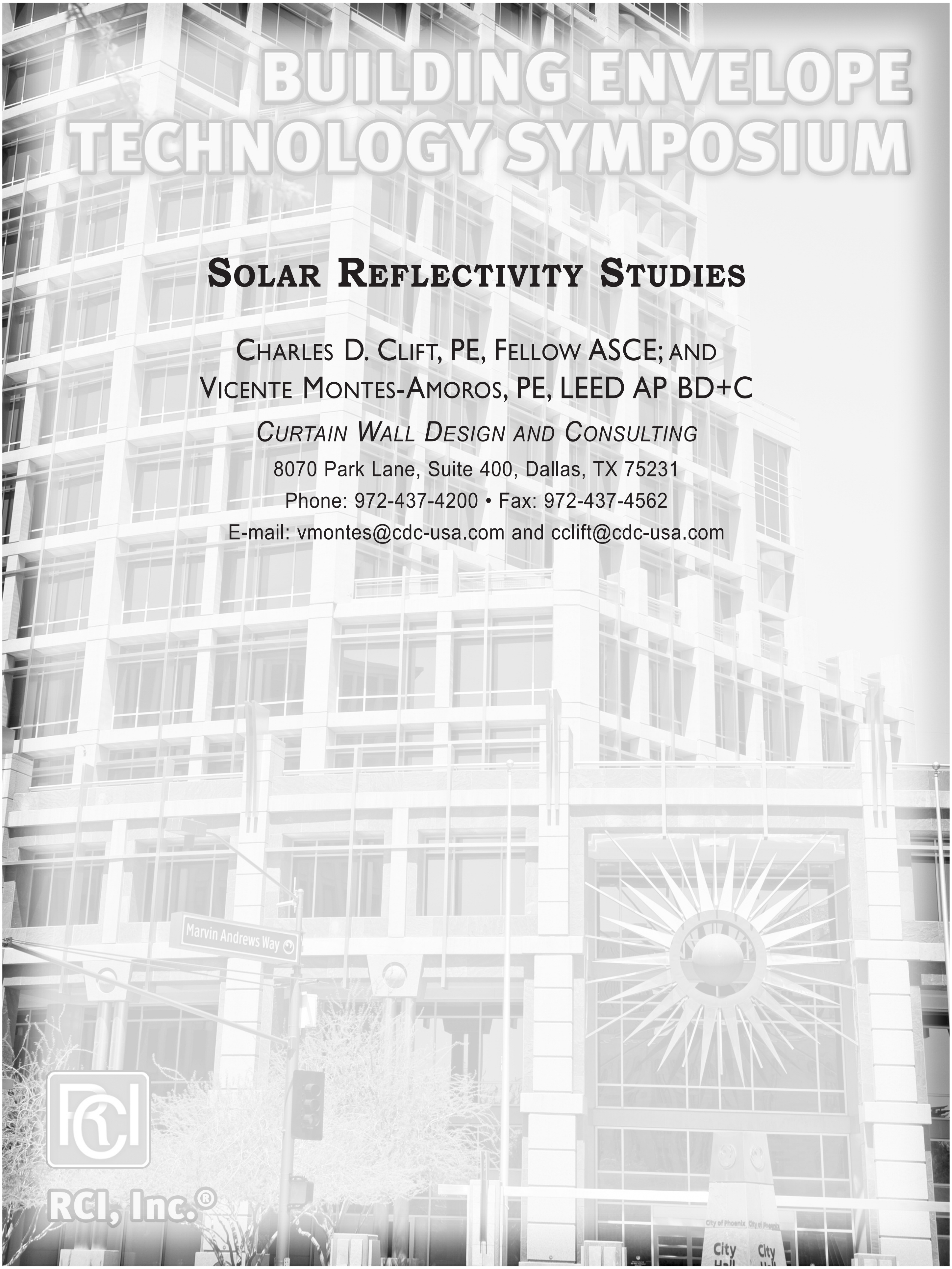


BUILDING ENVELOPE TECHNOLOGY SYMPOSIUM

Solar Reflectivity Studies

Charles D. Clift, PE, Fellow ASCE; and
Vicente Montes-Amoros, PE, LEED AP BD+C

Curtain Wall Design and Consulting

8070 Park Lane, Suite 400, Dallas, TX 75231

Phone: 972-437-4200 • Fax: 972-437-4562

E-mail: vmontes@cdc-usa.com and cclift@cdc-usa.com

RCI, Inc.®

ABSTRACT

Recent skyscraper designs have extensive exterior glass paneling that may cause hazardous glare to neighboring buildings or nearby traffic. Examples of recent problem designs include the Disney Concert Hall in Los Angeles, CA; The Vdara Hotel in Las Vegas, NV, which was reported in local newspapers to produce a “death ray” due to intense solar reflections from the concave curtain wall geometry; and the Nasher Sculpture Center in Dallas, TX, whose skylight features—tailored to filter indirect daylight to the art galleries—are now subject to direct solar reflections from a new curved tower with a metallic-coated glass façade.

Curtain Wall Design and Consulting (CDC) has developed a method to advance the current state of the art for solar reflectivity studies. Computational fluid dynamics (CFD) is used to emit a large number of rays and trace their trajectories inside a computational domain. The analysis allows accumulation of rays on discrete elements, thus compiling an intensity value at the unique element location.

SPEAKER

Vicente Montes-Amoros, PE, LEED AP BD+C — Curtain Wall Design and Consulting

VICENTE MONTES-AMOROS is a structural and façade engineer specializing in the design and engineering of building envelope systems, including natural stone, precast concrete panels, unitized and stick-built curtain walls, etc. He earned a maser’s degree in façade engineering at the University of Bath in the United Kingdom. Montes-Amoros has led the Solar Reflectivity program at Curtain Wall Desgin and Consulting, Inc. (CDC) since its creation and has continued its development to the present. He has published diverse articles on various building envelope topics.

NONPRESENTING COAUTHOR

Charles D. Clift, PE, Fellow ASCE — Curtain Wall Design and Consulting

CHARLES CLIFT is senior principal and president of Curtain Wall Design and Consulting, Inc. (CDC). Clift has worked at CDC in Dallas, TX, for 30 years, providing engineering design for curtain wall and other exterior cladding systems. His tall-building experience includes the Lotte World Tower in Seoul; Trump Tower, Chicago; Abraj Al Bait Towers, Mecca; CITIC Plaza, Guangzhou; U.S. Bank Tower, Los Angeles; The Center, Hong Kong; Emirates Tower, Dubai; and Bank of America Plaza, Atlanta. Clift was named as the Dallas AIA Consultant of the Year in 2010.

Solar Reflectivity Studies

REFLECTION

Historically, the study of light has captured the interest of many scientists and scholars who have contributed to a better understanding of its characteristics, behavior, and effects. The study of light is subjective in some specific aspects, such as color and glare, but very objective in aspects such as direction and reflection. It has been demonstrated that even though every type of light originates from an energy source such as the sun, an electric lamp, a lit candle, etc., most of the light we see in the physical world is the result of reflected light (Tippens 1999).

Reflection is a physical phenomenon that has been studied and classified using two different theories. One of the theories describes reflection using Maxwell's undulatory electromagnetic theory. It is simpler, however, to describe reflection by using the ray-tracing theory, which is the second theory. The tracing theory treats the light as rays and is generally known as geometrical optics, which is based on Huygens's Principle.

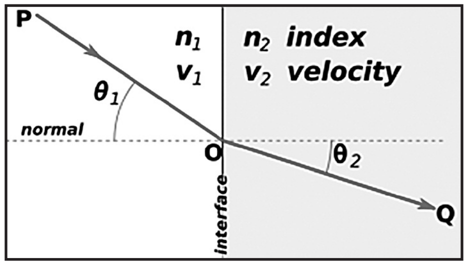
OPTICS

When a light ray travels in a medium and finds an obstacle such as a glass surface, part of the incident ray is reflected, and the rest is transmitted to the other side of the obstacle—in this case, glass. The transmitted portion changes direction when passing through the glass. This phenomenon is called refraction and is characterized by Snell's Law. Refer to *Figure 1* for the graphical representation of the refraction phenomenon.

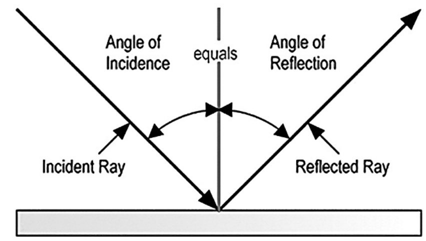
When glass is installed on building façades, the refracted portion of the incident light will penetrate to the building interior. Depending on the light, glass characteristics, and some other factors, the light transmitted exhibits a different range of phenomena, such as heat gain and UV transmission.

The type of reflection that this new methodology investigates is the portion of the light that is "bounced" from the glass surface and returned to the medium. The reflected light-directional behavior is described by the reflection laws listed below (Serway 1997):

- The incident angle is equal to the reflected angle (see *Figure 2*).
- The incident ray, the reflected ray, and the line perpendicular to the surface (the normal) are located on the same plane.



ur 1– t r r t .



ur 2– t w.

The reflection produced by glass and other smooth and polished surfaces is called specular reflection. The reflection from an irregular or rough surface is called diffuse reflection.

This new methodology focuses only on the reflection from flat architectural glass, which is specular; and in this paper, we will refer to it as reflection from this point on. It is important to mention that the light reflected from nonplanar or prismatic surfaces follows a different trajectory than the one illustrated in *Figure 2*. This new methodology deals only with planar surfaces.

SOLAR REFLECTION ON BUILDINGS

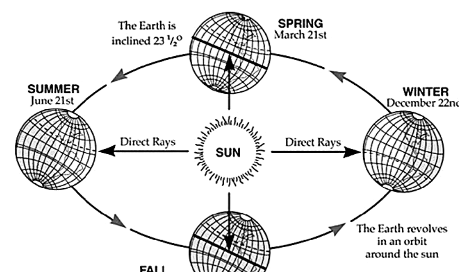
Following the laws of reflection, light emitted by the sun will be reflected on exposed surfaces in the built environment, such as: pavements, walls, roofs, etc. The amount of light reflected and absorbed by a building's façade depends on the properties of the façade materials and their position relative to incident rays. In the built environment, some of these reflections might produce discomfort or a hazard, depending on their intensity and direction.

The solar light reflection from a building depends on the geographic location of the project, the orientation, the climatology, the treatment of its surfaces, and other factors. This new methodology identifies reflections from a building's façade due to the use of architectural flat glass and provides some characterization as to potential for hazardous glare conditions.

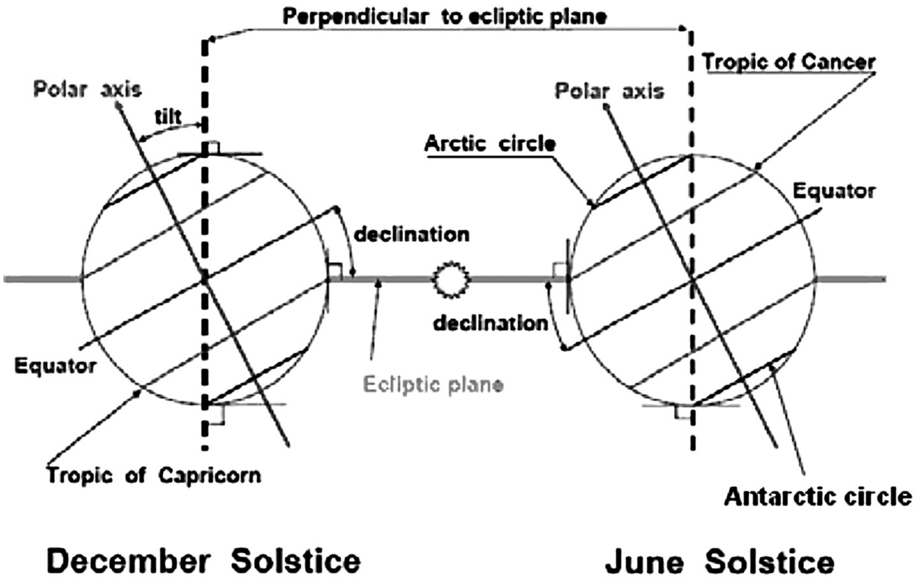
SUN MOVEMENT

For any given project, the variation in daylight duration throughout the different seasons of the year can be observed, recorded, and predicted. The most influential factor in the daylight duration is the earth's polar axis's natural tilt, which is equal to 23.4 degrees; if it was not for this, the difference between daytime and nighttime would not be as evident during the year. *Figure 3* shows the earth's movement around the sun during the entire calendar year; note that the tilt angle remains constant throughout the year.

As the earth moves around the sun throughout the year, the location of the sun with respect to the horizon changes every day. And as the earth revolves around its axis, the position of the sun with respect to



ur 3– rt v t r u t su .



ur 4 – t .

any given point on earth will vary from minute to minute. Another factor that affects the sun's position with respect to the horizon during the year is the geographical position of any given project. The further away from the equator, the greater the difference in altitude during the seasons; and hence, the difference between daytime duration throughout the year becomes more evident.

SUN TRACKING

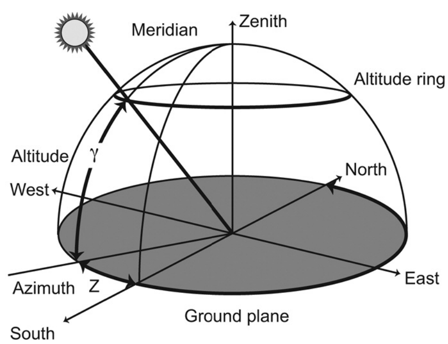
In order to calculate the sun's position throughout the year, one of the first steps is to determine the sun's altitude, which is also known as the solar elevation angle. To do this, the angle of declination needs to be calculated in order to take into consideration the earth's natural tilt. The angle of declination is defined as the angle between the equator and the ecliptic plane, as shown in *Figure 4*.

The angle of declination can be calculated with the following formula:

$$D = 23.4\sin\left[\frac{360(284+N)}{365}\right]$$

Where:
D = Declination
N = Day number

The angle of declination at the vernal equinox (March 21) and at the autumnal equinox (September 23) is equal to 0°. The angle of declination at the summer solstice (June 21) is equal to 23.4°, and the one at



ur 5 – r v t
s r ut .

the winter solstice (December 21) is equal to -23.4°. These four major events mark the seasonal changes.

By definition, "altitude" is the height an object is above the horizon. The altitude of the sun varies throughout the day, and it reaches its maximum around noon (varies during daylight savings schedules). As shown on *Figure 4*, the altitude of the sun will also change according the season and the previously listed factors. The solar position in the sky is called the solar elevation angle or sun's altitude and can be calculated for every day of the year. This angle is formed between the sun's apparent disk- or altitude-ring and the horizon.

To calculate the sun's altitude, the following formula can be used (*Figure 5* shows the altitude):

$$\sin\gamma = \cos H\cos D\cos L + \sin D\sin L$$

where:
γ = Solar elevation angle (altitude)
H = Hour angle
D = Declination
L = Project's latitude

As the earth rotates around its axis every day, the location of the sun with respect to any given point varies. This variation is called solar azimuth (refer to *Figure 5* for the graphical representation). By definition, the solar azimuth angle is the horizontal angle formed at the ground plane between the sun and a reference location. It can be found using the following equation:

$$\cos Z = \frac{\sin\gamma\sin L - \sin D}{\cos\gamma\cos L}$$

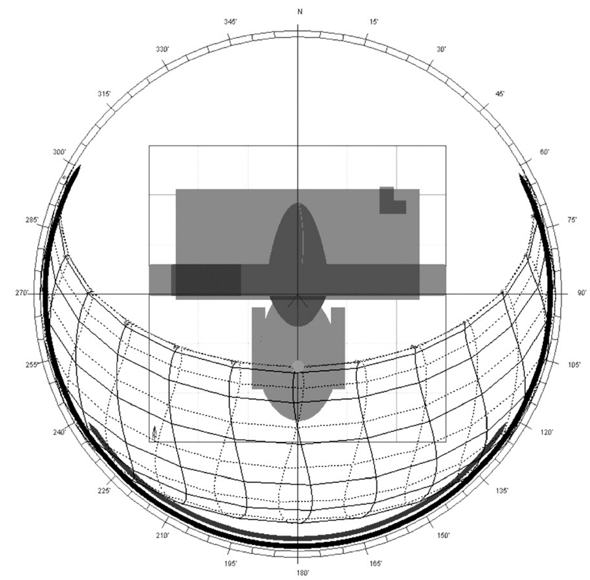
where:
Z = Solar azimuth angle
γ = Solar elevation angle (altitude)
D = Declination
L = Project's latitude

Using the information calculated from the equations above, a sun path diagram can be plotted in order to visualize the sun's trajectory during the year. *Figure 6* shows an example of a sun path diagram.

Figure 6 helps in understanding how the sun interacts with a given project at different times throughout the calendar year. Different hyperbolic blue lines and vertical blue lines are shown along the project's south orientation for projects located in the northern hemisphere. Each vertical line represents an hour increase; noon is located right at the center of the diagram. Each vertical line east of noon represents one hour's decrease from noon. Each vertical line west of noon represents one hour increase from noon.

Hyperbolic lines represent months in the calendar. Starting from the dark hyperbolic on the bottom, which represents December, it can be observed that the sun rises later in the day than it does in July. July is represented by the hyperbolic line farthest away from December. Moving back and away from December, each hyperbolic line represents one-month increase until the last hyperbolic line is reached. Once the last hyperbolic line is reached (July), we move back towards the first hyperbolic line at a one-month increase per hyperbolic line (Editor's note: this is more visually tracked in color.)

Identifying the sun's location at any given day at any given time can easily be done using this kind of diagram.



ur 6– u t r .

REFLECTIVITY IMPACT CONSIDERATIONS

Solar reflectivity is a common phenomenon, and it is caused by the interaction between the reflective materials on the façade and the structures around it (Naai-Jung and Yen-Shih, 2000). It can produce discomfort, and it can even be a threat for air traffic when the light is returned in the form of glare. There are three different glare types:

- Direct glare
- Reflective glare
- Disability glare

Direct glare is a phenomenon originated from light sources that cast luminance directly into the eye's visual cone. Reflective glare occurs when light rays bounce off a surface and cause a level of luminance to be perceived from the angle of incidence of the reflection. Disability glare is a level of change of luminosity that significantly reduces visibility of the observer. The first two types of glare listed above can create a discomfort effect that we call discomfort glare. For solar reflectivity on buildings, it has been observed that most of the cases dealing with glare are related to discomfort glare rather than disability glare (Naai-Jung and Yen-Shih, 2001a).

Energy performance criteria influence architectural design, encouraging use of reflective glass to reduce penetration of solar radiation into the building interior. However, while a highly reflective glass efficiently blocks solar heat gain, it causes a significant impact on the neighboring environment due to exterior reflections. Typical clear glass has an exterior reflectance value of 9%, whereas coated reflective glass exhibits an exterior reflectance value of approximately 20% to 40%.

GLARE LIMITS

The limits of solar reflectivity evaluation are subjective since they depend on diverse factors and dynamic circumstances and are variable for every person. Some of the factors that influence people's reflectivity perception are age, eye pigmentation, eye sensitivity (especially for people who have undergone any type of eye surgery in which the pupil's ability to rapidly adapt to light contrasts has been affected), and eyewear.

Currently, there are few approaches for criteria limiting solar reflectivity. One comparative benchmark addressing reflectivity is published and enforced by the Sydney City Council. It states that materials used on the exterior of buildings can result in undesirable glare for pedestrians and motorists, limiting the reflectivity of these materials to 20% of visible light. It also states that glare can impose additional heat load on other buildings. Unfortunately, with the erection of increasingly complex building shapes, this limit might not address reflected-light concentrations. A complex building shape clad with materials with a reflective coefficient of 20% could still produce undesirable glare.

A veiling luminance limit of 500 candelas per square meter for the comfort of motorists was suggested by Hassall (1991), but this limit goes hand in hand with his proposed approach for determining the solar reflectivity. Hassall's methodology is based on the preparation of sun path diagrams for every aspect on the development. After this, a check-zone diagram needs to be completed in order to determine the areas influenced by the reflections. Once this is done, the Holladay formula is used to calculate the luminance intensity. This is often graphically represented by a glare protractor. The Hassall approach is limited since it cannot determine the duration of time over which reflections occur to the surroundings, and it also ignores the effect of the type of glazing (Rofail *et al.* 2004). This approach also fails to address the limits of solar reflectivity on neighboring buildings.

GLARE NOTES

In addition to reflected glare coming from the glass, the metal frame may also reflect light that might act as a "blinking" light while a transportation vehicle passes by the building. This dynamic phenomenon depends on the relative movement between glare and a fast-moving vehicle. Such glare could possibly distract or delay the response to a sudden traffic situation (Rofail *et al.*, 2004). This effect is not simulated by this study.

PROPOSED GLARE THRESHOLD

Given the subjectivity of individuals' sensitivity to glare, the lack of an industry-wide accepted criteria, and the absence of any precedence related to the limits of this type of nuisance, a combination of the approaches described in the section above to determine the problematic areas and time of day of occurrence was used. The proposed design criterion for a threshold of acceptable intensity is based on comparison with common sources of light. The upper limit compares light reflected from buildings to direct sunlight. Depending on a building's shape, orientation, and other factors, reflected light could be concentrated at a given area, like a magnifying glass. These cases could produce disability glare, which could potentially affect visibility of people anywhere within the building's domain.

As a part of the proposed threshold, a custom scale was developed with this new methodology, which provides results as a fractional value of the reflected light. Ultimately, intensity of reflected light depends only on the material's reflectance coefficient. Therefore, by taking the results from this custom scale, together with the material's reflectance coefficient, we can obtain the intensity of reflected light, or glare. This scale provides the advantage of results as a fractional value of the reflected light, thereby giving flexibility to designers to change the specified glass without having to run all the models again.

If the reflectance coefficient of the glass is known—10%, for example—and we obtain from this custom scale a value of 1.0, it means that 1.0 times 10% of the incident light is returned in the form of glare. On the other hand, if we get an output of 10.0 from this custom scale, it means that 10.0 times

10% (glass reflectance coefficient) of the incident light is the "amount" of reflected light. In this last example, it represents that it could potentially be equal to direct sunlight.

It is suggested here, as a base threshold, that the intensity of reflectivity measured at an individual location be limited to no more than one times the natural intensity at the project site (*Figure 7*).

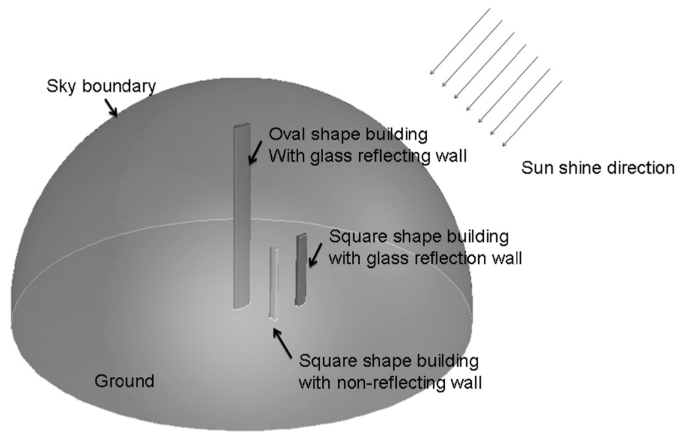
This threshold is reasonable because the project's areas are already receiving direct sunlight; hence, setting such value as the maximum intensity limit is conservative.

GLARE ANALYSIS

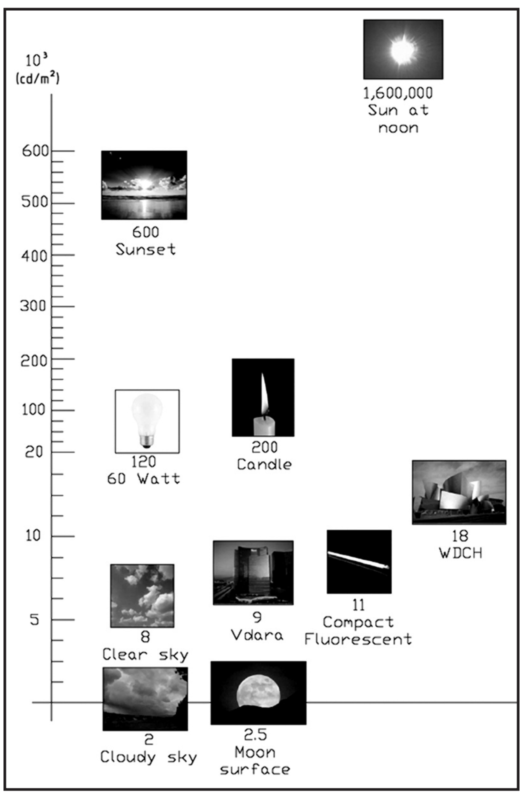
In today's market, several computer modeling software products exist for different purposes such as rendering, imaging, special effects, design, architecture, and lighting. These programs use a wide variety of techniques to estimate the luminosity intensity for any given model or image. But the complexity of the cases has increased, and the models used some years ago were developed to run under the radiosity method, which requires more time to compute problems. Recent advances in computational power and algorithms have made the Monte Carlo ray-tracing methods an excellent choice for most of the problems (Arvo *et al.*, 2003).

In order to obtain glare data for any given project, a new tool has been developed to advance the current state of the art for solar reflectivity studies using computational fluid dynamics (CFD). This proprietary tool generates glare data as follows:

- Using a custom Monte Carlo ray-tracing technique, the reflection zone (see *Figure 8*) is estimated.
  — Sun rays are "injected" into the model at a variable altitude and angle, depending on the day of the year and time of the day. A total of 500,000 rays are injected per iteration.
  — The algorithm traces the rays' trajectory and identifies the surfaces that are impacted by incident rays.
  — Following the laws of optics, the now reflected rays' trajectory is traced in the domain.
- Using a cell-face searching method, the entire domain is explored, and using geometry relationship only, we can determine the path of reflected light.
- Glare intensity is calculated depending on the distance, the direction, and the concentration of the reflected rays through a basic operation that correlates the reflected light zone from the ray calculation with the glare intensity at each cell.
- Glare intensity is reported using the custom fractional scale previously described. *Figure 9* shows an example of the custom fractional scale on the left-hand side.



ur 8– u t t r rs t t .



ur 7– r x s.

The algorithm described above provides glare data at a particular time of day. This means that the results are accurate for one particular month, at one particular day, at a given time of day. Therefore, several iterations are required in order to create representative data for the whole calendar year.

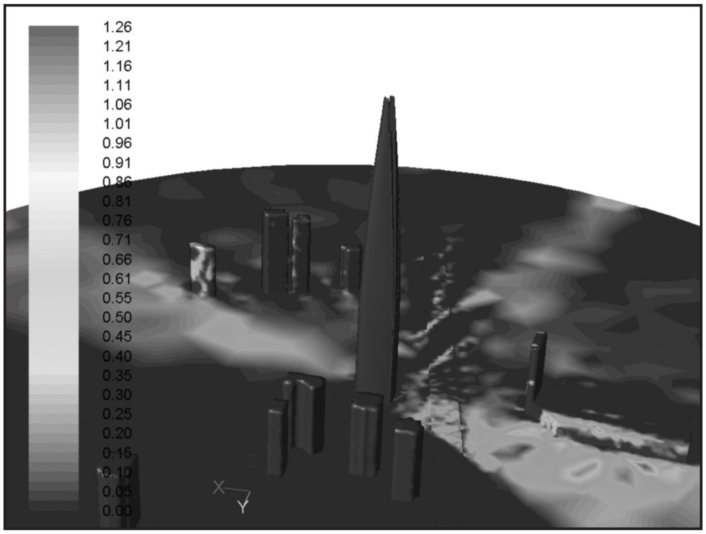
The model domain will require some level of accuracy with regard to the surrounding environment. Adjacent buildings may shade the project at various periods of daylight on certain days of the year. And conversely, roadways or neighboring façades may be sensitive to reflections bounced from the project's reflective surfaces. Engineering judgment will be needed to quantify the scope of the domain model and level of detail required to reasonably predict areas of concern.

Models can be simplified in different ways in order to accelerate computational processes—especially since the algorithm needs to be executed several times for a single project. It is important to take into consideration that this tool only captures primary specular reflection.

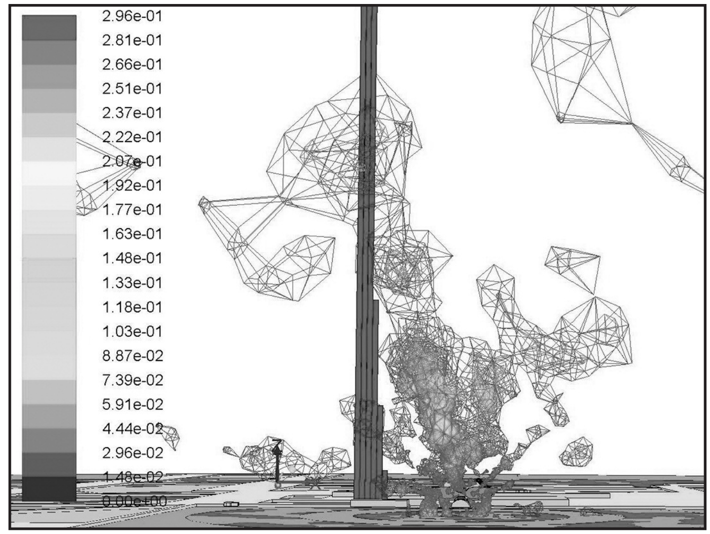
This new technology can also be utilized in determining glare conditions present in airspace matters and not only ground level glare. This type of application is used in quantifying potential glare problems in airports' runways, taxiways, control towers, approach vectors, glide slopes, and with air traffic. *Figure 10* shows an example of glare in airspace. Determining this type of glare is helpful for new construction in or close to airports. Vertical markers were added in order to quantify the distance traveled by the reflected light.

In order to analyze a project for potential solar reflectivity issues, the following information is required:

- Project location (latitude and longitude)
- 3-D "watertight" model of building, including surrounding buildings
- Building's orientation with respect to true north
- Reflection coefficient and exterior light for all exterior materials



ur 9 – r ys s ut ut x .



ur 10 – r rs , r r rts.

Reflected light can be looked at as a source of light that originates at the building's glazed façade. As such, there is heat associated with it that will be manifested around the building's domain. The amount of heat that reflected rays originate will depend on the number of reflected rays coinciding within a particular area at a given time. As a secondary step and using the data generated with the solar reflectivity analysis tool herewith presented, heat differential (temperature increase) can also be obtained.

FINAL NOTES

When designing a building, it is very important to consider the movement of the sun in interaction with the design in question. Factors that need to be carefully designed and taken into consideration in order to avoid solar reflectivity issues are the following:

- Highly reflective glass
- South-facing concave building shapes (for projects in the northern hemisphere)
- Elliptical building shapes in the vertical plane
- Change in planes throughout building elevations

These are just a few factors to consider, but location and neighboring buildings also affect the path of reflected light and its interaction with the entire project.

If designing for a downtown area or a densely developed site, it is important to consider street width, building orientation, building height, and cladding materials. In these cases, avoiding the potential for solar reflectivity issues could represent a bigger challenge, but it is something that can definitely be avoided or mitigated.

This new CFD tool is valuable, as orientation of the design can be easily rotated to search for optimum results with respect to mitigation of reflectivity. And the CFD's provision of a scale-of-intensity level is critical to judge the limit of primary surface reflectivity in regard to hazardous glare. With this new technology, one can determine whether or not the reflected glare is going to be a problem.

In addition to glare intensity information, the following can also be provided:

- Path of solar reflections
- Shadowing
- Solar data
- Temperature increase due to reflections

This can be applied to isolated buildings or target buildings, including their surroundings.

Since the creation of this new tool and its increasing demand, designers have become aware of the importance of this type of study. This tool has uncovered the need for an industry-wide accepted criterion for exterior glare, but it is too early to know when this will be incorporated into design codes, etc.

As architectural designs become increasingly complex in shape and geometry, the need for reflectivity studies is heightened. This new CFD tool is available to assist designers in making sound decisions and avoiding pitfalls of poor performance.

REFERENCES

J. Arvo, P. Dutre, A. Keller, H.W. Jensen, A. Owen, M. Pharr, and P. Shirley, 2003. Monte Carlo Ray Tracing. Siggraph 2003, Course 44, July 29, 2003.

D.N.H. Hassall, 1991. *Reflectivity: Dealing With Rogue Solar Reflections*. Published by author.

S. Naai-Jung and H. Yen-Shih, 2000, "The Computer-Aided Visualization of Curtain Wall Reflection Glare," *ASCE Conference Proceedings* 279, 205. August 14, 2000, Stanford, CA, ASCE, pp. 1574-1581.

S. Naai-Jung and H. Yen-Shih, 2001a. "A Study of Reflection Glare in Taipei," *Building Research and Information*, 29:1, pp. 30-39.

S. Naai-Jung and H. Yen-Shih, 2001b. "Volumetric Study of Reflected Glare From Glass Curtain Walls of Buildings," *Journal of Architectural Engineering*, Volume 7, Issue 3, pp. 87-93.

A. Rofail, B. Dowdle, J. Perry, 2004. "Reflectivity Impact on Occupants of Neighbouring Properties," ICBEST 2004. Sydney, Australia.

R. Serway, 1997, *Fisica, Tomo II*. 4ta ed. Mexico: McGraw-Hill.

P. Tippens, 1999. *Fisica: Conceptos y Aplicación*, 5ta ed. Mexico: McGraw-Hill.

U.S. Department of Transportation – Federal Aviation Administration, 2011. "Procedures for Handling Airspace Matters," Order JO 7400.2H.