Chapter

7 Conclusion

"These are the only ones of which the news has come to Ha'vard, And there may be many others, but they haven't been discavard."

TOM LEHRER

7.1 Summary

The accurate prediction of daylight illuminance using lighting simulation was the goal for this thesis. The foundation for the work was the validation of the *Radiance* illuminance calculation under real sky conditions. This work would not have been possible without the BRE-IDMP validation dataset. This dataset is believed to be the only one in the world that has simultaneous measurements of the sky luminance distribution and internal illuminance. As such, it must be considered the 'gold-standard' dataset for the validation of lighting simulation programs.

The validation exercise described in Chapter 3 and Chapter 4 confirmed that *Radiance* can accurately predict internal daylight illuminance under a wide range of naturally occurring conditions. The accuracy of the illuminance predictions was shown to be, in the main, comparable with the accuracy of the model input data. There were a number of predictions with low accuracy. Evidence was presented to show that these invariably resulted from imprecision in the model specification - such as, uncertainty of the circumsolar luminance - rather than the prediction algorithms themselves. On the basis of these results, *Radiance* can be used with confidence to accurately predict internal illuminance under standard overcast sky conditions (i.e. daylight factors) for ‘traditional’, that is, ordinary glazed, buildings. This covers the overwhelming majority of existing and new commercial building designs. Buildings more complex than the BRE office, e.g. atria, should not present difficulties provided that the ambient calculation is used effectively (see Section 4.8). This invariably means some convergence testing along the lines described in Section 2.4 and Section 2.5 will be required. Following the procedures outlined in these sections, less-than-expert *Radiance* users should be able to produce reliable daylight factor predictions for the majority of current building designs. Accurate illuminance predictions under non-overcast skies were also demonstrated in the validation. Though these needed to be identified and separated from the potentially unreliable predictions based on visibility of the circumsolar region.

The ability of sky models to reproduce sky luminance patterns for the purpose of predicting internal illuminance was investigated in Chapter 5. Four sky models and two sky models blends were assessed. Three of the sky models were designed to be applicable to a narrow range of sky conditions, i.e. overcast, intermediate and clear. Only the Perez model was designed to reproduce a wide range of sky conditions. The sky model blends were composites of an overcast and a non-overcast narrow-range model, i.e. the intermediate-overcast blend and the clear-overcast blend. For each of these, the weighting factor was a function of the sky clearness index. The configuration of each blend was based on the minimisation of RMSEs for the vertical illuminances.

Predictions of internal illuminance using sky models and sky model blends were compared against those using measured sky luminance patterns for all 754 skies in the validation dataset. Routine application of the narrow-range models resulted in large MBEs and RMSEs for internal illuminance because of the, occasionally very large, differences between the measured and modelled sky luminance patterns. The Perez model and the sky model blends performed comparably well. Illuminance predictions using measured skies, however, were markedly better than those using sky models/blends.

An implementation of the daylight coefficient approach for *Radiance* was described in Chapter 6. Five candidate daylight coefficient formulations for *Radiance* were described and examined. The form and magnitude of the daylight coefficients were related to the scene geometry and the discretisation scheme. One of the formulations (the 'naive method') was found to introduce large systematic biases in the illuminance predictions. The 'naive method' was eliminated from further testing. The accuracy of the remaining daylight coefficient formulations was verified using the validation dataset. Illuminance predictions for the office space were derived from daylight coefficients using the measured sky luminance patterns for all 754 skies. This was done for each of the formulations. The accuracy of daylight coefficient derived illuminance predictions for the best of the formulations was comparable to that using the standard *Radiance* calculation method. The performance of the other three formulations was only marginally worse than that of the best.

As given in Chapter 6, the daylight coefficient approach should be considered equivalent in accuracy to the standard calculation, and accordingly very accurate in absolute terms.[1] This being so, the daylight coefficient approach offers the potential to significantly advance the practice of daylight illuminance prediction. From a relatively small number of pre-computed daylight coefficients, the internal illuminance for many thousands of arbitrary sun and sky conditions can be speedily computed.

1. Issues regarding visibility of the circumsolar region notwithstanding.

For the first time therefore, the computation of internal illuminance based on hourly (or better) sky/sun conditions for a full year is a practical possibility. Examples for how this might be carried out were described in Section 6.4. Techniques to visualise and reduce the voluminous illuminance data were presented.

7.2 Suggestions for further work

Is there a need for additional validation work on *Radiance* of the type described in Chapter 3 and Chapter 4? For building designs using 'traditional' materials, further testing of the *Radiance* system is not urgently required. The modelling of so called 'advanced glazing materials' (e.g. prismatic films, mirrored louvres) however presents many difficulties for *Radiance* and, indeed, any other lighting simulation program. The transmission properties of advanced glazings materials need to be represented in some way in the simulation. This can either be as a function or as an interpolated data map of values, both of which will need to be based on measurements. Both the measurement and modelling of these materials is very complex. Validation of some kind is needed if the results of a lighting simulation for these materials are to be used with any confidence. Three advanced glazings materials were installed for short periods in the BRE office rooms (Section 3.1.2). The validation described in Chapter 3 and Chapter 4 could be repeated for these materials if the original samples, or identical copies, are still available for measurement. Otherwise, a new validation dataset for these and other materials will be required.

It would be instructive to compare the accuracy of *Radiance* illuminance predictions with alternative simulation programs for both overcast and non-overcast sky conditions. For this it would be preferable to use the BRE-IDMP validation dataset (Section 3.1) since this is currently the best available. As noted in Chapter 3, for previous studies using non-overcast skies it was impossible to determine if the sky luminance pattern used in the model was the same as that occurring at the time of measurement. As far as the author is aware, the validation described in this thesis is the only one to date that has used measured sky luminance patterns and simultaneous internal illuminance measurements.

Two “new generation” artificial sky simulators have recently been constructed in the UK (UWCC, Cardiff and UCL, London). These are designed specifically to reproduce non-overcast sky conditions for scale models. However, recent studies have questioned the accuracy of scale models for illumination prediction [Cannon 97]. Scale model illuminances under real overcast sky conditions were found to be ~60% greater than those measured in the actual building. Whereas under real clear skies, the scale model illuminances were 100% to 250% greater than those measured in the building (Figure 8 in Cannon 97). Those errors were largely attributed to construction of the scale model and uncertainty in the positioning of the photocell where there were steep illuminance gradients. It should be possible to reproduce the validation described in this thesis using a scale model of the BRE office in one of the sky simulators. This would offer controlled/repeatable sky conditions for scale model evaluation. The measured sky luminance patterns would need be recreated in the sky simulator. The illuminance predictions would be prone to the same source visibility related errors that affected the simulations, and the potentially unreliable predictions would need to be identified. It should be noted that the new sky simulators use an array of discrete light sources to simulate sky luminance patterns. It is possible that configurations with incomplete coverage - i.e. dark gaps between the light sources - may introduce errors related to the discontinuous nature of the sky luminance patterns. It remains to be seen if the accuracy of scale model illuminance predictions under non-overcast sky conditions (real or sky simulator) can rival that demonstrated for lighting simulation in this thesis.

The evaluation of sky models based on predictions for internal illuminance is an area where further research is needed. The work described in Chapter 5 could be expanded in several ways. Ideally, additional sky model types and blends should be assessed in subsequent studies using a larger number of measured skies. The effects of building orientation and prevailing meteorological conditions should also be examined. For future sky model studies, daylight coefficient based approaches are likely to be computationally more efficient than the techniques described in Chapter 5.

Performance evaluation of buildings at the design stage is necessary to achieve the twin goals of energy efficiency and occupant comfort. Analysis of the heating/cooling requirements for a proposed design is routinely carried out using dynamic thermal simulation (DTS). With DTS, the response of the building to time-varying meteorological parameters (and plant operation) is modelled. DTS is an established technique offering a considerable advance over earlier (non-dynamic) approaches based on static U-values. Currently, lighting analysis is - conceptually - far less sophisticated than dynamic thermal simulation. Daylight provision is invariably appraised using the daylight factor approach (Chapter 2). To make a parallel with thermal modelling - lighting modelling is presently at the static (or “U-value”) stage of development. The practical implementation of the daylight coefficient approach (Chapter 6) makes it possible to evaluate daylighting of buildings in a way which is, at least conceptually, on a par with dynamic thermal analysis. It is not yet clear how a daylighting evaluation based on hourly (or better) predictions of illuminance for an entire year would proceed, or indeed of what value the analysis would be to a designer/architect. The sheer wealth of information provided by the *Radiance* daylight coefficient formulation poses problems. Not only are there about four thousand illuminance values to consider for each of the calculation points[2], there are four components of illuminance. One could argue that there is value in treating at least some of the illuminance components separately.[3]

2. For an hourly test reference year.

3. It is often the case that direct sun illuminances are preferred less by occupants than equivalent diffuse illuminances, especially when computers are in use.

Evidently, there is considerable work to be done to develop a schema to interpret and apply the results of a daylight coefficient based evaluation. Allied to this is the investigation of the sky models mentioned earlier, since these will be used to generate luminance patterns based on TRYs. The daylight factor approach, whatever its shortcomings, is an established, one might even say entrenched, technique. It is important therefore to critically assess what advantages a daylight coefficient based evaluation may offer. It is hoped that this work will be carried out in the not-too-distant future.

The Radiance lighting simulation system

Does the *Radiance* system itself need to be further enhanced? It is the opinion of this author that, with the current release (version 3.1), the *Radiance* lighting simulation system is effectively 'complete'. This assertion may surprise, and some, might pose the question: "How can the system be 'complete' when 'usability' is still an issue?" But completeness and usability are not the same thing. The absence of a graphical user interface (GUI) for *Radiance* is often perceived, by newcomers at least, to be an enormous deficiency. Comments such as: "Surely there will be a user-friendly GUI for *Radiance* sooner or later", are not uncommon. However, not only is this unlikely ever to happen, the desire for one is based on a misconception. The standard (UNIX) version of *Radiance* has been effectively applied to many different lighting problems precisely because it is based on the UNIX toolbox approach. It is worth noting that, for all of this author's work, standard versions of *Radiance* were used; not a single line of source code was changed. The originator of the *Radiance* system (Greg Ward), did not anticipate many of the uses to which it has been put. Rather, he ensured that the toolkit of individual programs could be configured, in almost any combination, to solve highly specific problems efficiently. For this reason, a 'fully-featured' GUI for *Radiance* is something of a pipe-dream. All of the non-UNIX versions of *Radiance* offer, to a greater or lesser degree, some access to the core *Radiance* programs. However, in making a few straightforward tasks easier, they make others virtually impossible.

Potential users need to be aware of what can and, more importantly, cannot be achieved using the non-UNIX versions.

Another usability concern relates to the 'correct' setting of the simulation parameters. To date, none of the 'user-friendly' (that is, non-UNIX) versions have addressed this problem, other than repeating the recommendations that are supplied with the UNIX version. In this respect, the 'user-friendly' versions do not offer any advantage over the UNIX version. It is in this area, more than others perhaps, that 'usability' issues need to be addressed.

Creating a building model in *Radiance* format is not always a straightforward task. Translator programs for a few CAD formats are included with the standard UNIX release, and several others are available. However, it is often the case that not all of the primitives for any one CAD system can be translated to *Radiance* format. For this reason, it is perhaps best to construct a CAD model using only those primitives that do convert. Creation of the model is of course unrelated to the version of *Radiance* being used. The PC version of *Radiance* known as *'Desktop'*, currently in development, may provide an efficient way to create building models for lighting simulation.[4] This version aims to integrate *Radiance* with the popular CAD package AutoCAD. If *Desktop* does not however offer an equivalent to the scripting functionality found in UNIX *Radiance*, it is unlikely to supplant the original (UNIX) version.

In conclusion, it is proposed that there is a greater need to apply *Radiance* to existing and emerging lighting problems than there is to tinker with or modify *Radiance* itself.

4. The *Radiance Desktop* website: **http://radsite.lbl.gov/radiance/desktop.html**.

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Appendix

A Validation data

A.1 Equations

The relative error (RER) in a prediction is given as:

$$RER = 100 \times \left(\frac{Predicted - Measured}{Measured}\right) \tag{A-1}$$

The mean bias error (MBE) for N predictions is given as:

$$MBE = 100 \times \left(\frac{1}{N}\right) \sum_{i=1}^{N} \left(\frac{Predicted_i - Measured_i}{Measured_i}\right) \tag{A-2}$$

The root mean square error (RMSE) for N predictions is given as:

$$RMSE = 100 \times \sqrt{\left(\frac{1}{N}\right) \sum_{i=1}^{N} \left(\frac{Predicted_i - Measured_i}{Measured_i}\right)^2} \tag{A-3}$$

A.2 Scanid

The scan ID is given in Table A-1.

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360	175_92_13h15	361	175_92_13h30	362	175_92_13h45	363	175_92_14h00
364	175_92_14h15	365	175_92_14h30	366	175_92_14h45	367	175_92_15h00
368	175_92_15h15	369	175_92_15h45	370	175_92_16h00	371	175_92_16h15
372	175_92_16h30	373	175_92_16h45	374	175_92_17h00	375	175_92_17h15
376	175_92_17h30	377	175_92_17h45	378	175_92_18h00	379	175_92_18h15
380	175_92_18h30	381	175_92_18h45	382	175_92_19h00	383	175_92_19h15
384	175_92_19h30	385	175_92_19h45	386	175_92_20h00	387	182_92_11h30
388	182_92_11h45	389	182_92_12h00	390	182_92_12h15	391	182_92_12h30
392	182_92_12h45	393	182_92_13h00	394	182_92_13h15	395	182_92_13h30
396	182_92_13h45	397	182_92_14h00	398	182_92_14h15	399	182_92_14h30
400	182_92_14h45	401	182_92_15h00	402	182_92_15h15	403	182_92_15h30
404	182_92_15h45	405	182_92_16h00	406	182_92_16h15	407	182_92_16h30

Table A-1. Scan ID

#	ID	#	ID	#	ID	#	ID
408	182_92_16h45	409	182_92_17h00	410	182_92_17h15	411	182_92_17h30
412	182_92_17h45	413	182_92_18h00	414	182_92_18h15	415	182_92_18h30
416	182_92_18h45	417	182_92_19h00	418	182_92_19h15	419	182_92_19h30
420	182_92_19h45	421	183_92_11h30	422	183_92_11h45	423	183_92_12h00
424	183_92_12h15	425	183_92_12h30	426	183_92_12h45	427	183_92_13h00
428	183_92_13h15	429	183_92_13h30	430	183_92_13h45	431	183_92_14h00
432	183_92_14h15	433	183_92_14h30	434	183_92_14h45	435	183_92_15h00
436	183_92_15h15	437	183_92_15h30	438	183_92_15h45	439	183_92_16h00
440	183_92_16h15	441	183_92_16h30	442	183_92_16h45	443	183_92_17h00
444	183_92_17h15	445	183_92_17h30	446	183_92_17h45	447	183_92_18h00
448	183_92_18h15	449	183_92_18h30	450	183_92_18h45	451	183_92_19h00
452	188_92_11h30	453	188_92_11h45	454	188_92_12h00	455	188_92_12h15
456	188_92_12h30	457	188_92_12h45	458	188_92_13h00	459	188_92_13h15
460	188_92_13h30	461	188_92_13h45	462	188_92_14h00	463	188_92_14h15
464	188_92_14h30	465	188_92_14h45	466	188_92_15h00	467	188_92_15h15
468	188_92_15h30	469	188_92_15h45	470	188_92_16h00	471	188_92_16h15
472	188_92_16h30	473	188_92_16h45	474	188_92_17h00	475	188_92_17h15
476	188_92_17h30	477	188_92_17h45	478	188_92_18h00	479	188_92_18h15
480	188_92_18h30	481	188_92_18h45	482	188_92_19h00	483	188_92_19h15
484	188_92_19h30	485	188_92_19h45	486	188_92_20h00	487	196_92_11h30
488	196_92_11h45	489	196_92_12h00	490	196_92_12h15	491	196_92_14h30
492	196_92_14h45	493	196_92_15h00	494	196_92_15h15	495	196_92_15h30
496	196_92_15h45	497	196_92_16h00	498	196_92_16h15	499	196_92_16h30
500	196_92_16h45	501	196_92_17h00	502	196_92_17h15	503	196_92_17h30
504	196_92_17h45	505	196_92_18h30	506	196_92_18h45	507	196_92_19h00
508	196_92_19h15	509	196_92_19h30	510	196_92_19h45	511	265_92_11h00
512	265_92_11h15	513	265_92_11h30	514	265_92_11h45	515	265_92_12h00
516	265_92_12h15	517	265_92_12h30	518	265_92_12h45	519	265_92_13h00
520	265_92_13h15	521	265_92_13h30	522	265_92_13h45	523	265_92_14h00
524	265_92_14h15	525	265_92_14h30	526	265_92_14h45	527	265_92_15h00
528	265_92_15h15	529	265_92_15h30	530	265_92_15h45	531	265_92_16h00
532	265_92_16h15	533	265_92_16h30	534	265_92_16h45	535	265_92_17h00
536	265_92_17h15	537	265_92_17h30	538	266_92_11h00	539	266_92_11h15
540	266_92_11h30	541	266_92_11h45	542	266_92_12h00	543	266_92_12h15

Table A-1. Scan ID

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544	266_92_12h45	545	266_92_13h00	546	266_92_13h15	547	266_92_13h30
548	266_92_13h45	549	266_92_14h00	550	266_92_14h15	551	266_92_14h30
552	266_92_14h45	553	266_92_15h00	554	266_92_15h15	555	266_92_15h30
556	266_92_15h45	557	266_92_16h00	558	266_92_16h15	559	269_92_11h00
560	269_92_11h15	561	269_92_11h30	562	269_92_11h45	563	269_92_12h00
564	269_92_12h15	565	269_92_12h30	566	269_92_12h45	567	269_92_13h00
568	269_92_13h15	569	269_92_13h30	570	269_92_13h45	571	269_92_14h00
572	269_92_14h15	573	269_92_14h30	574	269_92_14h45	575	269_92_15h00
576	269_92_15h15	577	269_92_15h30	578	269_92_15h45	579	269_92_16h00
580	269_92_16h15	581	269_92_16h30	582	269_92_16h45	583	269_92_17h00
584	273_92_10h45	585	273_92_11h00	586	273_92_11h15	587	273_92_11h30
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596	273_92_13h45	597	273_92_14h00	598	273_92_14h15	599	273_92_14h30
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604	273_92_15h45	605	273_92_16h00	606	273_92_16h15	607	273_92_16h30
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616	311_92_11h30	617	311_92_11h45	618	311_92_12h00	619	311_92_12h15
620	311_92_12h30	621	311_92_12h45	622	311_92_13h00	623	311_92_13h15
624	311_92_13h30	625	311_92_13h45	626	311_92_14h00	627	311_92_14h15
628	311_92_14h30	629	311_92_14h45	630	311_92_15h00	631	311_92_15h15
632	311_92_15h30	633	311_92_15h45	634	311_92_16h00	635	311_92_16h15
636	318_92_10h30	637	318_92_10h45	638	318_92_11h00	639	318_92_11h15
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644	318_92_12h30	645	318_92_12h45	646	318_92_13h00	647	318_92_13h15
648	318_92_13h30	649	318_92_13h45	650	318_92_14h00	651	318_92_14h15
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656	318_92_15h30	657	318_92_15h45	658	318_92_16h00	659	326_92_10h30
660	326_92_10h45	661	326_92_11h00	662	326_92_11h15	663	326_92_11h30
664	326_92_11h45	665	326_92_12h00	666	326_92_12h15	667	326_92_12h30
668	326_92_12h45	669	326_92_13h00	670	326_92_13h15	671	326_92_13h30
672	326_92_13h45	673	326_92_14h00	674	326_92_14h15	675	326_92_14h30

Table A-1. Scan ID

#	ID	#	ID	#	ID	#	ID
676	326_92_14h45	677	343_92_10h30	678	343_92_10h45	679	343_92_11h00
680	343_92_11h15	681	343_92_11h30	682	343_92_11h45	683	343_92_12h00
684	343_92_12h15	685	343_92_12h30	686	343_92_12h45	687	343_92_13h00
688	343_92_13h15	689	343_92_13h30	690	343_92_13h45	691	343_92_14h00
692	343_92_14h15	693	343_92_14h30	694	343_92_14h45	695	343_92_15h00
696	343_92_15h15	697	344_92_10h30	698	344_92_11h45	699	344_92_12h00
700	344_92_12h15	701	344_92_12h30	702	344_92_12h45	703	344_92_13h00
704	344_92_13h15	705	344_92_13h30	706	344_92_13h45	707	344_92_14h00
708	344_92_14h15	709	344_92_14h30	710	344_92_14h45	711	344_92_15h00
712	363_92_10h45	713	363_92_11h00	714	363_92_11h15	715	363_92_11h30
716	363_92_11h45	717	363_92_12h00	718	363_92_12h15	719	363_92_12h30
720	363_92_12h45	721	363_92_13h00	722	363_92_13h15	723	363_92_13h30
724	363_92_13h45	725	363_92_14h00	726	363_92_14h15	727	363_92_14h30
728	363_92_14h45	729	363_92_15h00	730	363_92_15h15	731	363_92_15h30
732	363_92_15h45	733	364_92_10h45	734	364_92_11h00	735	364_92_11h15
736	364_92_11h30	737	364_92_11h45	738	364_92_12h00	739	364_92_12h15
740	364_92_12h30	741	364_92_12h45	742	364_92_13h00	743	364_92_13h15
744	364_92_13h30	745	364_92_13h45	746	364_92_14h00	747	364_92_14h15
748	364_92_14h30	749	364_92_14h45	750	364_92_15h00	751	364_92_15h15
752	364_92_15h30	753	364_92_15h45				

Table A-1. Scan ID

A.3 Composition of the validation array

Below are row index values for all the predicted quantities, Table A-2.

Index	178-188		189-199		200-210		211-221	
Param	glb.horiz. vertical N,E,S&W	single glazed office illuminance	glb.horiz. vertical N,E,S&W	single glazed office illuminance	glb.horiz. vertical N,E,S&W	single glazed office illuminance	glb.horiz. vertical N,E,S&W	single glazed office illuminance
Notes	Scanner sky		Perez sky model		Intermediate sky model		Overcast (with sun) sky model	

Index	222-232		233-243		244-254		255-260[a]
Param	glb.horiz. vertical N,E,S&W	single glazed office illuminance	glb.horiz. vertical N,E,S&W	single glazed office illuminance	glb.horiz. vertical N,E,S&W	single glazed office illuminance	Fraction of 6° circumsolar disc (CD) visible at p_cell location
Notes	Clear sky model		Direct sun component only		Direct sun component only - scanner sky		-

Index	261-284	285-386	387-392	393-398
Param	single glazed office illuminance derived from daylight coefficients - variants 1 - 4	Fraction of circumsolar disc (CD) visible at p_cell location	single glazed office illuminance	single glazed office illuminance
Notes	-	For CD angles: 0.2°,0.4°, 0.6°, 0.8°, 1.0°, 1.2°, 1.4°, 1.6°, 1.8°, 2°, 4°, 6°, 8°, 10°, 12°, 14°, 16°.	Scanner sky - hi-res ambient calc.	Scanner sky - lo-res ambient calc.

Index	399-404
Param	single glazed office illuminance
Notes	Scanner sky - lo-res ambient calc. with points reveresed

Table A-2. Predicted quanities by vector index

a. Although repeated at a later stage (see indices 285-386), this entry was kept to maintain backwards compatabilty with existing analysis programs.

The composition of the measured quantities (and identifiers) was given in Table 3-12. The file size of the validation array was - in its final updated form - 1.22Mb. This is a relatively small amount of data and the same approach could have been used un-modified on much larger data sets. For example, a full year's data at 15 minute timestep contains (approximately) 17,500 (daylight) entries. For this number of daylight entries, the validation array would have dimensions 17500 x 404 and file size (approximately) 28Mb. Which is small enough to be loaded directly into physical memory and explored interactively.

Appendix

B Published work

B.1 List of related publications

Mardaljevic, J. *The Radiance lighting simulation system* Building Performance (BEPAC) Issue 2, 6-17 (1999)

Mardaljevic, J. Notes on (1) Daylighting Applications, (2) Advanced Daylighting Calculations and (3) Validation Studies in *Rendering with Radiance: A Practical Tool for Global Illumination* ACM SIGGRAPH 98 Course Notes CD-ROM (Orlando, 1998)

Mardaljevic, J. *Daylight simulation - In Rendering with Radiance: The Art and Science of Lighting Visualization* (G. Ward Larson & R. Shakespeare) San Francisco: Morgan Kaufmann (1998)

Mardaljevic, J. and Lomas, K. *A Simulation Based Method to Evaluate the Probability of Daylight Glare Over Long Time Periods and its Application* National Lighting Conference, Lancaster, UK (1998)

Mardaljevic, J. *Validation of lighting simulation program: a study using measured sky brightness distributions* Lux Europa 97 proc. 555-569 (Amsterdam, 1997)

Mardaljevic, J. *Validation of a lighting simulation program under real sky conditions* Lighting Res. Technol. 27(4) 181-188 (1995)

Mardaljevic, J. Daylighting models in *Realistic Input for Realistic Images* ACM SIGGRAPH 95 Course Notes CD-ROM (Los Angeles, 1995)

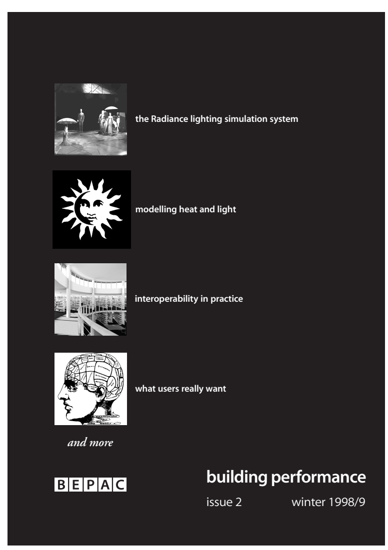
Mardaljevic, J. and Lomas, K. *Creating the right image* Building Services The CIBSE Journal 15 (3) 28-30 (1993)

Appendix C

The Radiance system

BEPAC Article

This article originally appeared in **Building Performance**, Issue 2, winter 1998/9 (**BEPAC**). It is reproduced here in its original form with permission. Note that the numbering scheme does not follow that for the rest of the thesis. Sections and figures in this chapter are not referenced elsewhere in this thesis.



The Radiance lighting simulation system

The Radiance system is a professional toolkit for lighting simulation. It can be used to model daylight and electric lighting in almost any environment and to almost any level of complexity, and it is used worldwide by both researchers and practitioners to solve a huge range of lighting problems. Radiance has been rigorously validated and proven to be highly accurate. Furthermore, the software (UNIX version) is freely available. Sounds (almost) too good to be true. Should all lighting designers be using Radiance? If not all, then who and why? In this major article, *John Mardaljevic*[1] considers these questions and addresses some of the myths and misunderstandings about the Radiance system.

Look carefully at the images in the centre of these pages. One is a photograph of the Computer Labs at MIT, the other a Radiance rendering. But which is which? Most people need at least a second glance to distinguish between the rendering and the photograph. (If you aren't sure, the answer is at the end of the article.) But even if you *can* tell the difference the rendering is impressive.

There are three reasons why this Radiance rendering looks like the real thing. Firstly, the model geometry seems to be a very full and exact representation of the real scene. Secondly, the luminaire photometry and materials specification were closely based on actual measured properties. Lastly, the simulation software has predicted the field of view luminance using a physically accurate model of light transport. This is what Radiance does.

What is Radiance?

Radiance (UNIX version) consists of over 50 tools (i.e. programs), many of which cannot be found anywhere else. These were developed over the course of 10 years, with funding from the US Department of Energy and the Swiss Federal government, primarily by Greg Ward Larson. They do everything from object modelling to point calculation, rendering, image processing, and display. The system was originally developed as a research tool to explore advanced rendering techniques for lighting design. It has evolved over the years into a highly sophisticated lighting visualization system, which is both challenging and rewarding to learn. Radiance is unique in its ability to accurately simulate light behaviour in complicated environments, which means two things: correct numerical results, and renderings that are indistinguishable from photographs. There is simply no other physically based rendering system, free or otherwise, with as much power and flexibility as Radiance. There are a few core Radiance programs

Real or rendering ? …

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that everyone will use, several that most will use, and many more that only a few will use. The most advanced users may even combine programs to create new functionality specific to their needs. Most users fall into one of the following categories:

- ***Computer graphics enthusiasts***
  People who want the most realistic rendering software available and/or are working with a relatively small budget.
- ***Researchers***
  Research students and university staff who want source-level access to advanced techniques in rendering and global illumination, or a basis for comparison to their own rendering algorithms.
- ***Designers***
  Architects, illumination engineers, and other designers who need accurate tools for predicting light levels and visual appearance in novel situations and who have the time and energy to invest in a sophisticated rendering system.
- ***Students***
  Computer graphics and design students using Radiance as part of their coursework in rendering or CAD modelling.

. . . . rendering or real?

- ***Industry professionals***
  Professionals working in the arts, entertainment, and litigation who need rendering tools with the latest in local and global illumination methods to obtain results of the highest quality and veracity.

For the majority of BEPAC members, the categories of interest will be *Designers* and possibly *Industry professionals*. Note the caveat: ". . . and who have the time and energy to invest in a sophisticated rendering system."

Newcomers to Radiance have found the complexities of the system rather daunting. Although the original (UNIX) version of the software is free, the system has to be learnt, and any small to medium-size practice needs to consider the cost implications of this. It is not easy for a practice to judge the cost effectiveness of a new and complex simulation tool. A manager may decide that, for todays work, the practice cannot afford to make the learning investment in this particular tool. In the future however, clients are increasingly likely to expect high-quality visualisation and daylight prediction as part-and-parcel of a comprehensive design analysis. More and more practices will feel the need to develop this expertise in-house so that they can offer a complete environmental or specialist lighting design evaluation.

This article will try to give an overview of the Radiance system and its application, without resorting too much to technical details. It will also attempt to address the "usability" issues — real and imagined — associated with this simulation package. To this end, testimonies from new and experienced users working in commercial practices are included also.

What makes Radiance unique?
What claim can a simulation package have for uniqueness when, on close inspection, the majority seem to be more similar that different? Radiance has, arguably, more claim than most for the following reasons:

1. Its singular flexibility. This is largely because the system is based on the UNIX toolbox model (see page 13).
2. The algorithms used to predict the transport of light are not found in any other lighting simulation system or package.
3. The development history of the software. In the nine years since the first release, Radiance has benefited enormously from user feedback: most of the enhancements made to the system were the outcome of real or perceived user requirements.

When and for what should Radiance be used?
The placing and size of windows on a building facade greatly affects internal conditions. At the design stage, the provision for natural lighting is invariably assessed in terms of the predicted daylight factor (DF). The CIBSE Windows design guide, or a simple PC program such as DAYLIGHT, will provide a reasonably accurate estimate for the average DF in simple rectangular-shaped spaces. Both the design guide and the DAYLIGHT program are intended for non-expert users, be they architects or engineers. So the application of Radiance for this task could be perceived as overkill.

Is there any advantage to using Radiance for simple DF calculations? There might be, provided that the user has sufficient knowledge of the system. For example, creating the geometry for a simple space can take less than 15 minutes, and the simulation time could be anything from a minute or two to several hours depending on the accuracy required. But note that even a quick simulation will give reasonably accurate predictions. Furthermore, it is possible to carry out fully automated parametric studies using custom scripts: almost any material or object property can be manipulated in a script. For example, the DF distribution could be calculated as a function of the proximity of a nearby obstruction using a simple script.

For complex spaces, the design guide and simple programs may give estimates that are wide of the mark. Complex here means a space that has one or more of the following attributes:

- non-rectangular shape;
- non-standard glazing, eg diffusing material;
- non-vertical and/or irregular glazing arrangement;
- internal/external obstructions and/or light redirecting devices, eg light shelf;
- spaces adjacent to light wells or atria.

For any of these, a lighting simulation (such as Radiance) or a scale model study may be required. The designer may, for a daylight factor evaluation, see little to choose between a scale model and a Radiance simulation. If the requirements go beyond daylight factors to include visualisation, then simulation may become the preferred option. This is largely because of the relative ease with which buildings complexity can be introduced (at any scale), especially if the building description already exists in a suitable 3D CAD form.

With physically-based lighting simulation, visualisation takes on a new meaning: the Radiance image file is a pixel map of spectral (i.e. with colour) luminance (or illuminance) values in a high-dynamic-range, floating point data format (see below). The image on the computer screen is just one way of "looking" at the data, albeit the most convenient and intuitive way. The information contained in the image (and scene) files could also be used, say, to locate glare sources. In place of a luminance map (i.e. "normal image"), a rendering could show the illuminance, as lux or daylight factor, on all the surfaces in the field of view, (a very useful technique to assess the illumination for art galleries and exhibition spaces). It is also possible to overlay illuminance (as contour lines) over a normal image.

The sections that follow show how Radiance can be used to solve a wide range of lighting design problems. Ranging from the possibly mundane (DF calculation) to the positively offbeat (tallow candle lighting), not to mention outer space, these images are testament to the power and flexibility of the Radiance system.

Radiance renderings: information content and display

The pixels of a Radiance rendering are real numbers corresponding to the physical quantity of radiance (recorded as watts/steradian/m^2). The visible part of radiance is luminance; the two quantities are interchangeable using a conversion factor. Each Radiance rendering also has a header that contains information on the generating commands, view options, exposure adjustments etc.

It is important to note that, while Radiance can accurately predict real-world luminances, all display devices without exception — VDUs, projectors and so on — have a very limited range of luminance output. Otherwise, we could get a suntan from a display of a rendering of the sun! To overcome this limitation, the "exposure" of the finished rendering has to be adjusted for display. For example, say that the rendering was for a room with a window to a bright daylit outdoor scene. The exposure (of the finished rendering) could be adjusted to reveal either low-luminance internal detail at the expense of "burning-out" the view through the window, or show the view outside but now with a darkened room where all shadow detail is hidden. Alternatively, some compromise exposure could be sought. (In principle, this approach is identical to what a photographer must do to record the same scene: expose the limited-range film for either the dark inside or the bright outside.)

This was the situation until the advent of Radiance version 3.1; the new release includes a powerful image conditioning program called *pcond*. The role of *pcond* is to compress the dynamic range of the rendering such that both dark and bright regions are visible in the displayed image. *Pcond* uses a variety of mathematical techniques to determine an appropriate exposure and (optionally) simulate loss of acuity and veiling glare, loss of focus, and loss of colour sensitivity. Renderings conditioned with *pcond* can result in displayed images that preserve the visibility of high dynamic range scenes, across the luminance range. In other words, the visual response evoked is close to that which would be experienced for an equivalent real-world scene.

For this article however, the images chosen were those that would reproduce (reasonably) well in monochrome. The original images were converted to grayscale and, for most, the contrast was adjusted to compensate for the loss of colour information. Links to the websites that have the original colour images are given where available.

Example applications I: workaday

Daylight factor prediction

Daylight factors were calculated at the work plane height across floor-plans for levels 1 and 3 of the atrium model shown in **Figure 1**, using a simplified version of the atrium model to reduce simulation time. The office cells containing the floor plans were modelled in detail, as was the atrium roof. But the rest of the structure was modelled as planar surfaces with bulk reflective properties. The predicted DFs are shown in **Figure 2**.

Visualisation - Interiors

The office model shown in **Figure 3** was used to assess the visual impact of external bronze grilles. The realistic carpet pattern was achieved using a pair of "procedural functions" that modified the carpet material's reflectance. One function produced the regular carpet weave pattern; the other added random larger-scale patches of slight darkening to mimic uneven brushing/wear of the carpet tufts. A similar technique was used to create the water pools for the atrium model (**Figure 1**): a procedural function was used to perturb the surface normal across the single flat sheet of glass material that served as the water surface. Thoughtful application of these and similar functions can produce very realistic looking materials, and also add a great deal of "visual interest" for very little modelling effort.

The new Engineering Building at De Montfort University Leicester has already been noted for its uses of a passive ventilation strategy. The building also contains some innovative daylighting features, notably light shelves in the computer rooms. These are intended to reduce glare and to redistribute natural light more evenly across the space. A rendering of the view along the length of the computer room is shown in **Figure 4**. The wall to the right shows the light shelf at eye level covering most of the length of the wall. This model was used to predict the daylight factor distribution for the space.

Visualisation - exteriors

Radiance has been used to assess the lighting schemes for several huge building projects. The two examples here are both in Hong-Kong. The first is a proposed lighting scheme for the entrance to the passenger lobby at Cathay Pacific's Headquarters, **Figure 5**. The other example is a rendering of the Tsing Ma suspension bridge, **Figure 6**. This model had thousands of accurately depicted light sources and required considerable computer power to render. For more examples of exterior lighting, see **http://appia.tcvc.indiana.edu/~tcvc/gallery/gallery.html**

Shading analysis

The movement of shadow patterns over a site can be assessed from a sequence of

Figure 1: Rendering of an atrium designed by Peter Foggo Associates, with water
and (below)
Figure 2: Predicted daylight factors in the Foggo atrium

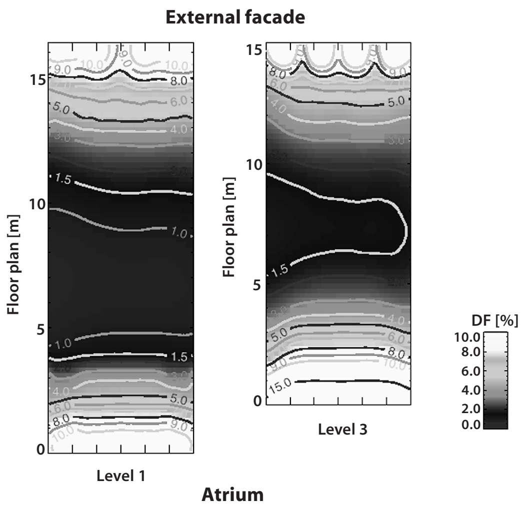


Figure 3: A model used to assess the visual impact of external bronze grills — note the weave in the carpet

Figure 4: A model of the computer room in the Queen's Building at De Montfort University used to predict DFs and assess the effect of light shelves

Figure 5: The passenger lobby entrance at Cathay Pacific HQ, Hong Kong

Figure 6: Tsing Ma suspension bridge, Hong Kong — with thousands of separate light sources and water

image pairs like **Figures 7** and **8**, created by Ove Arup & Partners. One of the images **(Figure 7)** is generated for a high viewpoint above the site, the other **(Figure 8)** shows the view of the site from the sun position.

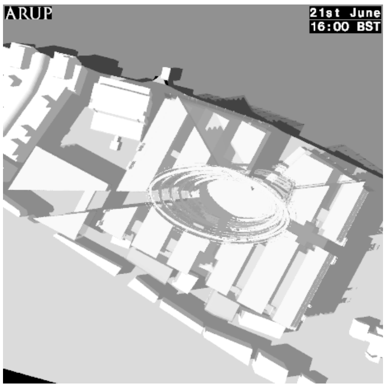


Figure 7

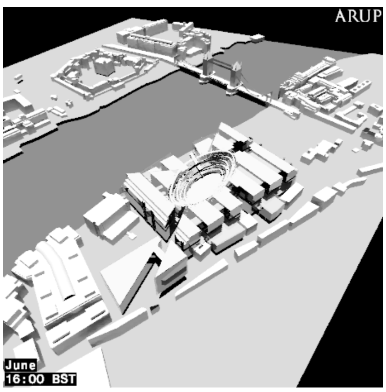


Figure 8

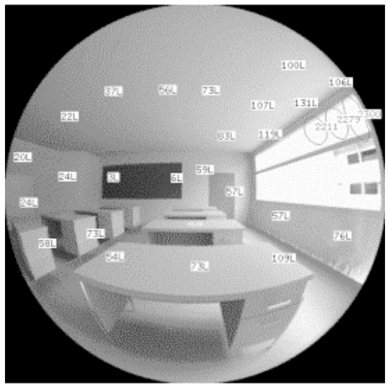
Glare analysis

The *findglare* program is used to locate potential glare sources in the field of view. In each of the three renderings shown in **Figure 9**, regions of high luminance have been identified and marked with an ellipse. The point luminance across several room surfaces has been marked also.

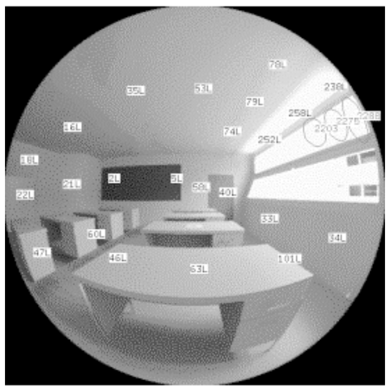
Rights to light

Here Radiance was used to determine the minimum separation between an existing building and a proposed cold store, **Figure 10**. The criterion used was based on the percentage of the working plane predicted to have a sky factor of less than 0.2%. In terms of lighting, this is a trivial problem to solve: inter-reflection is not an issue. Nevertheless, Radiance was an ideal tool for this job because the scene geometry - specifically the position of the proposed building - could be manipulated using scripts, making it a simple matter to automate a parametric study.

No light shelf



As-is light shelf



Conventional light shelf

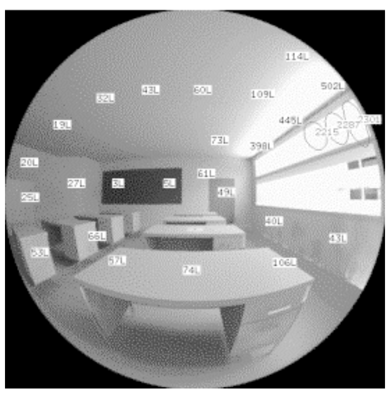


Figure 9: Glare analysis for three design variants

Student architecture

Architecture students at the ETH in Zurich regularly use Radiance to render their coursework designs; **Figure 11** is an example. The students have access to a tailored solution in which designs, created using Microstation CAD, are converted to Radiance format via a VRML intermediary. The complexities of Radiance are largely hidden from the users, and they are able to create renderings which although not always "perfect" are nonetheless a major improvement over the best that can be had using 3-D Studio. For more examples, see the CAAD website: **http://caad.arch.ethz.ch/teaching/radgallery/**

Example applications II: exotic

Historical building simulation

Radiance has been used to re-create the lighting conditions in historical theatres as it was actually experienced by performers and the audience, as shown in **Figures 12** and **13**. The model light sources were based on photometric measurements of an actual tallow candle with a period-type rag wick. The information that resulted from this form of building simulation gave valuable insight into aspects of period performance since this would have been influenced by the quantity and distribution of the lighting.

Space shuttle

The Graphics Research and Analysis Facility (GRAF) is an integral part of the Flight Crew Support Division (FCSD) at NASA. GRAF uses high performance computer graphics workstations interfacing with various graphics software modules to address human engineering issues in spacecraft design and analysis. One of these is Radiance, which GRAF uses to produce realistic images of complex environments. Measured data is used to develop models of shuttle and station artificial lights. Natural lighting, such as sun and earth shine, can also be incorporated into the lighting analyses. By incorporating the measured reflectances for each material into the lighting model, an accurate calculation of the amount of light entering a camera can be made. Then, using this calculated light distribution with the

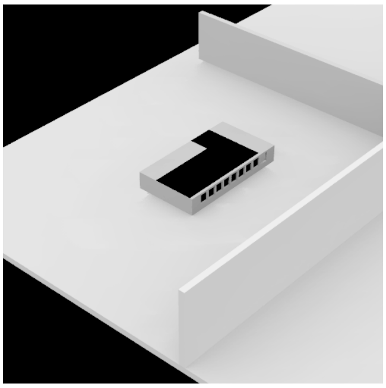


Figure 10

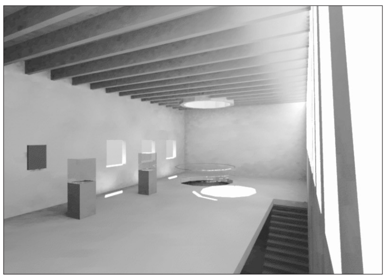
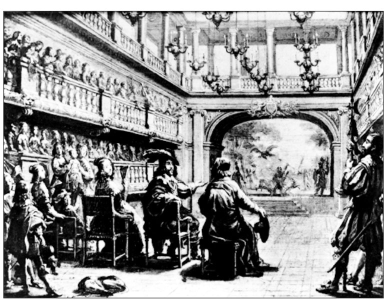


Figure 11

Figure 12: Simulation of tallow-candle lighting in a historical theatre

and (below)

Figure 13: A contemporary engraving of the same theatre



GRAF's model of the shuttle cameras, camera images can be simulated accurately. **Figures 14** and **15** show some of the results. You can visit GRAF at **http://www-sa.jsc.nasa.gov/FCSD/CrewStationBranch/GRAF/graf4.html**

Theatre lighting - modern

The Theatre Computer Visualization Centre at Indiana University have developed an interface that integrates the positioning and control of virtual theatre lighting systems with Radiance. With this, they can explore complex stage lighting scenarios using visualisation, as **Figures 16** and **17** show, and so refine the lighting design for a production in advance of any actual rehearsals. The stage lighting photometry can be very accurately described in the Radiance models. Effects such as beam focus, colour filters, colour changes due to lamp dimming, shutters, template patterns etc. can all be realistically portrayed. For the 'rock-n-roll' image (**Figure 18** (next page) — actually a still from an animation), stage fog was modelled using the Radiance mist material. For more images, visit **http://appia.tcvc.indiana.edu/~tcvc/**.

Emergency lighting - US Navy cruiser

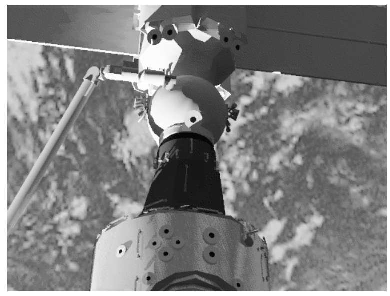
The effectiveness of an emergency lighting system for a US Navy cruiser was assessed using visualisation - stills and animation. **Figures 19** and **20** (next page) show the view under normal and emergency lighting.

Example applications III: research

Here, research is taken to mean any exploratory work using Radiance that is not addressing a specific lighting problem. Taking a wider meaning, many of the previously described applications would rightly be counted as research also.

Daylighting research at the Institute of Energy and Sustainable Development, DMU

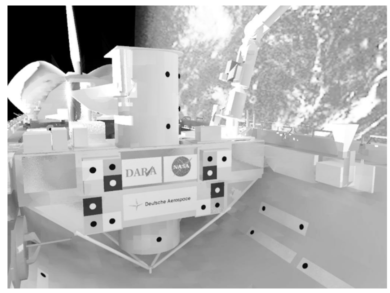
A great deal of Radiance-based daylighting research has been carried out at the IESD since Radiance was first used here in 1991. Firstly, Radiance illuminance predictions were rigorously validated using measurements taken in full-size office spaces under real sky conditions. For this work, Radiance used sky luminance patterns based directly on measured sky brightness distributions. The results from the validation proved that Radiance can predict internal illuminance to a high degree of accuracy for a large sample of skies which cover a wide range of naturally occurring sky conditions. As far as the author is aware, this validation



Figures 14: Simulation of an image from a camera on the space shuttle

and (below)

Figure 15: Another simulated shuttle photograph



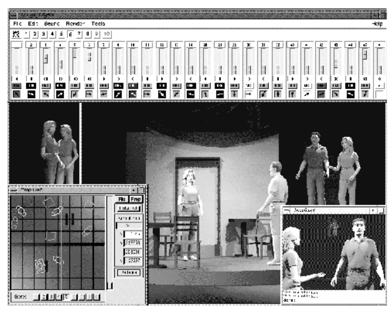


Figure 16: Exploring a complex lighting scheme for a theatre production

and (below)

Figure 17: A simulated scene

Figure 18: A still from an animation, with Radiance mist

Figure 19: Normal lighting in a USN warship

and (below)

Figure 20: Emergency lighting

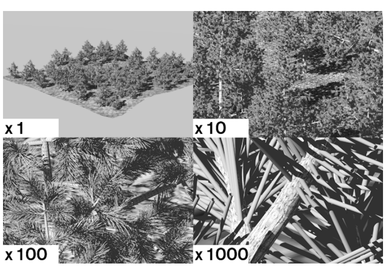


Figure 21: Renderings of a pine forest at four magnifications

study is the only one to date that has made use of measured sky brightness distributions and simultaneous internal illuminance measurements.

Next, Radiance was used to compare the absolute and relative performance of sky models. The validation exercise was repeated using sky models to generate the sky luminance distribution. This study compared the sensitivity of internal illuminance predictions to sky model type. Four sky models and two sky model composites were examined.

Guided by the results from these projects, the next task was to develop a methodology for predicting the annual daylighting potential of a space. This takes into account the varying internal illumination from sky and sun throughout the year. An explicit evaluation of the daylighting potential provided by a design would account for the internal illuminances produced by all the skies measured at or near the intended site over a monitoring period of a year or more.

If measurements were obtained as hourly values, the data for a normal working year would contain approximately 3,500 skies. With the latest generation workstations, modelling several thousand cases is a tractable, though still rather time consuming task. A more efficient solution is to use the daylight coefficient approach. This technique eliminates the need to perform the most computationally-demanding part of the simulation — the inter-reflection calculation — for every individual case. The daylight coefficient approach requires that the sky be broken into many patches, and the internal illuminance at a point from every patch of unit sky brightness be individually determined and cached. (The daylight coefficient approach was described in more detail in Building Performance issue 1, pp 21-2) . Thus, an internal illuminance prediction resulting from any sky brightness distribution can be obtained by appropriate scaling of the contribution from each patch.

A formulation for Radiance was devised, implemented and validated. The accuracy of the daylight coefficient derived illuminance predictions were found to be comparable to those for the individually modelled skies. This research formed the basis for the Dynamic Lighting System (DLS), a Radiance-based system to predict time varying illuminances. The DLS incorporates several artificial lighting control models so that luminaires are responsive to the varying daylight level predictions. The program calculates annual totals for lighting demand and energy use. Following initial testing, usability issues are being addressed and the system will be released early in 1999. This software will be made freely available. For news and updates of the DLS, visit IESD's Web site **http://www.iesd.dmu.ac.uk/dls/** and for information on daylighting research at the Institute visit the author's homepage **http://www.iesd.dmu.ac.uk/~jm/.**

Daylight Europe

The overall aim of the Daylight-Europe (DL-E) project is to generate daylighting design guidelines for architects and engineers. The basic method was to evaluate and exemplify the daylighting behaviour of 60 European buildings which typify the range of design types and climatic contexts. To this end, the techniques of monitoring, simulation and post occupancy evaluation were employed. The role of simulation was to ensure, firstly, that daylight utilisation was not being achieved at the expense of other performance parameters (such as thermal comfort or heating energy consumption) and, secondly, to determine the effects of design and climate parameter variations in order to generalise the results from the case studies. Radiance was used for all the lighting simulation work; **Figure 9** (page 10) is an example.

Computer graphics

Radiance is being used by graphics researchers as a testbed to try out other algorithms and parallel computing implementations, and also to investigate the perceptual equivalence of a rendered scene to a real scene.

Creating a Radiance model

How one creates a Radiance scene description for a design is largely a matter of choice. One of the basic precepts of Radiance is that scene geometry can be taken from almost any source. It is hardly surprising therefore that there are a wide range of CAD to Radiance converters available, including:

- *archicad2rad*: converts from ArchiCAD RIB exports to Radiance (for Macintosh)
- *arch2rad*: converts from Architrion Text Format to Radiance
- *arris2rad*: converts ARRIS Integra files to Radiance
- *dem2rad*: converts from Digital Elevation Maps to gensurf input
- *ies2rad*: converts from the IES standard

luminaire file format to Radiance

- *mgf2rad*: converts from the Materials and Geometry Format to Radiance
- *nff2rad*: converts from Eric Haines's Neutral File Format to Radiance
- *obj2rad*: converts from Wavefront's .obj format to Radiance
- *radout*: converts ACAD R12 to Radiance (ADS-C add-on utility)
- *rad2mgf*: converts from Radiance to the Materials and Geometry Format
- *stratastudio*: converts Macintosh Strata-Studio files to Radiance
- *thf2rad*: converts from the GDS Things File format to Radiance
- *tmesh2rad*: converts a basic triangle-mesh to Radiance
- *torad*: converts from DXF to Radiance (AutoLISP routine must be loaded from within AutoCAD)

What is perhaps surprising is that a number of users opt to create very complex models using only the scripting capabilities built into Radiance. The atrium model shown in **Figure 1** contains over 50,000 polygons and was generated by the author entirely without the aid of CAD. The majority of practitioners however seem to prefer a pragmatic approach — a mixture of CAD and Radiance scripting.

Scripting is required to make use of a very powerful Radiance technique for accommodating massive scene complexity within limited computer memory resources. In this, the octree of a compound object comprised of any number of surfaces can be "instanced" (that is, repeated) almost any number of times. Multiple occurrences of the same octree in a given scene will use only as much memory as that required for a single instance, plus a tiny amount to store the associated transformations for each instance's location. This technique is often used for furniture objects and the like — for example, to generate hundreds of seats for a theatre model. Instancing can also be applied hierarchically, where multiple instances of a single octree are used to create a second, enclosing octree. The enclosing octree can then be instanced further, and so on.

It is possible to model scenes with a virtually unlimited number of surfaces using this method. **Figure 21** shows renderings of a pine-tree forest model at four magnifications. The forest model contains 73 instances of a pine tree and 9 instances of a sapling. Each of the two instances were given a different size and orientation and dotted across the landscape. The image at x1000 shows that we can see detail right down to the individual pine needles, and yet the total data structure for this scene used less than 10 Mbytes of RAM during rendering. Note that whilst near-infinite scene complexity is possible using instancing, near-infinite variety is not. Totally unique objects must have their own description, and with these the scene complexity will grow in proportion to the number of surfaces.

How long does it take to create a Radiance model? This is a question that is often asked, especially by prospective clients. It is however extremely difficult to anticipate modelling timescales without first looking at the drawings/plans. Geometrical information from an existing CAD model can be used. But for this to be effective, the CAD model needs to be layered so that material properties can easily be assigned to the relevant surfaces. For many modern architectural designs, most, if not all, of the model could be created using Radiance scripts. Where visual realism is not intended, the scale of modelling complexity should generally be commensurate with the scale of the effect of the modelled structures on internal light levels. For daylight factor calculations therefore, a simple scene is appropriate. When visualisation is required, the complexity of the finished model will depend on the skill of the user and, of course, the fees associated with the project. Having worked-up the model, renderings for multiple views require little extra user effort.

So, how long does it take to generate an image? Once again, the answer must be: Well, that depends... Computer processing power is of course a key factor, but there is a complex relation between rendering time and the following:

- the number of light sources;
- the number of light reflections;
- the image size; and,
- the "accuracy" of the rendering parameters.

Also, computed inter-reflected light values can be saved to a file and reused for subsequent renderings of the same model for different views, shortening the computational time. Some experience is needed therefore before it is possible to accurately estimate the final outcome of a lighting analysis project.

Radiance can also be used to generate animations. One of the application chapters of the Radiance book describes how to do this, using (if available) multiple (UNIX/LINUX) workstations connected to a network.

Will the "real" Radiance please stand up!

A newcomer to Radiance may experience some confusion trying to decide what version to use. In addition to the original UNIX version, there are a few systems that integrate Radiance in CAD or other environments, and usually on the PC platform. It would be fair to say however that all of the current non-UNIX variants restrict, to a greater or lesser degree, the full functionality offered by the original UNIX version. To get the most from Radiance, the UNIX version is preferred; this will run under Linux, on a PC. If you require only a limited sub-set of the available functions, then one of the Windows-based versions may suffice.

One of the many myths about Radiance is that it is difficult to use because it does not have a user-interface. There is a certain amount of confusion here, originating with, I believe, the meaning of the word 'difficult'. The difficulties, and every new user has experienced them, result from the almost limitless possibilities that the system offers. It is important to distinguish between complexity that is associated with positive attributes like flexibility, accuracy and optimization and difficulties that stem from, say, poor system design. It is this author's assessment that Radiance is an extremely well designed system, and that the complexities, about which one must be candid, are part and parcel of its virtues.

The real problem people have when starting out in Radiance is that they are not used to the UNIX toolbox model, that is, having many individual programs that are optimized for specific tasks and meant to run together. Most people are instead used to the monolithic application model promoted by Microsoft and most other software companies, where a single, "seamless" interface is presented to the user, regardless of what goes on underneath. In truth, the toolbox model works very well, and is a very efficient method for building up a powerful and flexible software base. However, it takes more time to learn and is nearly impossible to master because the combinations one can create are so unconstrained compared to a menu-driven system.

Radiance and the UNIX toolbox approach

Using the UNIX toolbox model, Radiance programs are linked together in a command pipeline for a combined purpose. An example of a pipeline command tailored for a specific task is:

```
gensky $skypar \
   | oconv -w -i $oct - \
   | rpict -w -vp $xp $yp $zp -vd $xd \
     $yd $zd -x $dim -y $dim \
   | pfilt -1 -e 0.06 -x /2 -y /2 \
   | pcompos - 0 0 '\!psign -h 20 \
     '"$month"' '"$day"' '"$hrh" 0 0 \
     >! tmp1.pic
```

This command does, of course, look like gobbledegook to most people. What it does illustrate though is the versatility of the UNIX toolbox approach. This one command, spread out over a few lines, results in the execution of no less than six individual Radiance programs (underlined). The pipe (|) command is the link between the programs: reading left to right, the output from one program is 'piped' to the input of another. This example command was taken from a short UNIX shell script that was written by the author to generate a sequence of 280 images for an animation showing the solar penetration into a building throughout the year. Briefly, the example command does the following:

1 A sun description is generated (gensky) for a particular time of the year - the parameters are taken from the shell-variable $skypar.
2 The output from gensky is added to an existing octree for the building using the oconv command. The octree data structure is necessary for efficient rendering.
3 Using this octree, the rpict program generates a rendering based on the view parameters -vp etc.
4 The exposure for the rendering is adjusted and it is filtered down to half the original size using the pfilt program.
5 An image created by the psign program is added to the filtered rendering using the pcompos program. The psign command here is executed 'in-line' rather than in the pipeline. Its function is to generate a time-stamp label for each rendering e.g. "March 01 13h15".

A single frame from the sequence is shown in **Figure 22**. The complete script actually generated two views of the building: an external and internal view. The external was from the viewpoint of the changing sun position and shows the sun illuminated external surfaces. The other was from a fixed point above to show the sun penetration into the building. Radiance allows the user to set so called 'clipping planes' that eliminate foreground and/or background objects from the rendering. Using this option, the roof of the building was 'clipped-off', but the predicted transport of light in the model remains unaffected. The entire animation sequence is included on the **Building Performance** CD-ROM.

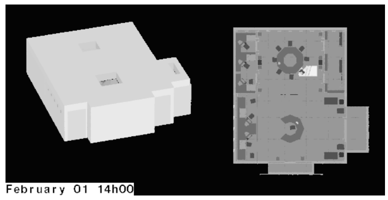


Figure 22: One of a sequence of renderings generated by a script to show how sun penetration into a building varies through a year

It would be extremely difficult if not impossible to design a 'user-friendly' graphical interface that preserved the flexibility and rich functionality offered by the UNIX toolbox approach, and yet spared the user the task of setting the various program parameters etc. In fact, an entire chapter of the Radiance book is given to an exposition of scripting techniques. To quote from that chapter's conclusion: "Without ever writing a line of C (program) code, one can do almost anything imaginable by combining the various rendering, filtering, and utility programs included in Radiance. Combining this knowledge with the C-shell and other command interpreters, we can create new command scripts that permanently extend the functionality of our system for ourselves and our fellow users".

The newcomer should not feel complete despair however: there is a user-friendly way to get going with Radiance.

The graphical interface

The UNIX version of Radiance comes with a simple user interface to help get new users started. Called *trad*, this graphical interface **(Figure 23)** helps to set up and optimize the rendering process based on a few easy to understand general parameters supplied by the user. For some of these parameters, the options on offer are intuitive — for example, Low, Medium or High. The interface does not access many of the features of Radiance, but it does give a gentle introduction to the system. And for many new users, the first thing they will want to do is to create some renderings — *trad* will help them do this.

The *trad* interface can also fulfil an important teaching role since the user can view the full set of rendering parameters that were generated from the simplified settings. So, with a little experimentation, he or she can begin to see the relation between the generated actual parameters and the resulting image quality. Trad is not just for beginners; many people with long experience of Radiance, including the originator of the system, continue to use it to manage routine rendering tasks.

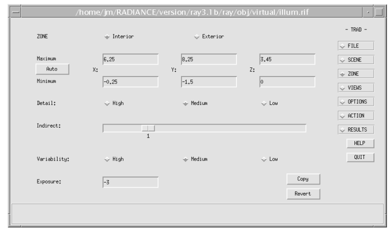


Figure 23: *trad*, a more user-friendly interface for the simpler features of Radiance

Non-UNIX versions of Radiance

There are several PC versions of Radiance available, some newer than others. A comparative evaluation is difficult to make because there are very few people, if any, that have used all the currently existing versions. The best known include:

- ***ADELINE***: A collection of CAD, simulation, and visualization tools for MS-DOS systems, which includes a DOS version of Radiance. This package is perhaps the best known PC version of Radiance. It was within the framework of the International Energy Agency (IEA) Solar Heating and Cooling Programme Task 12. Integration between components is of variable quality, but it does include a good translator from DXF format CAD files, and it includes LBNL's SUPERLITE program in addition to Radiance. This package is available from LBNL and other contributors. Visit LBL's Adeline pages at **http://radsite.lbl.gov/adeline/index.html.**
- ***GENESYS***: A lighting design package from the GENLYTE Group. It runs on MS-DOS computers. It includes an earlier DOS version of Radiance and has a nice user interface for designing simple layouts with a large catalogue of luminaires. There are contact details on **http://turboguide.com/cdprod1/swhrec/007/762.shtml.**
- ***SiView***: An advanced, integrated system featuring Radiance for MS-DOS and Windows platforms. It is available from Siemens Lighting in Traunreut, Germany.

It requires the separate purchase of both AutoCAD and ADELINE. There is more information (in German) on Siemens Website **http://w2.siemens.de/newsline.d/pressfor/nd96493.htm.**

- ***CANDLE***: A simple to use package that integrates a WINDOWS 95 version of Radiance with an object manipulating tool (PANGEA). The package includes a luminaire database and a materials editor. It was developed at the Bartlett, University College London and is currently undergoing testing. Contact Peter Raynham for further details at **p.raynham@ucl.ac.uk.**
- ***DESKTOP RADIANCE***: Currently under development, this package aims to include many of the quantitative and qualitative capabilities of UNIX Radiance in a WINDOWS NT/95 version. DESKTOP RADIANCE includes an AutoCAD-based graphic editor that allows the user to select from libraries for materials, electric lighting fixtures, glazing systems and furniture. It is being jointly developed by Lawrence Berkeley National Laboratory and the Pacific Gas and Electric Co. First release is planned for spring 1999. Visit LBL's Website for the latest information on **http://radsite.lbl.gov/radiance/desktop.html.**

None of these versions are free, and none of them are directly supported by the originator of the original UNIX version. *DESKTOP* is being developed at LBNL who maintain the UNIX release. It may be therefore that this PC version will have the greatest correspondence to the original UNIX Radiance. At present however, *ADELINE* is probably the most used of the PC versions, and the best one to try first.

Learning how to use Radiance

For some time now, both newcomers and experienced users have voiced the need for a definitive guide to the Radiance system.

The documentation with the UNIX release includes manual pages for all the programs, a brief tutorial, a guide to material behaviour and some technical notes. Useful though these are, they only give a glimpse of what is possible. What was needed was a thorough exposition of the basic functionality in the form of graded tutorials, material on specialist applications and a description of the calculation methods.

This eventually appeared in *Rendering with Radiance: The Art and Science of Lighting Visualization*, published by Morgan-Kaufmann in March 1998. This excellent book is accompanied by a CD-ROM containing the complete UNIX software (release 3.1), tutorial scene files, image gallery and much additional material. It is aimed primarily at users of the UNIX version of Radiance. The book contains a great deal that is not available elsewhere and it is strongly recommended to beginners and experienced users alike. The author must disclose at this point that he wrote one of the specialist application chapters, 'Daylight Simulation', for the book. *Rendering with Radiance* is reviewed by Milan Janak on page 17 of this issue of **Building Performance**, and there is a detailed contents list on the Radiance Web site **http://radsite.lbl.gov/radiance/**.

The response from readers has, so far, been very favourable. The majority were experienced Radiance users who had placed advance orders; the release of the book had long been anticipated. For this group, the book fulfilled several functions. First and foremost, it became the standard reference, containing the answers to a great many questions. Secondly, it served as a guide to "good practice". The tutorial and application sections contain plentiful examples from which even the most experienced user can learn. Lastly, the chapters on calculation methods, intended principally for researchers, provide a deeper understanding of the system and describe the key algorithms and their relation to rendering parameters.

However, the group that have most to gain from the book are newcomers to Radiance, for whom it is a definitive learning resource. With this book as a guide, newcomers will be spared much of the frustration that past users have experienced on the way up the Radiance learning curve. In fact, because both Radiance and Linux are freely available, learning how to use Radiance at home is a practical option: the only cost investment (beyond a PC) is the price of the book. This makes Radiance one of the few professional simulation toolkits that can be learnt, and used, at home without licensing costs.

Future developments

It is more than likely that the Radiance user-base will continue to expand, both in research and in practice. There are Radiance-based packages and systems that link with Radiance currently under development, and more can be expected in the not-too-distant future. Now that the dynamic calculation of daylight has been demonstrated, the linking of Radiance to dynamic thermal simulation models is an area that needs to be developed. (This was discussed in an article by Joe Clarke and Milan Janak on pp21-3 of **Building Performance** issue 1).

Work on Radiance is also being continued by the originator, Greg Ward Larson, who now works for Silicon Graphics. In addition to minor bug fixes and enhancements, Greg has developed some new visualization tools. One is a previewer that uses OpenGL (SGI's 3D graphics toolkit) to enable interactive walk-throughs of Radiance scenes with local lighting for checking geometry. A more advanced visualization tool employs a "holodeck ray cache" to enable interactive walk-throughs of complete lighting simulations, which can be computed in real time on one or more processors or precomputed in batch mode beforehand. This is like a "super-rview" program, called "rholo," which permits one to move about freely in the simulation, never losing any of the ray samples that have been computed. The calculation process may also be replaced, so that the ray computation could take place on a massively parallel computer or other specialized hardware. Greg hopes to release this as freeware later this year.

The modelling of complex materials, such as prismatic films, with Radiance is an important area of research. The system has the capability to model materials based on empirical bi-directional reflection transmission distribution properties. However, these quantities are only just being measured, and their use in Radiance is not straightforward.

Radiance in practice

*Views from David Baker of **CBS Simulations** and Jeff Shaw, Darren Woolf and Anne Selby-Smith of **Ove Arup & Partners***

CBS Simulations

CBS Simulations Limited is an independent consultancy which provides specialist simulation services to the building industry. We aim to provide creative building solutions by use of engineering judgement, supported by a wealth of information to be acquired through computational simulation. Radiance is just one of a range of tools we use for building environmental analysis.

Historically, CBS Simulations has used Radiance primarily for daylight factor analysis, solar shading refinement, solar penetration tracking and artificial lighting simulation, running on PCs under Redhat Linux 5.1. Very little use has been made of the photo-realistic visualisation, with the exception of a fly through video. The few perspective images generated have mainly been a by-product of other models, created by making minor modifications to surface finishes and view points. Generally there is very little or no funding available within tight project budgets for high quality perspective graphics, the emphasis being on the production of engineering and technical information in a timely manner. The provision of engineering information is one of the main reasons we use Radiance.

To the beginner, Radiance can be very daunting to use. The problem is not particularly the complexity of the software, but knowing where to start. There is minimal pre-defined structure or methodology imposed on the user and the resulting flexibility can be a hindrance at first. As experience with the software grows this is a bonus, but for a novice it can detract from project objectives. This means that to make Radiance commercially viable you have to be fluent in its use and application.

Until the advent of the Web site, and more recently the book, finding concise information on Radiance was piecemeal at best. Tutorials and demonstrations of functions in action are probably the most useful sets of information published. The online manual, as with all Unix packages, are only helpful once the subject is familiar.

Once mastered, the strengths of Radiance by far outweigh the initial difficulties. One of the most important issues to CBS's clients is that the software is validated. Also taking on a varied range of projects the geometrical flexibility provided by Radiance is vital. Simulations incorporating both daylight and artificial lighting schemes are a common requirement and this is simply undertaken providing a realistic interpretation of the real building environment.

Future improvements to Radiance could include an interface (though the *trad* interface is very useful). However user-friendliness can be a double-edged sword if it limits the inherent flexibility of the software by masking some of the features/ technical issues from the user.

Ove Arup

Building Engineering Group 4 is a medium-sized division of Ove Arup & Partners staffed by around 50 electrical, mechanical, structural and public health engineers. A large variety of projects are undertaken including office and retail developments, art galleries and museums.

Recent Radiance projects include the Rothko Chapel (Houston), Musee D'Art Moderne (Luxembourg), Walsall Art Gallery and some large office developments in London including Tower Place, 40 Grosvenor Place and London Bridge City. Visualization and quantitative design studies are undertaken on projects using a Silicon Graphics Indigo 2 workstation running Irix 6.2. The model building is done using a combination of up to three methods: a simple 3-D 'nodes & connectivity' generator called 'mpalm'; directly from Radiance; and importing through AutoCad.

Radiance has a wide variety of applications in Arup. These include visualisation and quantitative studies of electric and natural lighting schemes. One advantage Radiance has is its ability to accurately analyse the behaviour of light in models far more complex and irregular than any other computer design tool can cope with.

One application we have been using Radiance for recently is shadow (movement of shadow over a site) and sunview (view of the site from the sun's viewpoint) studies over typical chosen days (e.g. the equinoxes and solstices). Although this can be completed using a number of alternative programs, the ability to 'user program' enables job specific development on the quantitative design side using Radiance. The visualization is also much more realistic.

A number of skills need to be learnt to derive the maximum benefit from Radiance. These include model building, scripting (which can be complex at times) to the post-processing 'animated sequences' side. The tutorials are quite useful but it takes quite a bit of time to understand where everything is coming from and perhaps the alternatives available. Quite often a sensitivity study of the effect of a particular parameter is useful in indicating its role in the whole scene.

The new tutorials in the book give more in depth training, and allow for a slightly simpler leaning process. Furthermore, with its comprehensive index, the book is very useful as a tool (that did not exist before) for looking up advice on specific aspects of Radiance when a puzzle or problem is encountered. The book is also written in a language that is easier to understand by the inexperienced user than the original manual pages. That said, Radiance still has a steep learning curve.

Newcomers to Radiance would be well advised to go through the tutorials in the book in some depth, as they do demonstrate the use of the programs well. An understanding of the properties and behaviour of light and daylight is essential also, to allow meaningful studies to be carried out. The most is gained, however, in the long run, by applying this knowledge to real studies. As such one encounters real questions that need answering and difficulties that need solving. Even a very experienced user can learn new techniques of saving time and improving the quality of his or her output.

As for the wish list — there's not much I can think of right now. Radiance as it is is very sound. Most things we require can be achieved with time and patience. The only thing I am often searching for is better modelling techniques — AutoCAD isn't a great 3D modeller, but it is currently still the easiest program to transfer to Radiance models from. There are a few things that are missed out or difficult to find in the book also. One thing that would be nice would be an update of the manual (or a companion to it), making it more comprehensive, easier to read and giving better explanations of some of the more obscure arguments, and an explanation of the likely errors encountered.

A newcomer's view is interesting. Anne Selby-Smith, a new member of our office, has been doing some simple Radiance visualisations after having learnt from scratch using the book. She seems to have picked it all up pretty well so far. Anne says:

"I found the tutorials a good introduction - demonstrating the potential of Radiance but still understandable to a raw beginner. The modularity of the program was obvious and when I began to build my own simple models I was easily able to apply and adapt elements used in the tutorial examples.

The thing I would have liked most in addition to the information provided in the book was a brief explanation of the error and warning messages which Radiance uses. A short summarising/reference table of TYPEs and the parameters required to define each one would also be useful as an appendix to the book."

Glossary

UNIX scripts

A UNIX shell is a command interpreter. There are several available and they are largely interchangeable. Most UNIX scripts are written for the C-shell.

Octree

An octree is a compiled form of the scene files. The octree data structure is necessary for efficient rendering, and for including geometry with the instance primitive.

Linux

Linux is an operating system based on UNIX. It supports both 32 and 64 bit hardware and provides a stable multi-user operating system. Linux effectively offers a UNIX environment for a range of platforms including Intel PCs. Freeware versions are available.

OpenGL

OpenGL is a software interface for graphics hardware that allows graphics programmers to produce high-quality colour images of 3D objects. The rendering is fast but not physically-based. The (Radiance) program glrad uses OpenGL to permit interactive movement through a Radiance scene.

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All uncredited images/models were created by the author.

The first section of this article, *What is Radiance?*, is quoted by permission from the Preface to *Rendering with Radiance* by Ward Larson and Shakespeare. ■

Note: The printing process used for Building Performance cannot do full justice to the quality of this images in this article. To see them in higher quality, look at the PDF version of the journal on the CD.

The Radiance rendering is the image on the right.