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Building Integrated Heliostats

Practicalities of UV Light Filtering and High Temperature Optics

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Abstract. Heliostats offer a means of improving solar access in densely populated cities. Ocular and skin health considerations recommend control of UV radiation from heliostats in the urban environment. Lessons from integration of polycarbonate filter systems for UV control with building integrated heliostats are discussed, including the impact of solar concentration ratios, thermal stresses, material properties and fatigue. Options for further increasing solar concentration ratios in building integrated heliostat systems are proposed.

Keywords: Buildings, Heliostat, UV, Daylighting, Sunlight, Sustainable

1. Introduction

Optimisation of building internal spaces for daylight access and thermal comfort is a vast and well-developed field, with extensive published research into engineering, aesthetic, health, productivity and comfort aspects of buildings [1]. While many of the same principles and techniques are also relevant for outdoor spaces near buildings, the impact of reduced daylight access to our streets in high density urban environments is less well studied. The concepts of daylight factor, view and seeking / avoidance of direct sunlight remain relevant [2] but with slightly different priorities matching the changed use of the outdoor space (sit for lunch, take a walk, enjoy the sun, etc). The common assumption of abundant outdoor daylight may no longer be appropriate in building design for highrise cities, because the illuminance levels on the street are already much reduced. There is an increasing need to address both the issue of daylight access to the outside of the building and street, as well as solar access to the building's internal areas.

Recent research into UV radiation and human health indicates that critical health benefits from exposure to UV radiation relate to skin exposure to moderate levels of UVB radiation (290 nm – 320 nm) which results in production of previtamin D3 and assists in its subsequent conversion into vitamin D3 [3]. Excessive exposure to UV radiation can result in sunburn depending on the prevailing solar conditions, exposure duration, skin type and other factors. Atmospheric factors result in proportionally much higher rates of UVA radiation (320 nm – 400 nm) than UVB radiation (generally only available when the sun is high in the sky) so exposure to sunlight can readily result in skin burn without also yielding the helpful effects of vitamin D production.

Building integrated heliostat systems (BIHS) offer a means of redirecting sunlight around buildings, enabling solar access to areas that otherwise would remain shaded. With solar access comes the potential for improving personal health and wellbeing, attracting people to stay, work and utilise areas that otherwise would feel unattractive. Depending on the design of the BIHS, the character of warmth and light can potentially be quite similar to that of direct sunlight, but there are also many other possible configurations with direct and indirect illumination of spaces, and a wide range of visual effects [4].

Unfortunately, heliostat mirrors made of glass absorb all UVB radiation, so are not generally helpful for assisting vitamin D production. They do however transmit UVA radiation, so may contribute to skin burns (or ocular burns if directed into viewer's eyes [5]) unless the UVA radiation is otherwise controlled. As shown in *Figure 1*, heliostat mirrors made from metallised sheets and back-silvered glass contain significant UVA radiation unless removed by a filter material such as Polycarbonate. As the building integrated heliostat system (BIHS) is a controllable light source capable of directing significant radiation at people using a public space, the potentially hazardous nature of the light requires some consideration. A range of approaches to managing UV radiation from BIHS are discussed in [6].

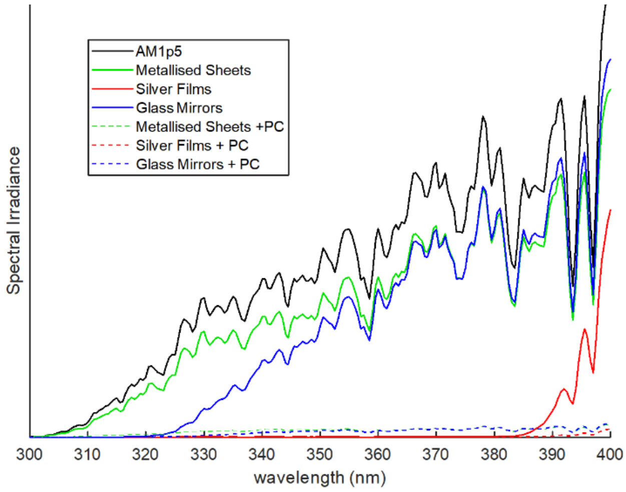

Figure 1. *UV reflectance spectra of heliostat materials, showing the impact of absorption due to two reflections of mirror material (a heliostat and a secondary reflector). Note that 'PC' refers to polycarbonate.*

Polycarbonate has the unique property of high transparency in the visible spectrum, but high absorption of UV radiation, so is well suited to application as a spectral filter. This paper discusses some of the engineering design and operational issues associated with polycarbonate use in building integrated solar lighting systems.

2. Polycarbonate integration techniques

Effective design of a BIHS requires redirection of sunlight over a large distance, using multiple reflection and transmission events before rays eventually reach the target illumination zone. Removing UV light from the beam with polycarbonate could be one of those such transmission events. The critical design challenge is one of maximising optical throughput, with large unobstructed sheets of UV filtering polycarbonate which minimally block the light beam.

2.1. Materials and connection design challenges

The basic design objective was to use polycarbonate material to filter out UV radiation, with minimal impact to the general function of the BIHS operation. In our system, an additional objective was the integration of LED edge-lighting of the polycarbonate material to provide an interesting night-glow feature. These objectives require maintaining all materials and structures within their normal operational limits in response to the various imposed loads (thermal, mechanical, self-weight, wind, etc.).

There are also some important interactions between imposed load conditions that conspire to exacerbate the impact on the material. For example,

- Concentration of sunlight increases the temperature of the polycarbonate and surrounding structure. The structural strength and stiffness of the polycarbonate reduces with increasing temperature.
- Increasing temperature of polycarbonate creates differential thermal expansion stresses at fixture points. These increased 'baseline' stresses make the polycarbonate more susceptible to strain and fatigue when also exposed to wind loads (stresses are additive).
- Numerous factors (variable heliostat tracking configuration, mirror and polycarbonate filter cleanliness) result in variable and unpredictable thermal loading on the polycarbonate.

One possible resolution of these interactions is to maximise the optical throughput at the polycarbonate UV filter system and its supports, and minimising the amount of heating in the polycarbonate and its supports. This requires either high transparency, or high reflectivity on all parts of the reflector structure, as well as regular cleaning and maintenance to avoid incremental reduction of optical properties.

Polycarbonate also has a number of critical limitations which must be considered at design point.

- It is easily scratched, by almost any mechanical contact (even touching with a dusty finger). It is not suited to any upward-facing collector surface which would accumulate dust, necessitating vigorous mechanical cleaning. Small amounts of dust can be removed with clean water pressure washing. Specialised 'hardcoat' versions of polycarbonate sheet are available, but at considerable additional cost. Scratching tends to reduce optical transparency and increase thermal loads.
- The flexural modulus of polycarbonate is low at 2.3 GPa (nearly 100 times less than steel, 30 times less than aluminium), so it tends to deflect a lot under modest loads. Engineering design based on control of deflections would require relatively thick polycarbonate sheets (and hence high material costs), or shorter spans and more mechanical fixtures (tends to reduce the optical throughput of the system, reducing overall efficiency). The yield pressure of polycarbonate exceeds 50 MPa across a broad temperature range [7], so it is capable of withstanding relatively large deflections without yielding. Engineering design on the basis of material stress relative to yield strength requires careful and detailed connection design.
- Polycarbonate material properties are standardised in AS4256.5 (Plastic roof and wall cladding materials – Polycarbonate). Design considerations are generally summarised in AS1562.3 (Design and Installation of sheet roof and wall cladding. Part 3: Plastic), with test procedures given in AS4040.0-1992 (Methods of testing sheet roof and wall cladding). More specific procedures for design from first principles in polycarbonate material are not standardised. Some relevant standards include AS1170 (Structural

Design Actions), structural reliability methods detailed in the National Construction Code (NCC BV1.2), AS4100 (Steel structures) – particularly fatigue analysis, and aspects of AS1288 (Glass in buildings).

- Numerous fatigue mechanisms exist for polycarbonate [8], with stress levels as low as 27% of yield pressure potentially leading to fatigue cracking over longer periods when considering higher mean stress levels and stress ratcheting [9]. Elevated temperatures cause increased brittleness and lower yield pressures [10].
- Adhesive bonds to polycarbonate are possible with structural silicone adhesives and are suitable to high temperatures (> 150°C), but only achieve bond strengths of the order of 1 N/mm^2. They are not generally transparent, so are difficult to integrate into optical systems without significant losses. Cyanoacrylate adhesives are transparent, and achieve higher strengths 5-20 N/mm2, but are not suitable for long term exposure to elevated temperatures. Methacrylates are not generally optically clear. Epoxy adhesives can be quite transparent, and can achieve high strength 27 N/mm^2, but are also not suited to elevated temperatures. Note that UV cure systems generally don't work through polycarbonate due to the high absorption of UV light in the sheet. Unfortunately there don't seem to be any viable means of using adhesive bonds to avoid the need for mechanical fixtures to withstand wind loadings on polycarbonate sheets.
- Mechanical fixtures in polycarbonate tend to create stress concentrations. They make the material susceptible to fatigue failure and reduced lifetime.
- UV-protected polycarbonate still sustains damage due to interactions with solar radiation (albeit at a slower rate than the unprotected material). Typical service lifetime for the material is of the order of 10 to 15 years (varies with manufacturer), and is less than that of other common building materials. An assumption of durability being similar to that of other building construction materials can potentially lead to compromised materials going unnoticed. Periodic inspection of polycarbonate sheeting, as well as lifecycle planning is an important part of effective system deployment.
- Polycarbonate is a petroleum product, so its cost tends to follow oil prices. Recent shortages saw the price of polycarbonate increase from ~3000 Eur/t to ~5000 Eur/t [11] over a two-year period. In 2022, standard UV protected polycarbonate was around 3 times more expensive than outdoor rated low iron solar mirror (volumetrically).

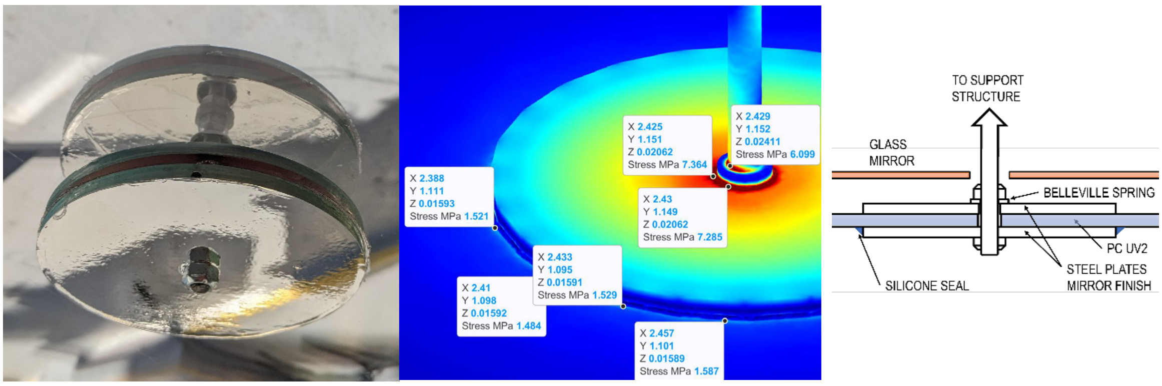

Figure 2. *Point support design for a PC UV filter system, showing fatigue stress levels (FEA) and arrangement of Belleville spring for relief of thermal expansion at elevated temperature.*

2.2. A connection solution for low concentration optics

One possible resolution of these competing design constraints is to use a point support approach for large sheets of polycarbonate. The solution involves supporting the polycarbonate sheet in front of a mirror (above) and supporting it at regular points using bolts and washers as shown in *Figure 2*. The mirror serves the general purpose of reflecting the solar radiation, while the polycarbonate serves the dual purpose of filtering UV radiation and enabling LED edge lighting systems for night-time effects.

Key features of the design include:

- The polycarbonate sheet is supported mid-face, limiting deflections and material stresses under full wind load conditions. Mid-face support system allows the polycarbonate material thickness to be significantly reduced, providing improved transparency and lower overall cost.
- Point support configuration eliminates the need for large framing members spanning the entire reflective face of the mirror. Large framing members across the face of the reflector (across the heliostat beam) would reduce the overall optical throughput of the system and create issues of thermal load (on all associated components including the polycarbonate) where they become very hot due to absorption of reflected radiation.
- Large support washers placed on either side of the polycarbonate sheet help maintain ultimate and fatigue stresses within reasonable bounds for the service life of the product.
- Low thermal cross section. The support washers are laminated with highly reflective mirror film [12] on all faces which reflect heliostat light out of the connection, reducing the amount of heating and thermal stress. This plasticised film also provides cushioning to the polycarbonate at stress concentrations around the perimeter of support washers, and resistance to corrosion of washers in harsh climates.
- The weather-prone side of the connection is sealed with transparent alkoxy neutral cure silicone adhesive to prevent water ingress (note that other silicone sealant cure systems may cause cracking in the polycarbonate). This reduces the chance that grit washed into the connection over time would cause abrasive scratching, reduced overall transparency and higher thermal load.
- Differential thermal expansion is managed with a Belleville spring washer. This ensures that the connection remains tight against the polycarbonate at all temperatures (no vibrations or ingress of moisture), while also absorbing differential thermal expansion of steel and plastic components.
- The glass mirror behind the polycarbonate (hermetically sealed casing) is not exposed to wind pressures, so has significantly reduced structural and mechanical engineering requirements.
- The connection system is readily adjusted for a range of different wind pressures (cyclonic, non-cyclonic) and assembly methods.

3. Solar concentration and high temperatures

A BIHS (as illustrated in *Figure 3*) was studied to understand operation temperatures of secondary reflectors as a result of heliostat concentration of sunlight. The heliostat concentration ratio was of the order of 2x to 3x, but infrared thermal imaging measurements identified surprisingly high temperature regions around the reflector frames and edges. Observation of degradation of natural rubber seals indicated that temperatures exceeding 150°C were possible in areas without ventilation or conductive heat dispersion. In areas where the optical transparency of polycarbonate became compromised (due to the degradation of nearby rubber seals), then temperatures exceeding 200°C in the polycarbonate were possible. Such high temperatures resulted in permanent damage to the polycarbonate, necessitating aspects of system redesign and replacement of damaged materials.

The results illustrate that even low levels of solar concentration have the potential to cause high temperatures at secondary reflectors, with implications for material structural integrity. In this instance, natural rubber seals were exchanged for semi-transparent high-temperature compatible silicone rubber materials, and reflective-protective films were installed to expel any radiation that would otherwise have resulted in heating of seals, supports and framing members. In hindsight, it was not appropriate to assume that relatively low solar concentration ratios (2x to 3x) would not cause dramatic thermal effects. The nature of building integrated heliostat systems (scale, novelty, site constraints and construction environment, every design so far is unique, etc.) may make the prospect of full thermal load testing and accelerated aging studies seem daunting. But those studies significantly reduce deployment risk, and likely provide a lower cost pathway than undertaking remedial works in the event of failure. Guidance from Appendices A and B of AS1170.0 is helpful in designing and undertaking such tests.

The secondary reflector design is down-facing, with beading around edges to encourage water droplets to fall from the edges in preference to running across the face of the reflector. Despite this, being on top of a tall building, the wind is highly turbulent, and often blows dust and water droplets across the optical face of the reflector. Soiling of the optical face of the reflector (the underside) is surprisingly rapid. Regular cleaning at approximately 6-month intervals was recommended to avoid accumulation of grit and the associated thermal loads.

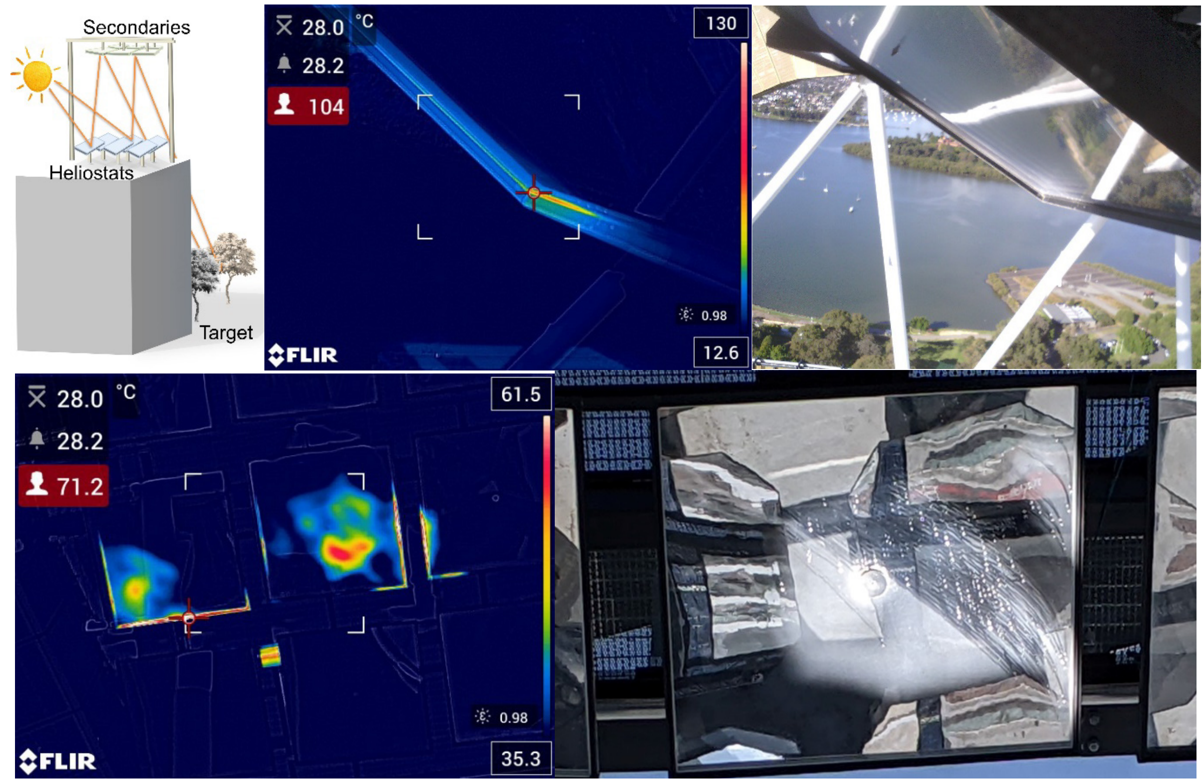

Figure 3. *(Top) A schematic of the tested BIHS showing arrangement of heliostats on building roof, redirecting sunlight to target via secondary reflectors. Thermal imaging measurements of hot spots on a secondary reflector frame exceed 100°C due to heliostat lights (shown beside a camera photo of similar viewpoint). (Bottom) Hotspots at around 60°C on polycarbonate UV filter sheets during operation, with increased temperature as a result of soiling.*

3.1. Further increasing concentration ratios

BIHS designs increasingly use concentration of sunlight to reduce size and cost of the elevated secondary reflectors. By focusing the heliostat radiation at the position of the secondary reflector, the size of the heliostat radiation beam is much reduced, so the size of the secondary reflector can be much smaller to still redirect all of the heliostat's radiation.

Heliostat concentration ratios of up to 20x are common, and exceeding 50x is possible where special care is taken in shaping mirrors and arranging the system optical layout [13]. For example, supposing that a heliostat size of 3 m x 3 m were selected, then the secondary reflector could be as small as 450 mm x 520 mm if concentrating optics were used (including an allowance for 30-degree cosine effect at the secondary reflector along one dimension). An array of such reflectors could be readily arranged along a slender beam, each redirecting light from a designated heliostat into the target zone. After the secondary reflection, the heliostat light quickly diverges such that when it arrives at the target zone, it is quite diffuse, with irradiance levels much less than that of direct sunlight.

A further advantage of the high concentration optical system is that the relatively small size of the secondary reflector means that it can be placed to equator side (north in the southern hemisphere) of the heliostat array without causing excessive shading over the heliostats. An equator facing heliostat array (north facing in the southern hemisphere) suffers less from cosine loss, so more light is captured over the nominal heliostat collector area.

An example of how such a system might work is given in *Figure 4*.

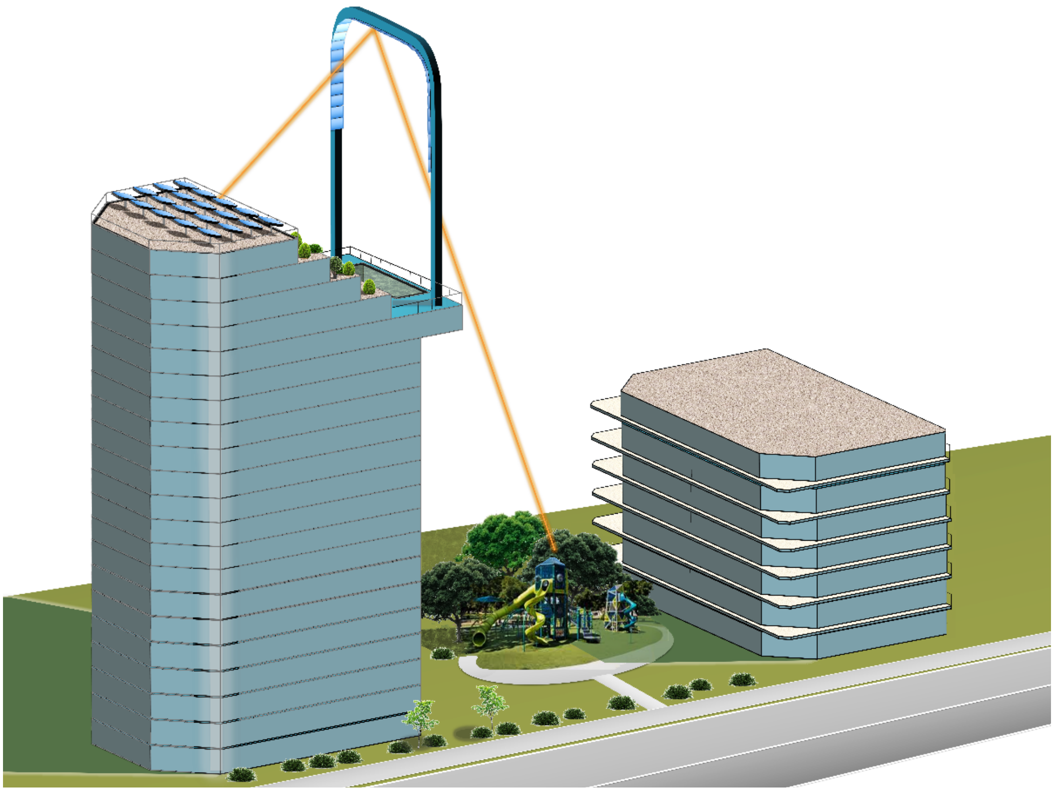

Figure 4. *Schematic illustrating the arrangement of a potential future building integrated heliostat system using concentrating heliostats. The array is equator-facing, but overshadowing of heliostats by secondaries is minimal due to small secondary reflector size.*

Concentrated radiation creates new engineering challenges in managing high temperatures at the secondary reflector. Differential thermal expansion, cyclic fatigue and reduced material lifetimes, corrosion and material compatibility issues all become more relevant. Furthermore, it is difficult to accurately predict heliostat concentration ratios at design point, because they depend on heliostat control system accuracy and repeatability; homing, calibration and emergency stop tracking characteristics, as well as heliostat mirror manufacturing accuracy. Hot spots are easily created in individual heliostat images, as well as in coalesced heliostat images, giving high flux throughput at the secondary reflector and high operating temperatures.

Fused silica materials have a number of unique properties which may be helpful in this case. Particularly helpful is the ability to withstand extremely high temperatures with minimal differential thermal expansion and low susceptibility to thermal stress cracking. Also important is the ability to produce highly reflective mirrors, including dielectric multilayer mirrors which may be tuned for particular spectral ranges (such as excluding UV radiation). However, while strong visible light reflection is common, reflection of both visible light and near-infrared light is less common (and more expensive due to more layers). So the mirrors may run hot due to significant absorption in the infrared.

There remain many challenges, including the design of a suitable system for connecting the mirror to the structural framing, while managing issues of differential thermal expansion, fatigue, corrosion, weather and cleaning induced degradation, and safety considerations in case of accidental breakage. Assuming that dielectric mirror systems (front surface mirror) are used, there may be options for fused silica lugs attached directly to the back side of the mirror. The range of ceramics offers numerous materials (silicone carbides, silicone nitrides and SiAlONs, alumina, aluminium titanates, etc.) with helpful properties for high temperature applications, but introduce further complexity in managing differential thermal expansion, bonding and adhesion systems, corrosion and weather. Fraunhofer ISE [14], DLR, CIEMAT-PSA [15] and others have relevant experience in development, testing and characterization of high temperature reflectors.

Soiling on mirrors results in absorption of energy and increased thermal stress, so cleanliness of optical components is an important consideration. Such a high concentration system would benefit from regular, automated cleaning as well as periodic inspection to ensure that there is no cumulative build-up of grime that could cause unusually high thermal loading and damage.

Further analysis is needed to assess whether a high concentration BIHS may result in ocular hazards for viewers in the vicinity. A number of factors are important (the apparent size of the reflected image, the residual UV content of the radiation, the natural aversion reflex, and the maximum possible exposure conditions) and will vary depending on the layout of the BIHS. A range of techniques [16-17] are available for characterization of ocular hazards and assessment of compliance with ICNIRP / ARPANSA guidelines.

4. Conclusions

It can be difficult to accurately predict characteristics of BIHS at design point due to practical uncertainties in manufacturing and operation, as well as their compounding interactions. Statistical design approaches may be helpful, but may be limited in the absence of real operational data. While the unique characteristics of each facility make practical lifecycle testing quite challenging, there are significant benefits in identifying and resolving issues early.

The future of BIHS is towards high concentration heliostat optics because of the potential for improved cost effectiveness and design flexibility. Numerous engineering challenges remain for in the design of suitable high temperature secondary reflectors. As thermal loads and ocular glare characteristics are difficult to estimate with modelling, detailed physical testing will be critical to ensure that products function as intended.

Data availability statement

Spectral data measured at UNSW is stored at ResData ResToolkit D0236190 and will be provided on request. Site data, measurements, and information relating to implementation and maintenance of a polycarbonate filter system was provided by Heliosystems Pty Ltd, and is restricted.

Author contributions

Alex Lehmann: Conceptualization, Investigation, Formal Analysis, Writing - Original Draft, Visualisation, **Nicholas Ekins-Daukes:** Supervision, Conceptualization, Writing – Review

Competing interests

The authors declare the following competing interests: Alex is director of the company Heliosystems Pty Ltd which is involved in the development of BIHS.

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References

[1] Solar Thermal Technologies for Buildings : The State of the Art, edited by M. Santamouris, CRC Press LLC, 2003. ProQuest Ebook Central, https://ebookcentral.proquest.com/lib/unsw/detail.action?docID=1679234, https://doi.org/10.4324/9781315074467
[2] Reinhart, Christoph F., John Mardaljevic, and Zack Rogers. "Dynamic daylight performance metrics for sustainable building design." Leukos 3.1 (2006): 7-31, https://doi.org/10.1582/LEUKOS.2006.03.01.001
[3] M. F. Holick, Chapter 2 in “Sunlight, Vitamin D and Skin Cancer”, Reichrath, Jörg (Ed.), (2020), 3rd ed, https://doi.org/10.1007/978-3-030-46227-7
[4] A Lehmann and N Ekins-Daukes, “Exciting Urban Spaces with Building Integrated Heliostats”, *Proc. APSRC* (2021)
[5] ICNIRP, “ICNIRP Guidelines on limits of exposure to ultraviolet radiation of wavelengths between 180nm and 400nm (incoherent optical radiation)”, *Health Physics,* Vol.87 (2004), Number 2, p.171-186, https://doi.org/10.1097/00004032-200408000-00006
[6] A Lehmann and N Ekins-Daukes, "Ultraviolet Light Management in Building Integrated Solar Lighting Systems", *Proc. APSRC* (2019)
[7] Richeton, J., et al. "Influence of temperature and strain rate on the mechanical behavior of three amorphous polymers: Characterization and modeling of the compressive yield stress." *International journal of solids and structures* Vol 43.7-8 (2006): p. 2318-2335, https://doi.org/10.1016/j.ijsolstr.2005.06.040

[8] TJ Chen, et al, “A fatigue crack initiation map for polycarbonate”, *Journal of applied polymer science*, Vol.49 – 11 (1993-09-15): p.1909-1919, https://doi.org/10.1002/app.1993.070491106

[9] S Holopainen, et al, “Continuum approach for modeling fatigue in amorphous glassy polymers. Applications to the investigation of damage ratcheting interaction in polycarbonate”, *International Journal of Plasticity* 91 (2017) 109-133, https://doi.org/10.1016/j.ijplas.2016.12.001

[10] JC Bauwens, et al, “Tensile yield-stress behavior of poly(vinyl chloride) and polycarbonate in the glass transition region”, *Journal of Polymer Science Part A-2: Polymer Physics*, 1969-10, Vol.3 - 12, p.1745-1754, https://doi.org/10.1002/pol.1969.160071010

[11] Plastics Information Europe, PIE Polymer Prices – PC transparent, 2022.

[12] M DiGrazia et al, “Reflechtech mirror film attributes and durability for CSP applications”, Proceedings of ES2009, San Francisco, ES2009-90336, https://doi.org/10.1115/ES2009-90336

[13] M.R. Rodríguez-Sánchez et al, “Development of a new method to estimate the incident solar flux on central receivers from deteriorated heliostats”, *Renewable energy*, Vol. 130 (2019) p. 182-190, https://doi.org/10.1016/j.renene.2018.06.056

[14] S Gledhill et al, “Secondary reflectors tested at high temperatures and high radiation intensities”, *Proc AIP*, Vol. 2815 (2023), No. 1, https://doi.org/10.1063/5.0148695

[15] N Estremera-Pedriza et al, “Optical Characterization of a New Facility for Materials Testing under Concentrated Wavelength-Filtered Solar Radiation Fluxes”. *Solar*, Vol. 3, No 1, 2023, p.76-86, https://doi.org/10.3390/solar3010007

[16] C Fell, A Lehmann and W Stein, “A new tool for rapid assessment of the optical hazard from bright light sources - applications for solar concentrators”, Proceedings of SolarPACES, Perpignan, France, September 21-24, 2010

[17] Ho, Ghanbari and Diver, “Methodology to assess potential glint and glare hazards from concentrating solar power plants: analytical models and experimental validation”, Journal of Solar Energy Engineering, Transactions of the ASME, Vol. 133, 2011, https://doi.org/10.1115/1.4004349