Abstract
Reflected sunlight from building integrated heliostat systems contains many of the same ultraviolet (UV) light hazards present in sunlight. Heliostat light is not the same as sunlight however, and the general public is unlikely to be able to accurately assess the nature of the hazard and choose the appropriate radiation protection strategies. Therefore, a number of standard risk management practices are discussed for effectively managing the hazards. Maximum irradiance levels for continuous exposure are calculated for a range of heliostat mirror materials as a function of solar spectrum. Higher irradiance levels are also possible by switching the system off for some time in the middle of the day. The addition of spectrally selective filters is discussed as a means of increasing irradiance from the heliostat without increasing the hazard. A range of additional options are discussed that encourage radiation safety and enhance the effectiveness of the heliostat.

1. Introduction
Remote source solar lighting is increasingly being employed in the built environment for brightening, warming and improving the amenity and ambience of cold, dark or unappealing spaces. The presence of sunlight has been shown to facilitate improved productivity and visual comfort in schools (Heschong, 1999). Other benefits include improved energy efficiency with reduction in reliance on electricity for lighting and heating.

The most common technologies typically fall in the categories of skylights, light-pipe and fibre optic lighting systems. Numerous studies have demonstrated their ability to light deep into multilevel building complexes, with managed dimmable lighting control and significant reduction in energy usage (Wong et al, 2012) (Li et al, 2010) (Kennedy and O'Rourke, 2015) (Paroncini et al, 2007).

Designs that use entirely reflective optics are becoming more common. With the aid of both fixed and sun tracking mirrors (heliostats), sunlight may be delivered over large distances into building spaces and surrounding public areas such as parks or gardens. These systems have the advantage of reduced cost, high throughput and flexibility for accurate placement of sunlight onto target areas of interest. Publications on this topic are few, and further research is helpful to fully understand their potential benefits.

1.1. The heliostat
Heliostats are sun tracking mirrors used to reflect the sun onto a chosen receiver target. They employ two axis tracking mechanisms and electronic control in order to follow the Sun’s path through the sky. Heliostats are most commonly employed in concentrating solar power (CSP) power plants where thousands of heliostats are employed to create high temperatures and generate electricity. Depending on the degree of curvature of the mirror facets, it is possible to concentrate or diffuse sunlight at the target zone and concentration ratios depend on the design and quality of the optics.
A common implementation of the heliostat in the built environment is shown in Figure 1, although there are many possible variations on the concept. The heliostats system is augmented with stationary 'secondary' mirrors that redirect light from the heliostats into the desired target areas. The advantage of using secondaries is that they give design flexibility, enabling light to be directed into more target locations, while overcoming issues with cosine losses that limit the directions to which a heliostat can direct its light.

Figure 1. Example layout of the key elements of a building integrated solar lighting system

1.2. Examples

Heliostat systems offer the possibility for iconic, high-value urban environments with dynamic, environmentally sensitive and attractive architecture. Perhaps the most notable example is the OneCentral Park development designed by French design group Ateliers Jean Nouvel and Australia's PTW. The building is a stylish integration of highrise residential and commercial shopping precincts with vibrant greenspaces. It features an iconic integrated heliostat system with large cantilevered secondary mirror array for redirecting sunlight into the building atrium as well as the nearby green spaces and facilities. One CentralPark won the International 'Best Tall Building Worldwide 2014' award (Chua and Hadley, 2014) and is an inspiration for advanced building design.

Another prominent example is the Rhodes Central development currently under construction in Sydney. This design by architects SJB includes a heliostat system with an impressive 'crown' structure on top of the eastern tower (Thomas, 2016). The crown supports an array of secondary reflectors which redirect sunlight collected by heliostats located on the roof. The system will enable sunlight to reach Rhodes Town Square park at times when it would otherwise be shaded by highrise buildings to the north.

The 'Corona Sun Beam' is an innovative example of heliostat lighting developed as a partnership between TILT, Zulu Alpha Kilo and Corona (Tilt, 2014). Inspired by the Rjukan heliostat (a ray of light to ease the winter chills in a Norwegian town), the heliostat reflects light down from the top of
a boom lift truck into beer gardens and outdoor patios (Webber, 2014). The system encourages people to stay, drink and socialise even after the sun has moved away.

2. Radiation Exposure Regulation

Light management in cities is an expanding area of research, and is critical to effective urban planning. Existing standards and building codes that govern the amount and type of radiation that buildings can emit into their surroundings do not adequately apply to building integrated heliostats (for example AS/NZS 1336:2014 Eye and face protection). Redirected sunlight brings with it a new set of characteristics and hazards that make it difficult to classify with codes historically intended for electric lighting.

While some heliostat systems may strive to produce lighting similar to the sun, they are certainly not the same as the sun once heliostat materials have modified the spectrum, direction, brightness and angular subtense of the light. It is not suitable to assume that solar hazard protection guidelines are applicable. A new approach is required to address the issues involved.

The International Commission on Non-ionizing Radiation Protection (ICNIRP) provides guidelines on permissible cumulative exposure to radiation that avoid long term harm. These guidelines are then implemented in Codes of Practice by national bodies such as ARPANSA (ARPANSA, 2006). Three key publications include the guidelines for exposure to broadband incoherent radiation (UV (ICNIRP, 2004) (ICNIRP, 2010) and Vis-IR (ICNIRP, 2013)). The guidelines specify effective exposure limits as a function of wavelength. The procedure generally involves the convolution of a damage sensitivity function with the input radiation profile in order to determine the effective exposure.

2.1.1. Skin

The implementation of limits to skin exposure to UV light is problematic due to the variability of physiological reactions depending on skin type. To resolve the difficulty with a specification of exposure limits for protection of the skin against sunburn, ICNIRP published the statement on protection of workers against UV radiation (ICNIRP, 2013). The publication reinforces the specifications provided on UV radiation (ICNIRP, 2004), and the condition in Equation 1 must be met in order to protect from sunburn:

\[ \sum_{180}^{400} E_\lambda \cdot S(\lambda) \cdot \Delta \lambda \cdot t < 30 \text{ Jm}^{-2} \]  

Equation 1

where \( E_\lambda \) is the incident spectral irradiance profile, \( S(\lambda) \) is the damage sensitivity function (see ICNIRP, 2004), \( \Delta \lambda \) is the wavelength interval of the data sets (the sum notation is simply an approximate integration), and \( t \) is the maximum viewing time of 8 hours per day (28800 seconds). In the case where shorter exposure time is involved, then the same daily limit of 30Jm\(^{-2}\) applies, but the irradiance level may be higher during the short period of exposure. Care should be taken to consider the total exposure from all sources during the 8 hour period so as not to exceed the limits (for example, people might be exposed to direct sunlight at other times of day).

ICNIRP specifies that the exposure limits should be interpreted as a "desirable goal value" rather than a "ceiling value" as they are interpreted in the context of ocular hazard. For example, when considering the AM1.5 solar spectrum on a bright sunny day with direct normal irradiance (DNI) 1000Wm\(^{-2}\), the first condition limits the exposure time to less than 5 minutes in an 8 hour period. ICNIRP reports that the limit is exceeded in less than 6 minutes under clear sky or tropical conditions at solar noon (ICNIRP, 2010). On the other hand, spectra with reduced UV content (typical of mornings, afternoons, hazy or polluted environments etc) will yield much longer exposure times. For example, a typical afternoon spectrum in a coastal Australian city, with DNI 900 Wm\(^{-2}\) yields a maximum exposure time of around 2.5 hours within the 8 hour period.
Being a dose rate relationship, the UV hazard depends on the spectral irradiance arriving at a chosen target plane (the geometry of the light source is not important). Therefore it is possible to develop a number of results relevant to building integrated heliostat systems by analysis of irradiance levels, as described in the following section.

Outside of the UV hazard range, ICNIRP guidelines suggest that very high irradiances are required to produce thermal injuries to the skin, and no specific controls are specified for general exposure (ICNIRP, 2013). Natural aversion to thermal burns (depending on deep tissue temperature) appears to adequately protect the skin for visible (400nm to 700nm) and infrared radiation when delivered at irradiance levels typical of solar radiation (not high power pulsed radiation). It is assumed that hazards associated with visible and infrared burn of the skin may be ignored for heliostat based solar lighting systems.

2.1.2. Eyes
The eyes are subject to a number of possible damage processes including:

- Photochemical injury to the cornea and lens (UV hazard)
- Photochemical injury to the retina (Blue-light hazard)
- Thermal injury to the retina (Retinal thermal hazard)
- Thermal injury to the cornea and lens (Near-infrared hazard)

A full treatment of these hazards is given by ICNIRP (ICNIRP, 2004), (ICNIRP, 2013) including the effects of the apparent angular size of the bright object, the impact of aphakic vision and the viewing times. In general the specifics of the optical design (the shape of mirrors, distances, other bright objects etc) will determine what the ocular hazards will be and there is no common rule that can be used to characterise the hazards. In general a site specific approach will be necessary to assess ocular hazards from particular building integrated heliostat systems. A method for simply implementing the ICNIRP guidelines has been described by Fell et al (Fell, 2010), and unpublished work developed at CSIRO Department of Energy Technology extends that to allow recommendation of standard sunglasses shades for intended viewing of bright light sources. An alternative technique is described by Ho et al (Ho, 2011), and may also be used to assess the hazards posed by a specific design.

As discussed by ICNIRP (ICNIRP, 2010), the Coroneo Effect means that any UV light (including wide angle diffuse UV light) that strikes the eye will likely be refracted and concentrated into the lens, contributing to the net UV dose. The aversion reflex does not directly protect viewers from wide angle UV light because the viewer does not need to look towards the radiation source to be affected. Therefore, in cases where UV light falls on the eyes and face, the additional constraint in Equation 2 applies:

$$\sum_{315}^{400} E_\lambda \cdot \Delta\lambda \cdot t < 10^4 \text{ Jm}^{-2}$$

Equation 2

The applicability of this constraint depends highly on the geometry of the viewer and the light source; if the viewers eyes are protected by the brow and lids (effective against light from overhead) then higher irradiance levels of UVA radiation may be acceptable.

3. Design Constraints
A conservative approach to the system design is to maintain that continuous exposure for any exposure duration, will not exceed the daily UV exposure limits. This has the following implications:

- A person may choose to expose themselves to the heliostat light source at all times that it is operational, and would therefore not be at risk.
Someone who spent a long time in the sun elsewhere and subsequently chose to expose themselves to the heliostat light source could exceed the daily UV limit. However, it is readily argued that the person did not use appropriate sun protection earlier on, and would have been safer to simply remain under the heliostat light source continuously. The majority of the damage happened elsewhere.

Another design approach would involve designing the light source such that continuous exposure for the duration when the heliostat light source is switched on, will not exceed the daily UV exposure limits. This is a higher risk approach, as it potentially places people in a situation of using the entire UV dose 'quota' on the heliostat system, and placing them at risk from exceeding the quota where exposure occurs from other sources. While the heliostat light source is nominally safe, it may not be considered particularly responsible.

Results relevant to these two design philosophies are presented in the following sections.

3.1. Heliostat materials and continuous exposure

The choice of heliostat reflector affects the amount of UV light that is directed onto a target area where the general public may be exposed. A range of materials were studied and are classified as defined in (Good, 2016a) (Good, 2016b). They include

- metallised polymer films typically made with copper and silver layers and sealed with a protective coating (referred to as AgFilms).
- metallised aluminium sheet, typically made from a silver (or aluminium) coating applied to aluminium sheet via physical vapour deposition and covered with a protective weather resistant coating (referred to as Films&Sheets).
- back-silvered glass solar mirrors with low iron glass (AgGlass)
- back-silvered glass mirrors with standard float glass (AgNonSolar).

The maximum irradiance level to meet the UV dose limit in 8 hours depends on the UV content in the incident sunlight. Given that the solar spectrum varies from site to site, the following results show maximum irradiance levels for different types of mirrors as a function of ASTM airmass. Results are presented for single reflections, double reflections (right - systems where two reflectors are implemented), as well as with and without the Coroneo UVA condition.

In each case, the results show a range of maximum irradiance values depending on the spectral reflectance curve for different types of materials. Note that for some materials, the UV reflectance can be higher for wide incidence angles, meaning that the impact spectral irradiance in the UV could be higher than expected at higher angles of incidence. The range of irradiance limits for different material types shown in the above plots is due in part to this, as the spectra were taken from variable angles (7°, 15°, 45°, 60°) as reported in (Good, 2016a) (Good, 2016b).

In choosing a suitable airmass value, care should be taken to use data from bright clear days, such that the irradiance value is also appropriate for less bright days. The airmass value would be the minimum airmass value measured at the site for all operational time periods. Results that exclude the Coroneo UVA condition should only be chosen where UV light from the heliostat does not reach the eyes from any direction.
3.2. Higher irradiance for shorter time

Active control of the heliostat system may be an effective way of managing UV exposure. For example; bright clear days may be rare at a particular site, so in that case it may be possible to design for a higher irradiance level in the target zone and switch off the system on the occasions when a bright clear day would otherwise result in too much UV light. Such a system would require onsite measurement of the solar DNI and a calculation of the UV dose delivered to the target zone.

A heliostat system typically maps a given input irradiance, to some proportional output irradiance, where the ratio of the irradiance levels is a function of the system optics. This is termed the ‘throughput efficiency’. While the input irradiance may not be predictable, the UV irradiance can readily be expressed in terms of the prevailing solar conditions (such as known DNI value, known solar spectrum, and known spectral reflectance / transmittance properties of the reflectors).

A study was conducted to relate the maximum system ON time for clear days as a function of system throughput efficiency and the choice of reflector materials. The location was Sydney.

\[1\text{ Typically depends on the position of the sun in the sky, cosine losses, blocking and shading losses and other features of the system. Ray tracing can be an effective means of quantifying system the throughput efficiency.}\]
Australia. Hourly DNI spectra were simulated using SMARTS, based on measurements of ozone (WMO Antarctic Ozone Bulletin 2016), carbon dioxide (CSIRO - Cape Grim), pressure (BOM Daily Weather Observations), humidity, temperature and turbidity (AQMS - ROZELLE). Spectra included circumsolar radiation based on a 2.9 degree aperture. In order to determine system operation limits on the brightest sunny days, a clear day DNI profile was extracted from raw data available from the One Minute Solar Data resource (Australian Bureau of Meteorology, 2017) for the site closest to Sydney (Wagga). The solar data is shown in Figure 3.

Irradiance levels at the target zone were calculated for various system throughput efficiencies. High throughput efficiency of 1 means that the system will deliver the same irradiance level at the target zone as was incident in the solar DNI. Both irradiance values are relative to the appropriate spectrum (ie, at the target zone, the spectrum will include changes due to heliostat reflections). In practice, a throughput efficiency of 1 would require slightly concentrating optics to accommodate for system optical losses. Note that the throughput efficiency may differ from apparent relative brightness when the spectrum differs from that of incident sunlight. In that case, lux levels may be a useful measure of the apparent visual brightness.

![Figure 3. (Left) Representative clearest day DNI profiles for summer and equinox. (Right) Hourly solar spectra used for UV dose assessments on a summer day.](image)

Cumulative UV doses were determined for each reflector material as shown in Figure 4. The system was switched off for the shortest amount of time in the middle of the day such that the total permissible UV dose was not exceeded in the target zone. Note that all of the results assume that there are no other sources of UV radiation also incident on the target zone. In general, responsible operation would stop short of the ranges described to give the general public an allowance for exposure at other times.
4. Design Alternatives
As is evident from the previous discussion, the UV content in reflected sunlight potentially results in excessive UV doses rates if the irradiance levels are high. The choice of reflector material affects the maximum safe irradiance limits. If those irradiance limits are still insufficient for producing the desired visual displays in outdoor public spaces, then it may be desirable to adopt additional measures to control UV hazards.

Figure 4. Heliostat system ON/OFF times to avoid exceeding UV dose limits as a function of system throughput efficiency. All results are for two reflections (heliostat and secondary of the same material), and are switched off in the middle of the day as necessary. A range of switch times for systems excluding the Coroneo UVA condition is indicated by blue and red curves based on variations in material properties. Switch times for systems including the Coroneo UVA condition are indicated by the broken green curves. Left hand figures are for the clearest midsummer day. Right hand figures are for the clearest equinox day.
4.1. Diffusers
Perhaps the most obvious solution is to use diffusers in the optical system. As shown in Figure 5, bright light arriving from the heliostats is directed onto the diffuser, which then distributes the light over a wide angle. At the target zone the net irradiance is relatively low, but the visual effect of the bright light on the diffuser is still present. The design could be implemented in reflective mode, or via transmission and may include secondary reflectors between the heliostat and the diffuser. One example is the use of a water film above the atrium roof in the OneCentral Park development. Wind effects and other turbulence serve to distribute light from the secondaries as it filters into the atrium area. Designs should consider careful placement of the diffusers to avoid issues with ocular glare.

![Figure 5. Target zone indirectly lit with scattered light from a diffuser](image)

4.2. Spectral filtering
Spectrally selective filters that remove unwanted parts of the spectrum may be a cost effective and easy alternative. UV filtering films are commonly employed for protecting sensitive artefacts and are available as sheets, films or coatings applied to windows. If the film absorbs or scatters the UV light it would be suitable for placement anywhere in the optical system. If it simply reflects UV light, then that film could only be useful when laminated to a clear roof above the target zone.

Polycarbonate (PC) material has a strong absorption edge at 400nm (see Figure 6) and is available with UV stabilisation (to avoid yellowing), antireflection coatings and hardwearing finishes (scratch resistance). Thin films of PC can also be laminated to the front surface of glass heliostat mirrors, to reduce UV radiation while offering improved safety and resistance to breakage. Thin film durability is typically less than the specialised PC sheet products, so it may be necessary to replace thin films periodically to maintain mirror specularity and clarity. A wide range of other acrylic materials are also available with varying degrees of transparency, toughness, UV resistance and UV filtering capability. Choice of the most appropriate filter materials will depend on the application and will typically require measurement of material reflectance and transmission properties and UV hazard calculations as detailed above.
Supposing that the Coroneo UVA condition does not apply, the addition of a single UV stabilised PC sheet to a two reflection heliostat system enabled at all times for glass and film reflector materials and throughput efficiencies up to 2x. Operation time constrains still remained for the metallised aluminium sheets (Films & Sheets) as shown in Figure 7. This category of reflector has a reasonably wide range of UV absorption rates (different materials, surface finishes, measurement angles etc), so some reflector types and system configurations will require shorter OFF times to stay below UV dose limits.

If the Coroneo UVA condition applies, then the system with additional PC sheet required no system OFF time for irradiance throughput efficiency up to 1.4x when using metallised polymer film mirrors (AgFilms). Extended operation time was also seen for metallised aluminium sheet mirrors, requiring no system OFF time for irradiance throughput efficiencies up to 0.18x. Glass mirrors could be operated without OFF time and irradiances up to around 0.25x. Adding both a PC sheet and a 115μm PC film permitted most mirror systems to operate uninterrupted for throughput efficiency levels of at least 0.8x all year round.
Other plastics such as PMMA (acrylic), and modified polyethylene compounds such as ethylene-
tetrafluoroethylene(ETFE) or fluorinated ethylenepropylene(FEP) also offer some absorption of UV
radiation (ICNIRP, 2013). Plastic mirrors (security mirrors) based on substrates that absorb UV
light could be very suitable, but may not offer the necessary specularity and durability required for
outdoor applications. The phenol group is commonly used for absorbing UV radiation as it capable
of both absorption and rapid dissipation of the absorbed energy in a stable manner. Materials
suitable for spin coating on a range of substrates were reported with room temperature cure
requirements (Zayat et al, 2007), but long term stability remains problematic for outdoor use
(Parejo et al, 2010).

Common inorganic materials such as TiO$_2$ CeO$_2$ and ZnO have band gaps in the UV-A region, so
remain substantially transparent to visible light, while absorbing UV. Depending on the surface
topology, scattering can also be a significant factor. These materials may be coated on mirror
surfaces to add UV filtering, but may require relatively high anneal temperatures. In general, the
surface of secondary reflectors is likely to be the best place for inorganic films because they are
usually down-facing and less likely to be exposed to rain.

One example is the use of ‘self-cleaning’ TiO$_2$ nanoparticle coatings developed for architectural
applications. While these coatings are sensitive to rain, the use of binders such as hydroxyapatite
(HAP) has been shown to improve durability (Sassoni et al, 2018). Results from measurements on
TiO$_2$ films indicates that UV absorption would be achieved only with thicker films, and in that case
the relatively broad absorption band of the TiO$_2$ would disrupt the transparency of the system
(Jesus et al, 2015). Combinations with SiO$_2$ improved the film durability but did not provide better
UV spectral selectivity. ZnO films show promising results with a sharp absorption transition at
around 390nm, reduced to around 370nm when doped with Aluminium or Nitrogen (Silva et at,
2014)(Balasubramanian et al, 2012). While annealing temperatures between 300°C and 500°C
make these films are suitable for glass substrates, they have also been deposited on flexible
polyimide substrates using pulsed laser deposition (Jacobs et al, 2017). Further research is
required to develop inorganic films suitable for heliostat lighting systems.

4.3. UV harvesting systems

One configuration of the heliostat solar lighting system design includes the potential for
concentrating optics in the heliostats. As shown in Figure 8, it is possible to use the heliostats to
focus light onto a smaller secondary reflector, before it again diverges before arriving in the target
zone. While the design puts some constraints on the arrangement of light in the target zone, the
small size of the secondary reflector means that it may be more cost effective to implement more
advanced spectral selectivity.

The design opens up a number of interesting possibilities for the best materials and systems to use
for the secondary object. Possible options include multilayer Bragg spectral filters that are tuned to
reflect the visible wavelengths, while transmitting the UV (and possibly IR) wavelengths onto a
solar PV cell or thermal absorber. Another system could use a mirror covered by a fluid chamber
containing particles that preferentially absorb the UV radiation while remaining transmissive to the
visible wavelengths. An example of this would be the luminescent solar concentrator. A similar
configuration would be to use the fluid to absorb the UV wavelengths converting that energy to
heat which is removed by recycling the fluid.
Figure 8. Heliostats concentrate light onto a reduced number of secondaries where UV light may be efficiently removed. The remaining light then diverges as it travels to the target zone.

5. Other risk factors
In addition to the hazards identified above, further unexpected hazards may result from redirecting sunlight, including stray reflections and multiple exposure.

5.1. Stray reflections
Stray reflections refer to unwanted light reflected from heliostats or secondary reflectors. One example involves sunlight striking secondary reflectors and landing in unwanted locations around the building. Even though the secondaries may be optimised for reflecting light from heliostats, it is critical to consider the effects of direct sunlight also. Depending on the design, there are a number of possible solutions:

- provide fairings / edges around the secondary mirrors that shade the secondary reflector from those unwanted light sources.
- design the array of secondary reflectors such that they shade each other from unwanted secondaries.
- consider the motion of heliostats when switching on and off (traversing adjacent secondaries) to avoid or minimise the impact of unwanted strays.

5.2. Multiple Exposure
Multiple exposure relates to areas where a person may be exposed to higher levels of radiation than would be experienced on a clear sunny day. This could occur as a result of heliostat images directed to areas that are already exposed to full sun. It could also involve concentrated light from heliostats that reaches irradiance levels higher than that typical of direct sunlight.

If the heliostat light does not contain UV light, then the skin burn hazard is not substantially affected with multiple exposure, and general radiation protection methods are quite suitable for the multiple-exposure area. In this case, multiple exposure may be acceptable so long as the peak irradiance levels are not so unreasonably high as to be unpleasant on the skin or eyes.

If the heliostat light does contain UV radiation, then the situation is more complicated. It could be argued that the heliostat lighting system 'takes ownership' of the hazard in the target zone (already high due to the sunlight). Then, being different from standard 'direct sunlight', people may be confused about the appropriate hazard management approaches, leading to sunburn or inconvenience. In that sense it is safest to avoid multiple exposure where possible, by switching the heliostat system off.
6. Design process

Sunlight exposure is a delicate problem. Under certain solar conditions it is possible to exceed the total daily exposure limits within a matter of minutes. On the other hand, a certain amount of exposure is helpful and important for a healthy life, although this can vary widely with different skin types.

While the design objective for the heliostat integrated lighting system is generally to provide a useful and interesting lighting feature in the building, there are limitations due to the implications of radiation exposure.

The approach to the problem has two main objectives:

- **PRIMARY OBJECTIVE**: Ensure that the light source is safe while it is in operation
- **SECONDARY OBJECTIVE**: Use design practices to encourage the general public to follow suitable hazard management practices.

6.1. Primary Objective

In order to meet the PRIMARY OBJECTIVE, the maximum UV dose should be limited according to one of the practices discussed earlier, such as limitation of the peak irradiance, and/or limitation of the total system ON time. Methods for making this assessment could be as follows:

1. Determine the solar spectrum and solar DNI typical of the local area. This could be via measurement and/or via credible simulation. Note that these may change with time of day, leading to different hazards at different times. In the absence of information, use data that characterises the peak UV irradiance conditions.
2. Calculate the target irradiance profile from the heliostat system. This will likely involve ray tracing simulations and spectral reflectance / transmittance measurements.
3. Assess the contribution from other light sources. This could be direct sunlight, reflected sunlight from neighbouring buildings or other sources. Determine the total UV irradiance levels at the target zone.
4. **Consider controls:**
   - (Elimination) Reduction of the irradiance through divergent optics or modification of the lighting strategy. Switch off heliostats to avoid multiple exposure.
   - (Elimination / Engineering controls) Modify the spectrum with suitable UV filtering materials.
5. Verify that the total exposure from the heliostat light source (while it is switched on) is within the limits for the 8 hour period as specified according to the ICNIRP methods. Preferably the design should be appropriate for continuous exposure, however, in the case where systems are switched off to reduce exposure, make some allowance for exposure to UV light at other times (don't use the entire UV budget in a short period).

6.2. Secondary Objective

The SECONDARY OBJECTIVE involves the public perception of hazards. In general, people are accustomed to managing the risks of solar exposure characteristic of their environment. Therefore, if the new solar heliostat amenity provides an environment that is perceived to be similar to normal solar exposure, and the hazard is readily recognised as a solar hazard, then it is likely that people will apply the same risk management approaches. Some examples include:

- aversion reflex; look elsewhere
- wearing hats, sunglasses, protective clothing, limiting exposure time
- retreating to cool shady locations nearby
Suggestions for system design techniques that help to manage the risks of radiation exposure include the following:

1. Design the system in such a way that mimics direct solar exposure (necessary for the aversion reflex, and also to prompt standard hazard management responses). The sun comes from the sky above a pedestrian area, not from below or from strange unexpected angles. Ensure that ocular hazards are not unusual and that the aversion reflex readily protects people as they go about their daily business. Light should preferably not shine directly onto the eyes and face, and if it does, it must comply with Coroneo Effect UVA exposure limits. Observe standard design practices for protecting people from excessive solar exposure, including
   a. provision of a shaded or alternative path,
   b. placement of distributed shaded areas to encourage people to manage their solar exposure, seeking shade when necessary
2. Assess the typical exposure durations for the affected area. For example, a pedestrian path or an escalator is likely to have lower exposure rates as people walk past the hazard. This may mean that the irradiance in those areas could be safely increased. On the other hand, seating areas or pools are likely to have higher exposure rates because people may stop for longer periods, and intentionally expose their skin to sunlight. These areas should have more strictly limited dose rates.
3. Consider controls:
   (Substitution): provide alternative lighting if the heliostat lighting system is impractical.
   (Engineering): Modify the environment to dissuade people from remaining in highly irradiated areas (move pools, tables chairs, convert grass areas to gardens etc). Provide barriers for restricted access or provide additional shading options.
   (Administrative) Provide users with appropriate warnings about radiation safety. Warning levels appropriate for different dose rates are discussed by ICNIRP for solar exposure (ICNIRP, 2012), but may be insufficient for heliostat systems where the solar spectrum has been modified. Additional guidance may be offered by national regulatory bodies such as ARPANSA.
   (PPE) Provide users with protective equipment such as sunscreen, hats etc.
   For further information, refer to the ARPANSA Code of Practice (ARPANSA, 2006).

The One Central Park building sets a good example. The fact that the general public can't easily see the heliostats when inside the building, gives the feeling that it's just sunlight coming down through the atrium roof, and therefore people are more likely to apply standard hazard management procedures. The fact that plants are growing in a garden that is lit by the heliostats further encourages the feeling that it is simply sunlight and should be treated as such. The use of gardens also segregates areas (defensible spaces) of higher irradiance, protecting people from those higher irradiance levels because they don't choose to walk in the garden. One Central Park also provides a water diffuser on the atrium roof. While the water may not substantially reduce the UV component of the radiation entering the atrium area, it does diffuse it, thus reducing the peak irradiance levels and associated UV hazard.
7. Conclusions

Building integrated heliostat lighting systems that redirect sunlight generally contain hazardous UV radiation. While the general public may be accustomed to managing the hazards of normal solar radiation, the hazards from heliostat light will not necessarily be perceived in the same manner, resulting in potential for accidental burns and cancer in the longer term.

A number of options exist for helping heliostat system operators to responsibly manage UV light hazards. These include the use of specific combinations of mirror materials and spectrally selective filters that reduce or eliminate the UV component of the light delivered to a target zone. Other options include limiting the total operation time of the heliostat system to ensure that daily UV radiation dose limits are not exceeded. Careful analysis of spectra and raytracing of irradiance maps in the target zone permits informed decisions about the choice of materials and system layouts prior to construction.

The applicability UVA hazard conditions relevant to the Coroneo Effect (ocular exposure), as well as other visual and infrared radiation conditions will depend on the specific system geometry. While the aversion reflex may be applied in many cases, heliostat systems that potentially shine light onto the face and eyes (even if the viewer does not look directly at the light source) will be subject to more stringent hazard management criteria. In general, safe system design would not allow a heliostat system to consume the full UV dose allowance, leaving room for exposure to other unrelated UV sources over the full 8 hour period.

Furthermore, designing a heliostat light source to be 'sun-like' will encourage people to use standard sun protection measures. It will help reduce glints and glare and reduce the ocular hazards. Indirect lighting may be effective, such as the use of gardens, sculptures, water features and other types of optical diffusers that reduce the UV hazard by first diffusing light toward the target zone.

References

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