforts to date (Garstang 1986, 1989, 1991; Luginbuhl *et al.* 2009b and references therein). The larger reflectivity chosen to characterize the mining site (0.25) is based on a conservative interpretation of expected crushed-rock surfaces provided by engineers working for RCM.

Table 1. Atmospheric and Ground Parameters

Parameter	Value	
	Towns	Mine
K	0.10	0.10
E_b	0.30	0.10
β	0.10	0.80
Ground Reflectivity	0.15	0.25

Mine Generated Dust.

In addition to dust arising from natural sources throughout the region, dust generated by the RCM itself was included in this study. As described in DSP 2011, effects of the mine-generated dust are modeled by including a cylindrical volume over the mine with a greater particulate loading (K parameter) than found in the surrounding atmosphere.

The analysis described in the Alternative Scenarios Modeling Summary (2011), yielded the dust concentrations given in Table 3, while Table 4 gives the ratio of the total dust concentration ratio to the pre-mine levels shown in Table 2.

Table 2. Pre-mine particulate concentrations (μg/m^3).

Emission	Max 24 hr	Annual Avg
PM10	33.0	11.9
PM2.5	10.8	3.7

Table 3. Maximum Ambient Concentrations for the Barrel Alternative (μg/m^3).

Emission	Max 24 hr Year 7	Annual Avg Year 7
PM10	185.6	49.9
PM2.5	94.8	12.0

Table 4. Particulate concentration ratios: total/pre-mine.

Emission	Max 24 hr Year 7	Annual Avg Year 7
PM10	5.6	4.2
PM2.5	8.8	3.2

These results show that the dust generated by mining activities would increase the total atmospheric dust over the mine by as much as a factor of 9. Using these values yields a revised value of K of 1.0 which is twice the value used in the 2011 study.

Rosemont Copper Mine Lighting

The number and types of lights to be modeled in this study were based on the lighting plan for this project detailed in M2012a and M2012b. Table 5 gives the details of the mine lighting sources, while Table 6 gives the locations and lighting associated with all modeled light sources, for the RCM as well as seven cities, towns and jurisdictions expected to be contributors to sky glow in the region.

Lighting required for nighttime mining operations on the project would consist of five types: 1) fixed lights at the mine headquarters and the pit processing area for parking, walkway, security and general nighttime activity; 2) lighting on shovels and loaders and portable light towers with individually aimable fixtures located at the active mine site that would be moved as the mining operations shift; 3) lighting for the dry stack conveyor; 4) roadway lighting at conflict points on the entry road from Highway 83 to the mine site and within the mine site itself, and 5) lighting (i.e. headlights) on mining vehicles, also assumed to be located at the active mine site and along the mine roads.

The fixed lights in the ore processing/facilities area consist of a mixture of FLED and ALED lamps (see Table 5) producing a total of 2,605,780 lumens most of which is within fully shielded fixtures, i.e., none of the light is emitted directly upward. A total of 100,000 lumens is FLED lights with a 5% uplight fraction. The mine pit lighting consists primarily of FLED lights mounted on the active shovels and drills and produces a total of 1,514,366 lumens. This lighting is directed toward the active mining location is not fully shielded. Though new clean fixtures containing this lighting direct about 10% or less of the emitted light upward, DSP estimates that about 20% of this lighting will be direct uplight when operating in a dusty environment.

Dry Stack Conveyor lighting consists of a combination of FLED and ALED lights producing a total of 1,924,660 lumens.

Roadway lighting for the entry road uses equal amounts of FLED and ALED lights for a total of 218,800 lumens.

For the vehicular lighting we have no specific information either on the manufacturers and types of the mining vehicles to be used, nor for the lighting that would be installed on this equipment. To estimate the light output from the vehicles, we scale the lumens from values typical of automobile headlights. From Schoettle et al. (2004), car headlights average 3786 effective lumens/vehicle with an uplight fraction of 0.11. We assume the same uplight fraction, but increase the light output from each mine vehicle to 10,000 lumens, about three times that of a typical car. All vehicular lighting is assumed to be quartz-halogen incandescent (QH), and located at the active mining site; i.e., no attempt has been made to model lighting produced when the vehicles are transporting materials on roadways.

Table 5. Details of proposed Rosemont Copper Mine lighting

Location	Lamp Type	Initial Lumens	Uplight Fraction	Uplight Lumens
Ore processing	FLED	1,876,730	0.00	0
Ore processing	FLED	100,000	0.05	5,000
Ore processing	ALED	629,050	0.00	0
Mine pit	FLED	1,514,366	0.20	302,873
Road	FLED	109,400	0.00	0
Road	ALED	109,400	0.00	0
Dry stack conveyor	FLED	1,541,760	0.00	0
Dry stack conveyor	ALED	382,900	0.00	0
Vehicles	QH	160,000	0.11	17,600
TOTAL		6,423,606		325,473

There are 5 alternatives proposed for RCM lighting, and the lighting detailed in this section is for the so-called Barrel alternative and includes no lighting in the leach field. The other alternatives include lighting for the leach field, but as there are no details available for lighting under the other alternatives no modeling was done for them. DSP comments on the possible impact of additional leach field lighting under the alternatives in the Discussion section of this report.

Cities, Towns and other Jurisdictions:

The largest source of nighttime lighting relevant to this study is eastern Pima County, including

Tucson itself and several incorporated and unincorporated communities in this part of Arizona. Data used in this assessment were taken from an earlier study (Davis et al., 2006) which evaluated the nighttime light produced in Pima County based on census tract population data and lumen/capita data derived from references cited therein. The light outputs for all other towns included in this study were calculated assuming 1710 lm per capita with 10% uplight fraction and projected 2010 populations from the U.S. Census Bureau. These are typical values for communities without any outdoor lighting controls (Luginbuhl et al. 2009a and references therein).

A spectrum of the nighttime lighting for these jurisdictions was needed for the spectral analysis done in this study. DSP generated such a spectrum (Figure 4) as a mixture of HPS, LPS and a small amount of mercury vapor lighting, determining the relative fraction of each by matching spectral features from night sky spectrum obtained at FLWO (Massey and Foltz, 2000).

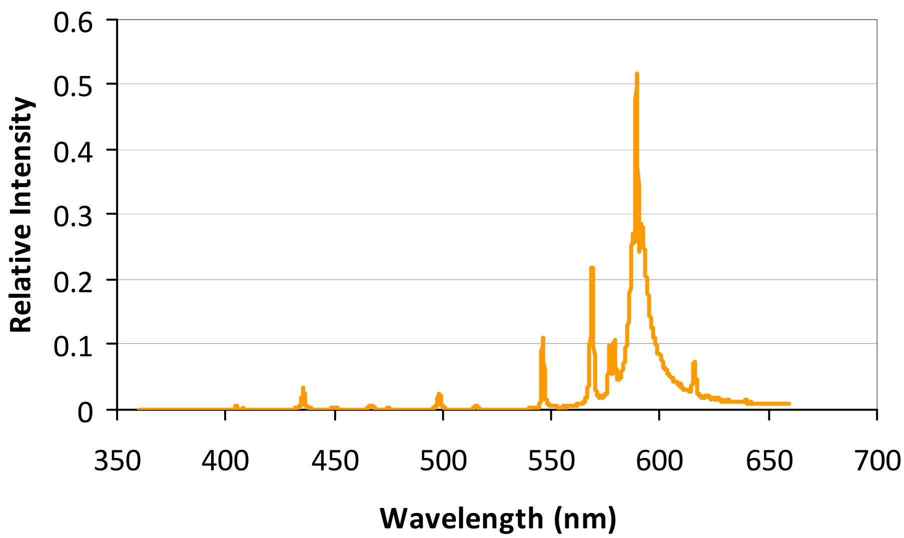

Figure 4. Spectrum of the artificial lighting for Tucson and other towns, consisting primarily of HPS and LPS.

Observation Points

The observation sites listed in Table 6 were set in consultation with SWCA and were reviewed by the Forest Service. These sites were chosen because they represent: a) nearby astronomical sites that are dark-sky critical, b) nearby towns and c) a site on state highway 83 which will experience the maximum visual impact due to RCM operations visible from public roadways.

Table 6. Light Source Locations and Outputs.

Location	Latitude (d:m:s)	Longitude (d:m:s)	Elevation (meters)	Population	Lumens	Uplight Fraction
Rosemont Mine Site						
Ore Processing Area	31:50:18	–110:44:58	1570		2,605,780	0.002
Mine Pit	31:49:51	–110:45:44	1630		1,514,366	0.200
Road Conflict Points	31:51:08	–110:43:20	1490		218,800	0.000
Dry Stack Conveyor	31:49:30	–110:44:37	1590		1.924,660	0.000
Vehicles	31:50:18	–110:44:58	1570		160,000	0.110
Total					*6,423,606*	*0.051*
Other Communities						
Tucson/Eastern Pima	--	--	810	1,050,000	1,795,500,000	0.082
Nogales, SON	31:20:00	–111:00:00	800	160,000	273,600,000	0.100
Nogales, AZ	31:33:41	–110:59:55	1103	19,573	33,469,830	0.100
Benson	31:58:54	–110:16:52	1067	4,833	8,264,430	0.100
Sonoita	31:40:46	–110:39:21	1490	910	1,556,100	0.100
Tubac	31:36:46	–111:02:30	982	2,000	3,420,000	0.100
Sierra Vista	31:32:44	–110:16:38	1394	43,320	74,077,200	0.100

Table 7. Observation Sites

Observation Sites	Latitude (d:m:s)	Longitude (d:m:s)	Elevation (meters)	Distance From Pit (km)	Azimuth (Deg)
FLWO (Mt. Hopkins)	31:41:19	–110:53:07	2600	19	37
Jarnac Observatory	31:58:37	–110:43:10	1060	17	194
Sonoita	31:40:46	–110:38:50	1490	20	327
Corona de Tucson	31:57:21	–110:45:49	1040	14	179
Highway 83	31:49:28	–110:42:51	1520	4.5	277
Empire Ranch	31:47:32	–110:37:44	1392	13	288

III. IMPACT OF PROPOSED ROSEMONT COPPER MINE LIGHTING ON NIGHT SKY BRIGHTNESS

We calculated predicted sky brightness for the current condition (based on 2010 population) and with the addition of the RCM lighting as seen from the six observation points listed in Table 7. For each case, we calculated the sky brightness from the horizon directly above the mine site (zenith angle of 88°) to the horizon directly opposite (zenith angle of –88°), passing through the zenith. We show both the total sky brightness in nanoLamberts (nL) and the fractional increase in sky brightness due to RCM lighting as listed in Table 5.

To help understand the visual impact of the numbers and ratios described in the following subsections, readers should be aware that a brightness ratio of 1.1:1 (or 10%) is only just perceptible to most people when the two sources of light can be directly compared, with one appearing directly adjacent to the other. In this sense a 10% brightening may seem to be likewise only just perceptible. A brightness ratio of 50% (1.5:1) would be perceptible to most observers.

When considering the results presented in the following subsections, readers should be aware that localized and unpredictable variations in very low altitude atmospheric dust content, caused for example by low-level winds or by the mining operations themselves, can make actual sky brightness near the horizon much brighter or fainter than predicted here. The values indicated for the zenith angles of 85° or greater should be taken only as a general indication, but not likely accurate to better than 50% in predicting absolute sky brightnesses for any given night. Because of these uncertainties calculations were not made for angles greater than 88° from the zenith or 2° altitude.

A. Fred Lawrence Whipple Observatory

Figure 5 shows the variation in sky brightness as observed from FLWO along the semicircle passing through the mine site (right side of the graph), the zenith (middle of the graph) and ending at the horizon opposite the mine site (left side of the graph). The predicted current sky glow arising from natural air glow plus artificial sky glow from the seven cities and towns listed in Table 3, as well as the effect of the proposed lighting at the RCM, are shown as the curves lying above the natural curve and distinguishable particularly toward the RCM (right side of the graph). The lowest curve shows the natural condition, i.e., the sky glow that would be observed without any artificial light in the region.

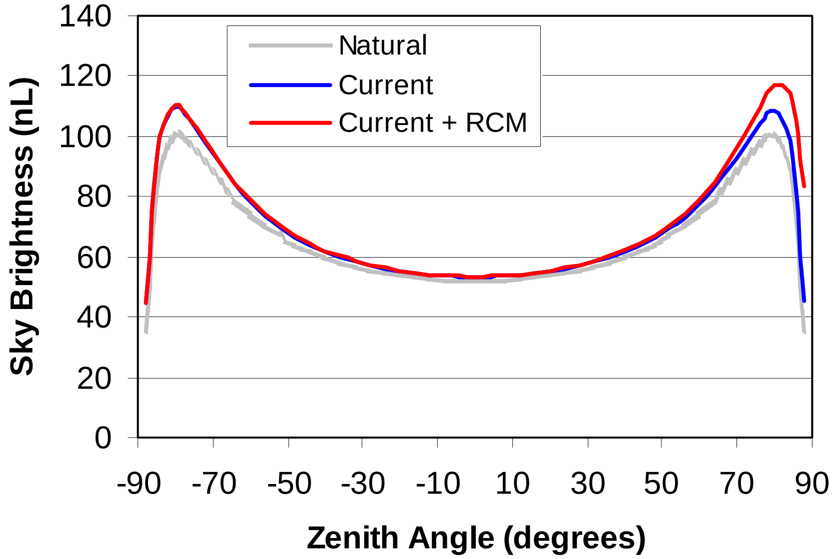

Figure 5. Horizon-to-horizon sky brightness at FLWO on the semicircle originating toward the RCM site (azimuth 37°, zenith angle +90°) and ending at the point on the horizon opposite (azimuth 217°, zenith angle –90°). The blue line shows the predicted current sky brightness profile arising from the 7 existing cities and towns listed in Table 6; the red line shows the predicted additional contribution of the RCM lighting described in Table 5.

To more clearly display the effects of the RCM lighting on the night sky, Figure 6 displays fractional sky brightness increases due to proposed RCM lighting, i.e., ratios of the predicted sky brightness to the current condition. A value of 1.10 means that the indicated condition is 10% brighter than the reference condition; 1.05 is 5% brighter.

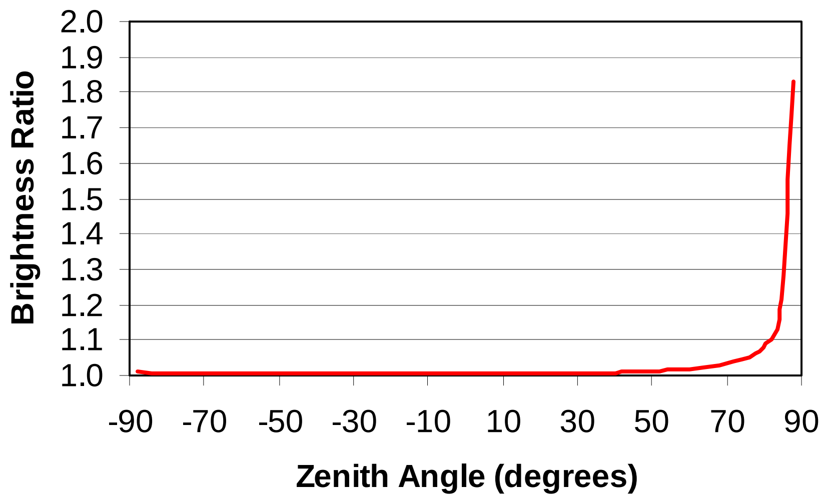

Figure 6. Brightness ratio as viewed from FLWO toward the RCM site.

Table 8. Sky brightness ratios as viewed from FLWO at selected zenith angles toward the RCM.

Zenith Angle	Brightness Ratio (predicted/current)
0°	1.004
44°	1.009
60°	1.018
70°	1.033
80°	1.080
88°	1.831

From Figure 6 and Table 8 it can be seen that the proposed RCM lighting would brighten the sky by about 0.4% at the zenith, increasing to 3.3% at a zenith angle of 70° (20° above the horizon), 8% at a zenith angle of 80° (10° above the horizon), and 83% at 88° (2° above the horizon). We note that, due to the altitude difference, the RCM will appear 3° below the horizon as viewed from FLWO.

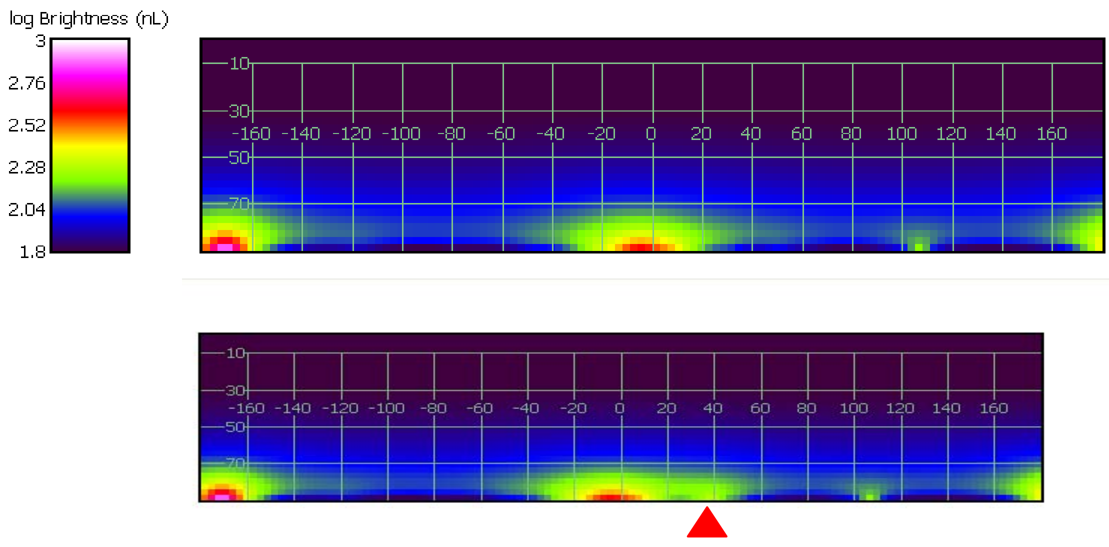

Figure 7. An all-sky false-color panoramic map of the sky glow visible from FLWO. The upper panel shows the current condition; the lower the condition predicted with the addition of the proposed RCM lighting. The grid and numbers on this and the following images indicate zenith angle and azimuth; the red triangle indicates the azimuth of the RCM.

Figure 7 shows false-color panoramic maps of the current and predicted sky brightness over the entire sky as viewed from FLWO. The increase in the sky glow above the RCM site (azimuth 37°, indicated by the triangle) is discernible. The other distinct sky glow domes at azimuth 0°, 190° (–170°) and 108° arise from Tucson, Nogales and Sonoita, respectively.

B. Jarnac Observatory

Model results for the Jarnac Observatory observation point are shown in Figure 8, Figure 9, Figure 10, and Table 9.

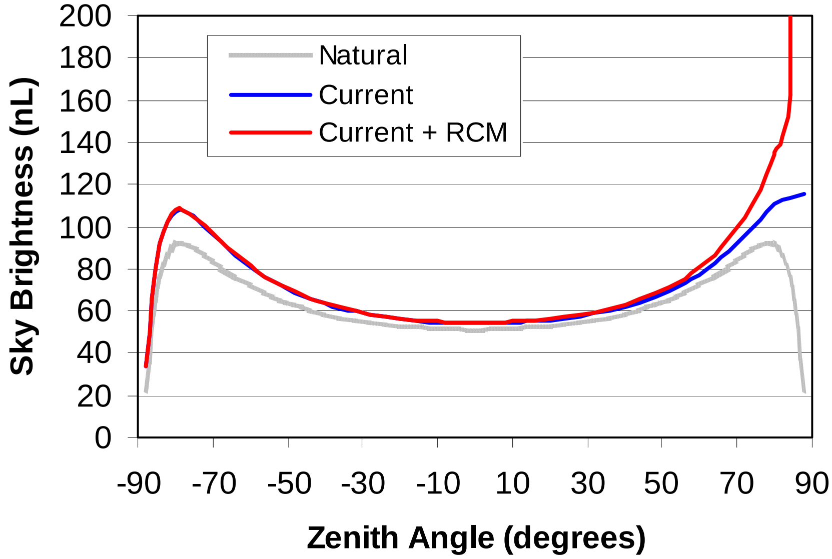

Figure 8. Horizon-to-horizon sky brightness at Jarnac Observatory on the semicircle originating toward the RCM site (azimuth 194°, zenith angle +90°) and ending at the point on the horizon opposite (azimuth 14°, zenith angle –90°). The blue line shows the predicted current sky brightness profile arising from the 7 existing cities and towns listed in Table 6; the red line shows the predicted additional contribution of the RCM lighting described in Table 5.

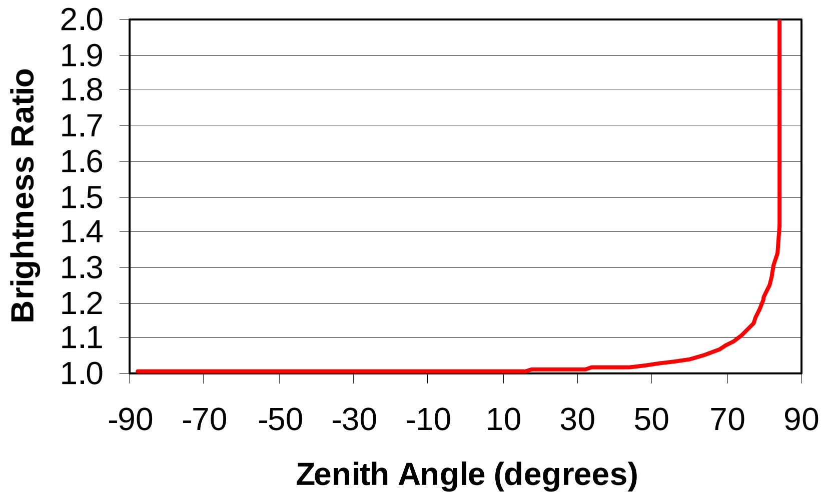

Figure 9. Brightness ratio as viewed from Jarnac Observatory toward the RCM site.

Table 9. Sky brightness ratios as viewed from Jarnac Observatory at selected zenith angles toward the RCM. The entry at zenith angle 88° is very close to direct line-of-site to the RCM at ZA 88.2°.

Zenith Angle	Brightness Ratio (predicted/current)
0°	1.007
44°	1.019
60°	1.042
70°	1.080
80°	1.211
88°	70

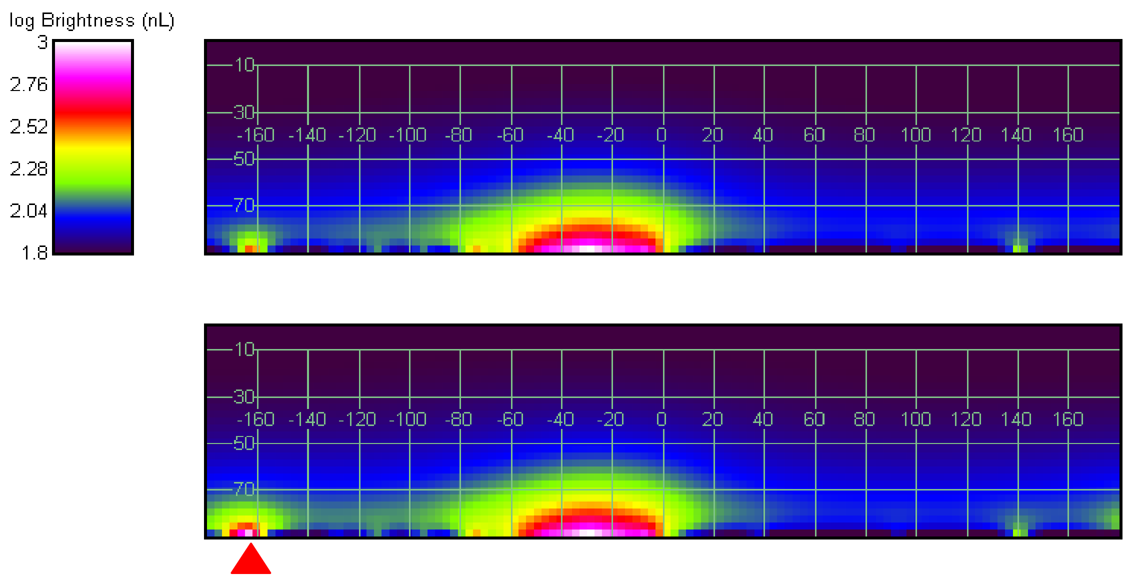

Figure 10. An all-sky false-color panoramic map of the predicted sky glow visible from Jarnac Observatory. The triangle indicates the azimuth of the RCM, which from this observation point is nearly coincident with Nogales.

C. Sonoita

Model results for the Sonoita observation point are shown in Figure 11, Figure 12, Figure 13, and Table 10.

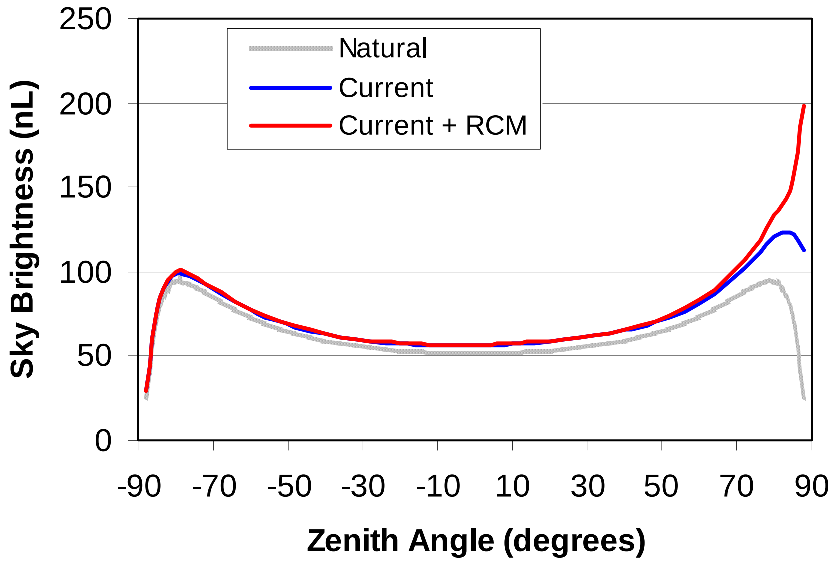

Figure 11. Horizon-to-horizon sky brightness at Sonoita on the semicircle originating toward the RCM site (azimuth 327°, zenith angle +90°) and ending at the point on the horizon opposite (azimuth 147°, zenith angle –90°). The blue line shows the predicted current sky brightness profile arising from the 7 existing cities and towns listed in Table 6; the red line shows the predicted additional contribution of the RCM lighting described in Table 5.

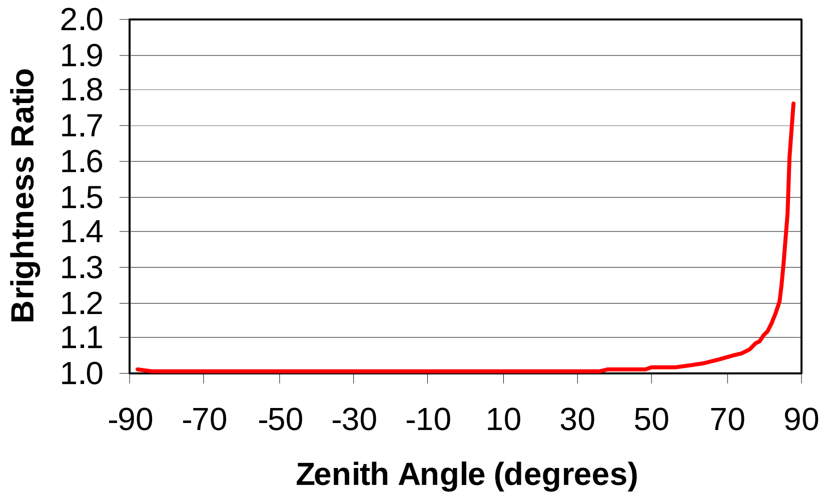

Figure 12. Brightness ratio as viewed from Sonoita toward the RCM site.

Table 10. Sky brightness ratios as viewed from Sonoita at selected zenith angles toward the RCM.

Zenith Angle	Brightness Ratio (predicted/current)
0°	1.004
44°	1.011
60°	1.023
70°	1.044
80°	1.108
88°	1.764

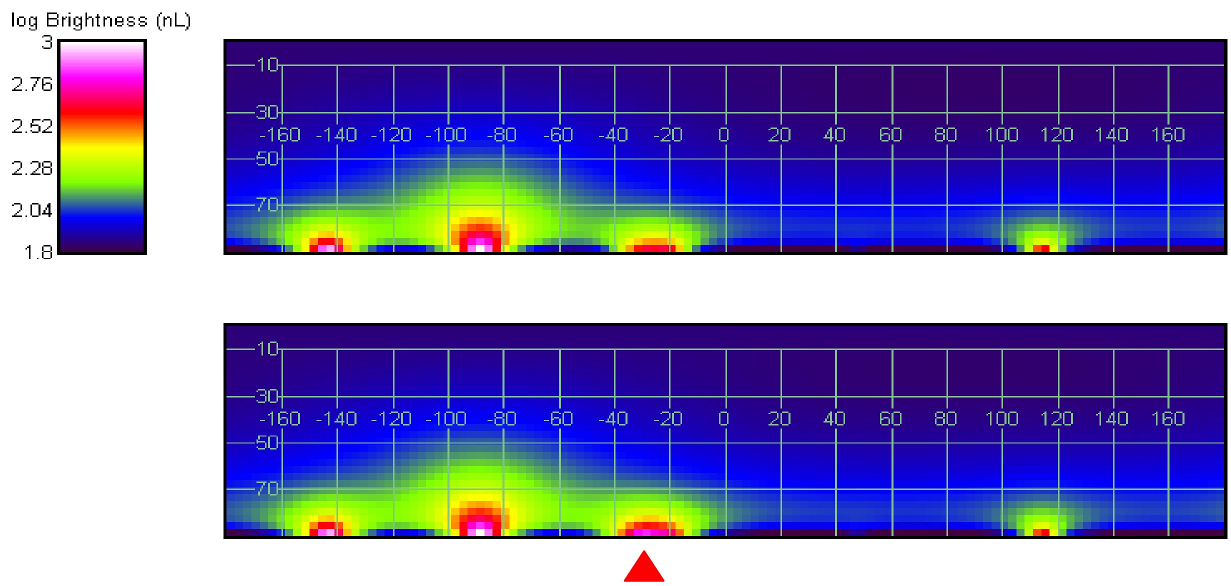

Figure 13. An all-sky false-color panoramic map of the sky glow visible from the Sonoita observation point. The upper panel shows the current condition; the lower the condition predicted with the addition of the proposed RCM lighting. The triangle indicates the azimuth of the RCM. Here the principal light domes at azimuth 215º (–145º), 270º (–90º), 335º (–25º), and 115º, arise from Nogales, Sonoita, Tucson and Sierra Vista, respectively.

D. Corona de Tucson

Model results for the Corona de Tucson observation point are shown in Figure 14, Figure 15, Figure 16, and Table 11.

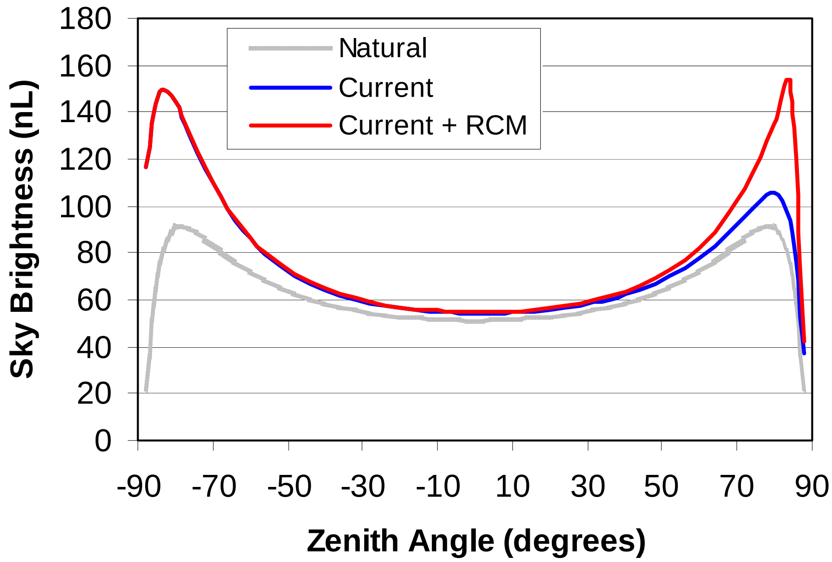

Figure 14. Horizon-to-horizon sky brightness at Corona de Tucson on the semicircle originating toward the RCM site (azimuth 179°, zenith angle +90°) and ending at the point on the horizon opposite (azimuth 359°, zenith angle –90°). The blue line shows the predicted current sky brightness profile arising from the 7 existing cities and towns listed in Table 6; the red line shows the predicted additional contribution of the RCM lighting described in Table 5.

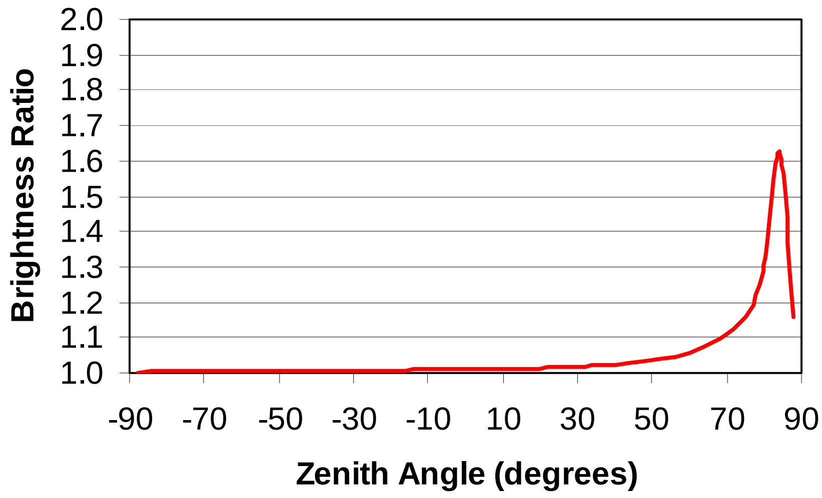

Figure 15. Brightness ratio as viewed from Corona de Tucson toward the RCM site.

Table 11. Sky brightness ratios as viewed from Corona de Tucson at selected zenith angles toward the RCM. There is no entry at zenith angle 88° because the RCM appears at ZA 87.8°.

Zenith Angle	Brightness Ratio (predicted/current)
0°	1.010
44°	1.028
60°	1.058
70°	1.109
80°	1.286
88°	--

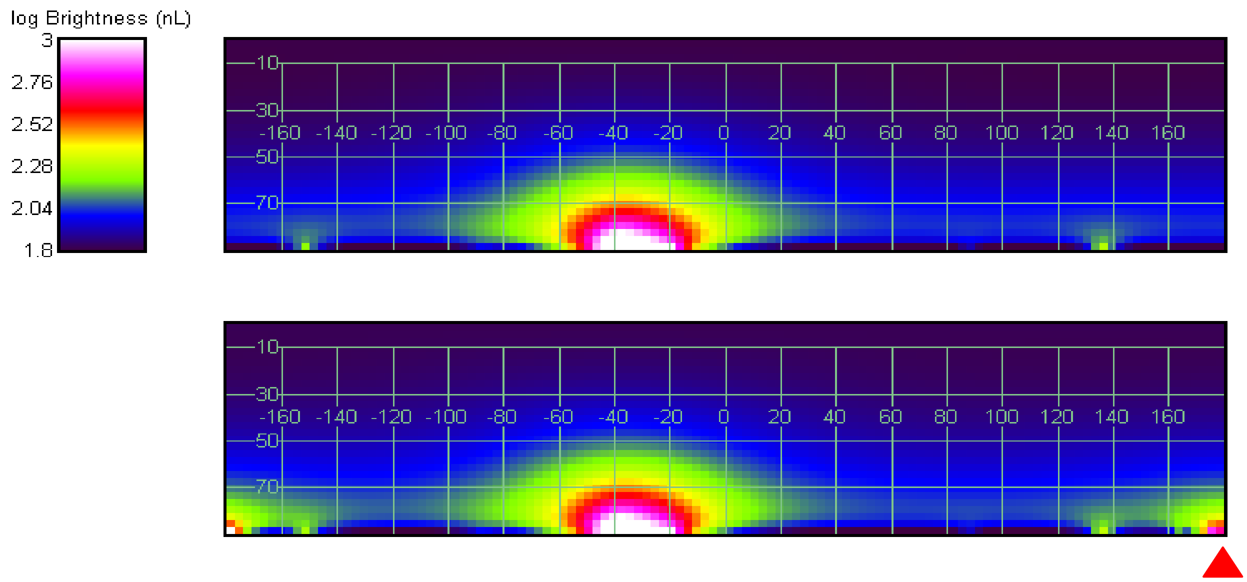

Figure 16. An all-sky false-color panoramic map of the sky glow visible from Corona de Tucson. The upper panel shows the current condition; the lower the condition predicted with the addition of the proposed RCM lighting. The triangle indicates the azimuth of the RCM. Here the principal light dome at azimuth 340º (–20º) arises from Tucson.

E. Highway 83

Model results for the Highway 83 observation point are shown in Figure 17, Figure 18, Figure 19, and Table 12.

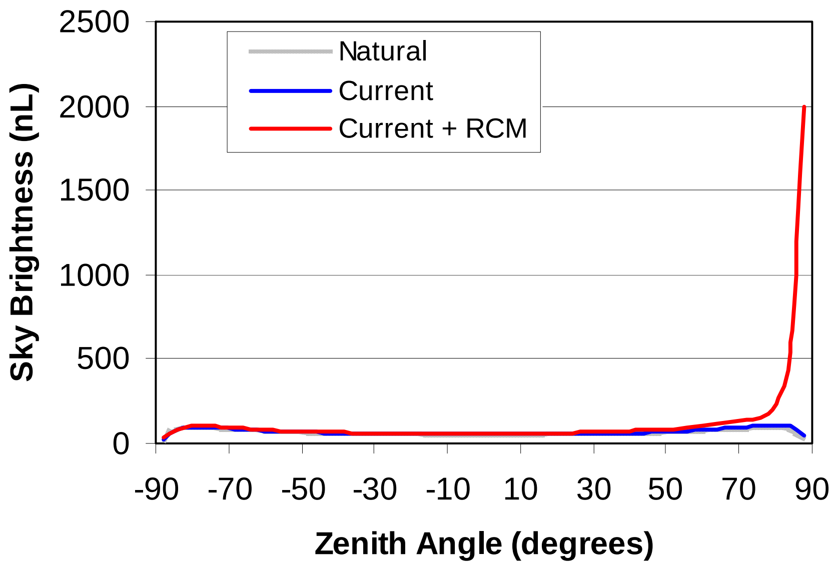

Figure 17. Horizon-to-horizon sky brightness at Highway 83 on the semicircle originating toward the RCM site (azimuth 277°, zenith angle +90°) and ending at the point on the horizon opposite (azimuth 97°, zenith angle –90°). The blue line shows the predicted current sky brightness profile arising from the 7 existing cities and towns listed in Table 6; the red line shows the predicted additional contribution of the RCM lighting described in Table 5.

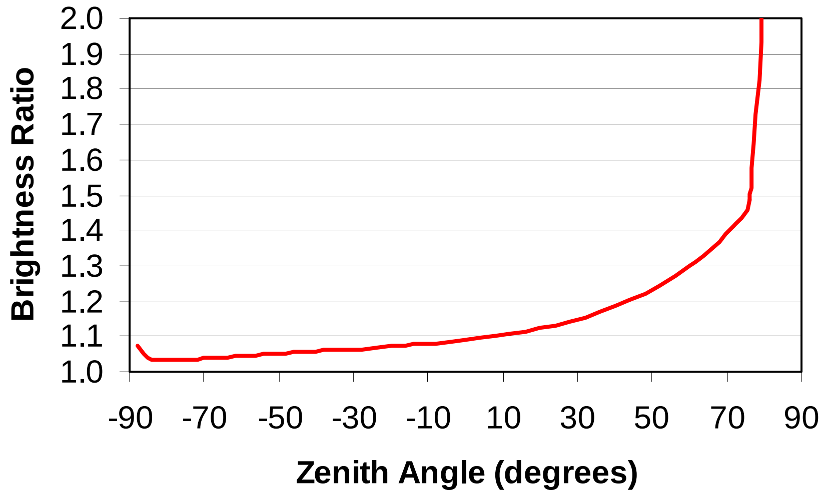

Figure 18. Brightness ratio as viewed from Highway 83 toward the RCM site.

Table 12. Sky brightness ratios as viewed from Highway 83 at selected zenith angles toward the RCM.

Zenith Angle	Brightness Ratio (predicted/current)
0°	1.090
44°	1.202
60°	1.297
70°	1.390
80°	2.179
88°	40

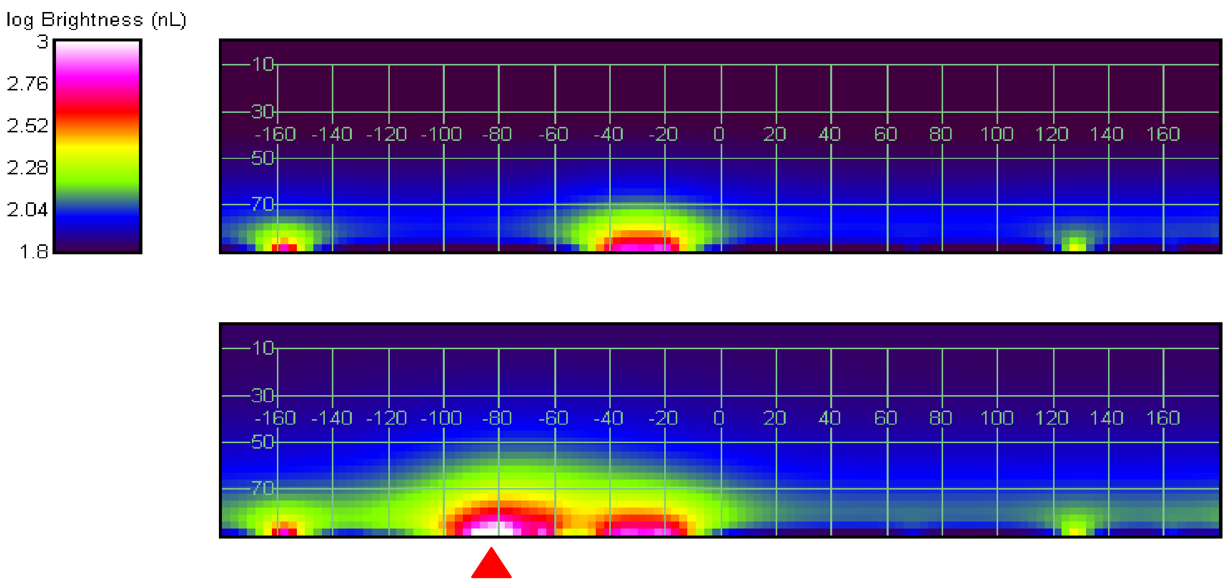

Figure 19. An all-sky false-color panoramic map of the sky glow visible from Highway 83. The upper panel shows the current condition; the lower the condition predicted with the addition of the proposed RCM lighting. The triangle indicates the azimuth of the RCM. Here the principal light domes at azimuth 205º (–155º), 330º (–30º), and 125º, arise from Nogales, Tucson and Sierra Vista, respectively.

F. Empire Ranch

Model results for the Empire Ranch observation point are shown in Figure 20, Figure 21, Figure 22, and Table 13.

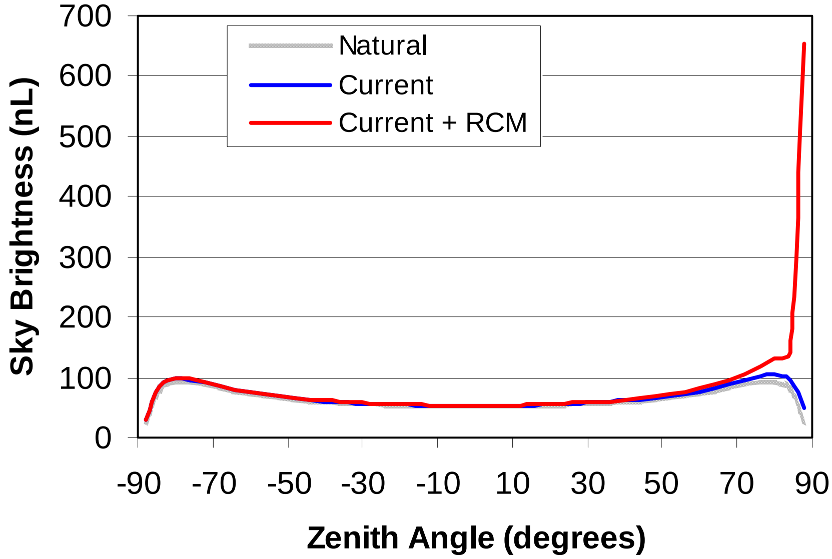

Figure 20. Horizon-to-horizon sky brightness at Empire Ranch on the semicircle originating toward the RCM site (azimuth 288°, zenith angle +90°) and ending at the point on the horizon opposite (azimuth 108°, zenith angle –90°). The blue line shows the predicted current sky brightness profile arising from the 7 existing cities and towns listed in Table 6; the red line shows the predicted additional contribution of the RCM lighting described in Table 5.

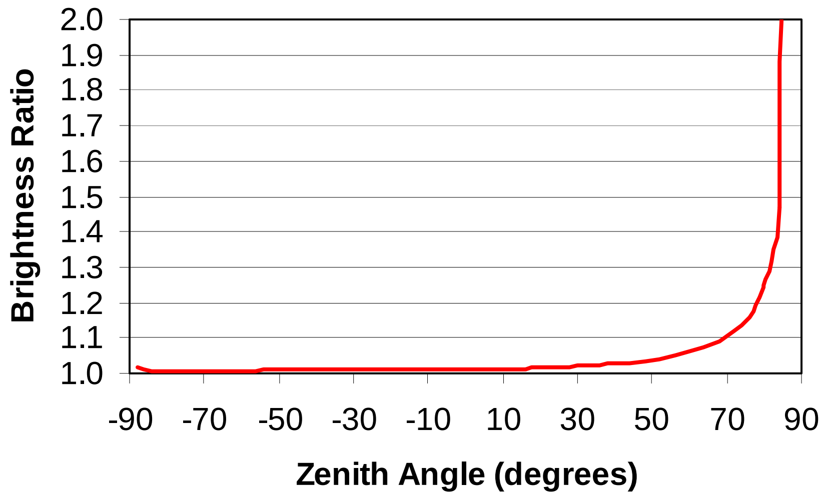

Figure 21. Brightness ratio as viewed from Empire Ranch toward the RCM site.

Table 13. Sky brightness ratios as viewed from Empire Ranch at selected zenith angles toward the RCM.

Zenith Angle	Brightness Ratio (predicted/current)
0°	1.011
44°	1.030
60°	1.060
70°	1.105
80°	1.242
88°	13

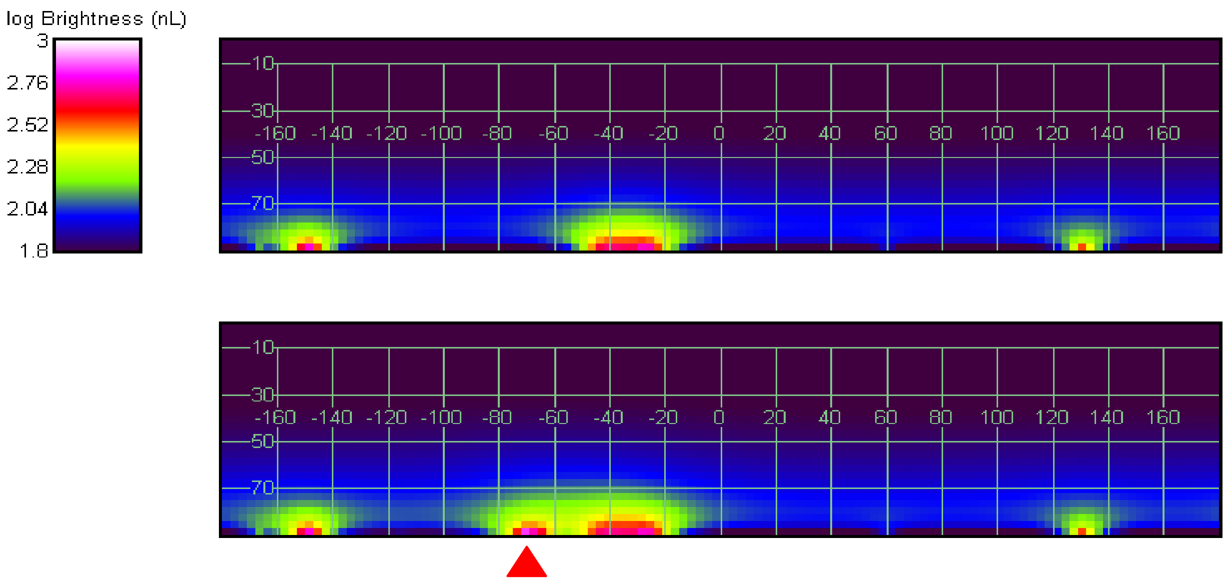

Figure 22. An all-sky false-color panoramic map of the sky glow visible from Empire Ranch. The upper panel shows the current condition; the lower the condition predicted with the addition of the proposed RCM lighting. The triangle indicates the azimuth of the RCM. Here the principal light domes at azimuth 210º (–150º), 330º (–30º), and 130º, arise from Nogales, Tucson and Sierra Vista, respectively.

IV. Potential Mitigation Strategies

In rough order of importance or mitigation effectiveness, the following strategies could be employed to decrease the impacts of the lighting used at Rosemont Copper Mine.

A. Hours of Operation

Performing mining operations during daylight hours only would allow the elimination of a large fraction of the lighting, though the fraction is unknown due to lack of a detailed lighting plan in M2012a.

B. Portable Fixture Aiming

Direct upward emissions have disproportionate impact on sky glow, particularly at large distances (Luginbuhl, Walker and Wainscoat, 2009). Therefore, keeping the portable light fixtures located at the active mine site aimed as far as possible below the horizon and away from the directions toward sensitive sites would substantially reduce sky glow as well as direct visibility impacts. Without specific photometric information for the fixtures or information on aiming constraints the improvements expected cannot be quantified.

C. Regular Cleaning of Equipment-Mounted Lighting

Keeping optical surfaces of equipment-mounted lighting clean would reduce the uplight fraction scattered from dirt and dust accumulating on these fixtures, providing any cleaning procedures preserve the optical quality of the fixture optics. According to M2012b, the uplight fraction for new, perfectly aimed lights would be closer to 10%; hence a significant reduction in this major contributor to RCM sky glow could be obtained.

D. Lamp Type

Lamps with lower short wavelength emission produce lower visible sky glow impacts in dark areas, as the dark-adapted human eye has increased sensitivity to shorter wavelengths. This spectral shift (called the Purkinje shift) means that yellower lights produce less impact. A useful measure of the relative impacts of different sources is the “scotopic to photopic” ratio, or S/P (see for example Berman and Clear, 1999). The S/P ratios for several light sources are shown in Table 14.

Table 14. Scotopic to photopic or S/P ratios for lamps.

Lamp Type	S/P Ratio
LPS	0.24
ALED	0.24
HPS	0.60
FLED	0.92

The M2012b lighting plan analyzed in this report uses a mixture of ALED and FLED. Though ALED and LPS have similar S/P ratios, the S/P ratio and thus the visible sky glow impact of the FLED light is about 50% greater than for the HPS lamp used in earlier designs. As the M2012b lighting plan uses almost five times as many lumens in FLED lamps as in ALED, reduction in the amount of FLED lighting – through removal, switching off during periods when not needed, or substitution with ALED – could substantially reduce the visible sky glow increase of the RCM lighting, and confine the impact to a much smaller range of wavelengths.

V. Discussion and Conclusions

The modeling performed for this study indicates that the proposed outdoor lighting for mining operations within the RCM would produce an increase in sky glow from 0.4% to 1.1% at the zenith for five of the six observation points analyzed; the brightening reaches a maximum of 9% at the zenith when observed from the nearby portion of Highway 83.

At the astronomical Observatory sites, including FLWO, Jarnac, and Empire Ranch, the increase in brightness of the zenith is 0.4%, 0.7%, and 1.1% respectively. In the portion of the sky most used in professional astronomical research, which we consider here to be out to zenith angle of 70°, the brightening at these sites due to the proposed RCM lighting will be much more significant, reaching 3%, 8%, and 11%, respectively, in the direction of the mine operations.

The analysis presented here is based on the M2012b Rosemont lighting plan for the Barrel alternative which eliminates the leach field and associated lighting. Other alternatives have been presented which, while no lighting plan has been forthcoming, would presumably include leach field lighting. In the absence of any lighting plan for these other alternatives, DSP can only estimate the potential impact of this additional lighting based on leach field lighting as described in M2012a. In that report, leach field lighting consisted of 105,538 lumens with zero direct uplight. This amount of additional lighting represents an increase of about 1.6% in total RCM lighting, translating into a very small increase in sky glow as seen from all observing sites (i.e. a 10% increase would change to 1.016 x 10% or 10.16%).

As noted earlier, there is only a small increase in sky glow at wavelengths below 500 nm due to Rosemont operations; virtually all of the LED light from Rosemont would be of longer wavelengths. However, when compared with HPS and LPS lighting, the LED lights, on a purely spectral basis increase the spectral extent of the added skyglow and thus increase the impacts. As seen from Figure 3 and Figure 4, the LED lights produce substantial output at wavelengths between 500 and 700 nm while HPS+LPS confine their principal output to wavelengths between 540 and 640 nm, about half the spectral region of FLED+ALED lights.

The current lighting plan has reduced outdoor lighting compared to the 2011 plans and uses shielding for most applications. Options that could produce further reductions in sky glow impacts are limited. Aiming of moveable unshielded lighting as far as practical below the horizon and regular cleaning of lighting on equipment could reduce the uplight fraction for these components, though potential damage to the optical surfaces from frequent cleaning make make this potential improvement elusive. Though restriction of mining operations to daylight hours may be unlikely, this would be the only way to substantial reduce impact on the night sky of Southern Arizona.

Monrad (2012a) refers to sky brightness measurements made by Craine *et al.* (2011), intended to provide observational baseline data on sky brightness in this region of Southern Arizona. DSP was not able to use these data due to: 1) the spectral bandpass mismatch between the data and the visual/V-band in which DSP results are presented; 2) lack of information on calibration for the Craine *et al.* data; 3) lack of a spectrum for their data. Though the Craine *et al.* data might provide a basis for long-term monitoring of sky brightness in the region, the analysis presented in this study, based on a modeled baseline condition, provides robust results concerning overall impacts of the proposed RCM on sky brightness.

VI. References

Arizona Arts, Sciences and Technology Academy (2007), "Astronomy, Planetary Sciences and Space Sciences Research: Opportunities to Advance Arizona's Economic Growth"

Berman, S. and Clear, R., (1999). "Some Vision and Lighting Issues at Low Lighting Levels," EPRI/LRO Fourth International Lighting Research Symposium, TR-110738, © 1999, Electric Power Research Institute.

Craine, E.R., Craine, B.L., Craine, E.M., Craine, P.R., Fouts, S. and Craine, M.H. (2011). SkyBrightness and Light at Night: Santa Rita Mountains, Arizona 1. Airborne and Ground based Reference Data Collection. STEM Tech Rep 11, 1201.

Dark Sky Partners (2011). An Assessment of the Impact of Potential Mining Operations at the Rosemont Copper Mine on the Night Sky of Southern Arizona, prepared for SWCA.

Davis, D.R., Luginbuhl, C.B., Boley, P., Miller, D. and Crawford, D.L. (2006). "An Assessment of the Impact of Growth on the Dark Skies of Pima County," International Dark-sky Association Report. Available at http://www.darksky.org/

Duriscoe, D. M., Luginbuhl, C. B., Moore, C. W. (2007). "Measuring Night-Sky Brightness with a Wide-Field CCD Camera," Pub. Astron. Soc. Pacific 119, 192.

Garstang, R.H. (1986). "Model for Artificial Night-Sky Illumination," Pub. Astron. Soc. Pacific 98, 364.

Garstang, R.H. (1989). "Night Sky Brightness at Observatories and Sites," Pub. Astron. Soc. Pacific 101, 306.

Garstang, R.H. (1991). "Dust and Light Pollution," Pub. Astron. Soc. Pacific 103, 1109.

Luginbuhl, C.B., Lockwood, G.W., Davis, D.R., Pick, K., and Selders, J., (2009a) "From The Ground Up I: Light Pollution Sources in Flagstaff, Arizona," Pub. Astron. Soc. Pacific 121, 185.

Luginbuhl, C.B., Duriscoe, D.M., Moore, C.W., Richman A., Lockwood, G.W., and Davis, D.R., (2009b). "From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona," Pub. Astron. Soc. Pacific 121, 204.

Luginbuhl, C.B., Walker, C.E. and Wainscoat, R.J., "Lighting and Astronomy," Physics Today, 62:32, 2009

Monrad, C.M., Benya, J. and Crawford, D.L., (2012a). Rosemont Copper Project Light Pollution Mitigation Recommendation Report - Revision 1 - June 18, 2012.

Monrad, C.M. (2012b). Rosemont Mine - Mitigation Recommendation Report Addendum. 17 August 2012.

Alternative Scenarios Modeling Summary (2011). Prepared by JBR.

Schoettle, B., Sivak, M., Flannagan, M.J., and Kosmatka, W.J., 2004, Technical Report No. UMTRI-2004-23 (Ann Arbor: The University of Michigan Transportation Research Institute)