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SCALE MODEL MEASUREMENTS FOR A DAYLIGHTING PHOTOMETRIC DATA BASE

M. Spitzglas, M. Navvab, J.J. Kim, and S. Selkowitz

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ABSTRACT

We present initial results of a study to produce a high-precision photometric reference data base using scale model photometry and computational daylighting prediction tools. For this study the SUPERLITE computer code was used. We illustrate the importance and difficulty of fine-tuning the scale model experimental set-up and measurement procedures to produce highly precise results. We discuss the advantage of separating the direct component of illumination from the internal reflected component as an aid to understanding discrepancies between measurements and calculations. We use results of the study to suggest the circumstances in which calculation procedures should be used to generate the references, and those in which the precise scale model photometry is the recommended technique. Future research directions in the field are described.

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I. INTRODUCTION

When quantitative evaluation of daylighting designs in buildings is needed, a designer can use two prediction methods: scale model photometry or calculation.

Scale model photometry is based on an analog simulation in which one creates a scale model of the design to be analyzed and performs photometric measurements within it. Within the history of modern lighting design, this approach would be considered a traditional method [1]. It permits both qualitative evaluation and quantitative assessment of a lighting design. As photometric measuring instruments and related data acquisition systems are improved, the usefulness of this approach expands.

Calculation methods are mathematical simulations based on the physics of photometry. Lighting calculations have been performed for many years, predating the invention of the electric light. However, in their latest form, as computer codes, these methods are evolving rapidly.

The two approaches (scale model photometry and calculation procedures) compete in accuracy and convenience of application. This leaves some potential users uncertain about which method to use. This work is intended to clarify the relative strengths and weaknesses of each approach for daylighted spaces.

Scale model photometry has the theoretical potential to deal with almost any design case, limited by the proficiency of the model builder and the availability and accuracy of photometric instruments. While computer codes are improving constantly, they have some basic limitations. First, as building designs become more complex and detailed, with increasing numbers of building elements, codes for daylighting design rapidly reach the upper limit of their capacities in terms of time required to input large numbers of surfaces and computational time needed for such geometries. Thus the practical use of computer codes is limited to relatively simple designs. Second, most available programs cannot model surfaces that have specular or semispecular (nonlambertian) reflectance properties.

This study is an initial step in an ongoing effort to help answer the questions:

* What are the relative strengths and weaknesses of experimental scale model photometry and of calculation methods in various

applications?

* Is scale model photometry presently the only tool that can provide accurate quantitative prediction in some design situations?

* What are the tolerance penalties of extending the use of calculation methods beyond their limits?

* Once a calculation method has been validated for a particular design case, over what range of design variations can it be considered an valid evaluation tool, and how do we define the range of these similar designs?

The ultimate objective of this study is to provide daylighting designers with guidelines for determining which tool will be most efficient under specific design circumstances. To achieve this objective, we are creating a reference data base to validate daylighting evaluation tools. We suggest the following approach, which utilizes a coordinated set of measurements and calculations:

(1) Determine and define the design forms and details that a tool will cover.

(2) Apply initial scale model measurements to only the simplest of the forms. Complete initial parametric computer simulations.

(3) Analyze measured results. Perform sensitivity tests and measurements. Suggest basic improvements in experimental set-up and computer runs.

(4) Repeat the measurements and calculations to resolve discrepancies.

(5) Use the computer program(s), within validation boundaries, as data base generator(s).

(6) Proceed to more complex design forms, following the previous process of repetitive analysis and measurements until satisfactory convergence is reached.

(7) After the final experimental photometric measurements and overall data sorting and analysis, rearrange the computer-generated database components into a complete picture, systematically covering the range of variables in which users may be interested.

(8) Prepare a set of guidelines for designers as to: a) what tool is preferable in specific design circumstances (the type and complexity of the geometry involved), and b) what tool will work best in terms of information needed and the tolerance allowed within the application.

This report presents results from elements of the first four steps in the above plan. This represents an initial quantitative inquiry into the problems of using scale model photometry to create an experimental data base.

II. THE EXPERIMENTAL METHODOLOGY

Strategy of the Scale Model Approach

Within the limitations of the existing experimental infrastructure (see figure 1), our goals were:

* to reduce the photometric "risks" by reducing and simplifying the modeling parameters;

* to maximize the density of the measured information;

* to simplify the translation of scale model geometric properties into computer program inputs; and

* to conduct the measurements so as to facilitate analysis by making it easy to identify the contributions of the different variables and illuminance components.

Planning the Measurements

The computational algorithms of most daylighting calculation programs treat the direct component of daylight (the flux initially entering the space through the window) separately and differently from the way they treat the reflected component (the contribution to illuminance levels due to the bounces of the initial flux between the surfaces of the enclosure).

Thus, a generic property of a calculation tool is its capacity to account separately for the direct component contribution to light levels and the reflected component contribution. We therefore designed the experimental process to similarly distinguish between direct and reflected component data. Since photosensors inside a scale model respond to all the incident flux, without distinguishing its origin, we make the separation by taking two sets of measurements, once with the desired room conditions and again in a "black" room with a direct component only. The "black" room is achieved by utilizing very low-reflectance textures and by manipulating the geometry of the space to produce as small a reflected contribution as possible. The reflected component in a space with non-black walls is then obtained by subtracting the measured direct component in a black room from the total in the non-black room of the same geometry.

We built a scale model having a highly absorptive interior (reflectivity = 1.5%; see figure 2, Model A). Model A represents the type of space defined by the dimensions of Model B, the same window wall (figure 2), except we enlarged the height and width of the space by a factor of three, thus significantly enlarging the area of the interior without interfering with the geometry that affects the direct component. This situation ensured further reduction of the reflected component so that the total measured light level will be as close as possible to the basic definition of the direct component.

Illumination Conditions

To simplify the daylighting conditions and avoid introducing additional parameters, we used uniform sky conditions in this phase of the work. Because high-precision modeling of an infinite, uniform ground is complicated, we simulated a 100%-reflective ground. This means that, under uniform sky conditions, the visible flux reaching the vertical window plane from directions under the horizon is of the same intensity and directional distribution as the flux originating from above the horizon. In other words, there is a uniform luminance seen from the window surface within the full hemispherical field of view. These illumination properties were achieved in our sky simulator by aiming the windows of the scale models toward the zenith of the simulator. All the scale model measurements reported in this paper (except the courtyard measurements) were taken in this way.

Rationale Behind Selected Measurements and Their Sequence

The basic approach to the measurement and calculation comparison is given below:

* Direct Component Comparison:

  Test the capacity of the experimental set-up to generate data on the direct component of illumination for one specific window size and compare it to the calculation code (figure 3). The calculation code, the SUPERLITE program, was tested previously against the analytical formula (Ref. 1, p. 109) and was proven to generate precisely the same results for this component of illumination.

  Test the capacity of the experimental set-up (and compare to the calculation code) to generate data on direct component of illumination with changing window dimensions (figure 4).

  Increase the complexity of the window element by adding outside (nonreflective) overhangs (figure 5).

* Reflected Component Comparison:

  Test the capacity of the calculation code for different interior reflectances and window sizes; examine the effect of the number of iterations on the calculation (figure 6).

  Increase the geometric complexity of the inner space by adding partitions (figure 7).

  Increase the complexity of outside elements by adding reflective, well-type skylights (figure 8).

* Exterior Reflected Components:

  Measure light level distributions inside a space facing a courtyard, given different courtyard reflectance properties and different overhangs on the window (figure 9).

III. THE SCALE MODELS AND CALCULATION METHOD

The Scale Models

We designed and constructed four scale models, each simulating different daylighting design conditions. All the dimensions are given in modular terms (1 module ≃ 3.5 cm).

- Model A (figure 2): An expanded rectangular space (dimensions: 21 x 28 x 21) having highly absorptive (ρ = 1.5%) interior and one vertical exterior wall that can accommodate windows of dimensions 1 x 1, 5 x 4, or 7 x 10.

- Model B (figure 2): A vertical window that supplies daylight to a deep longitudinal space (dimensions: 7 x 28 x 7). A variety of optional overhangs can be attached to the window. Interior partitions can also be added, and interior reflectance can be varied.

- Model C (figure 2): A square floor space (16 x 16 x 8) with a square (in-plan) skylight (4 x 4). The depth of the skylight well can be varied (0, 2, 4, or 6).

- Model D (figure 2): A smaller rectangular space (9 x 10 x 5), the front window of which faces an external courtyard (32 x 32) having interchangeable reflectance properties, allowing us to study the external ground-reflected component.

Several specialized photometric test facilities were used in this work, including:

o A 24-foot-diameter sky simulator [2] that uses a computer-controlled array of 120 fluorescent lamps to produce a uniform luminance distribution, providing average sky luminance of 1750 cd/m^2 (figure 1). (The facility can also produce standard CIE overcast and clear sky luminance distributions).

o The primary photometric instrumentation in the models is an array of 40 silicon photodiodes (with cosine and photoptic correction), a multi-channel scanner with microvolt resolution, and a computer to collect, analyze, and store data. The photocells were calibrated over their operating range using Tektronix Model J6511 and Spectra Pritchard Model 1988A illuminance meters.

Design and Construction of the Scale Models

The models were designed as small as possible to limit expenses, maximize ease of handling, and optimize the use of the simulator (its simulation properties improve as the size of the model decreases). The limiting parameter in this case is the dimension of the standard Licor photocell [3]. The diameter of its face is slightly less than 2.5 cm (the diameter of the light-sensing diffuser on top of it is approximately 0.6 cm). Therefore, we decided that the size of the basic module, which defines the dimensions of the scale models, would be 3.5 cm, only 1 cm larger than the diameter of the photocell face. We use consistent modular dimensioning of the scale models for all of the surfaces: walls, floors, ceilings, windows, and shading elements. Thus dimensions are defined numerically without specific units.

All dimensions are defined in terms of interior envelope dimensions. The models' interior surface materials can be replaced to vary reflectance properties. To avoid calculation problems related to modeling wall thickness for the window facade, we used thin crescent-board material (0.2 cm). Even for the smallest window, the ratio of the smallest dimensions of the opening to the wall thickness is 17. For the 4 x 5 window, this ratio is 68. The primary photometric measurements are made in the horizontal plane along the center line of the model, perpendicular to the window facade. This divides the model into two symmetrical halves. In the case of the skylight model (Model C), the sensors are arrayed along the diagonal of the square model.

The faces of the photocells were placed flush with the bottom of the model so that the photocells and cables would not interfere with the visible flux distributions. In this case, the bottom surface of the model represents the work plane surface rather than the floor surface.

The model surfaces were gray in color to avoid unbalanced spectral reflectance. The surfaces have highly diffuse reflectance properties; the bidirectional reflectance of the surface finishes was tested to ensure those properties. Because textures of 0% reflectance do not exist in practice, there is no experimental technique to directly measure the direct component of illumination with no trace of interreflected light. The lowest reflectance we could provide was ~ 1.5%. We achieved those surface properties by distributing a highly oxidized carbon powder over an adhesive surface.

The Calculation Tool

For this work, the computer program SUPERLITE [4] was used to represent daylighting calculation codes. A brief review of the characteristics of the SUPERLITE calculation process, which is representative of many illuminance models, reveals the potential sources of error in any computational model:

* Rooms are defined as a series of planar surfaces. Each plane is divided into a finite number of grid elements, each of which is assumed to be of uniform luminance. Their size can be user-defined.

* The direct illuminance on each surface due to exterior light sources (sky or sun) is calculated for the center points of the grid elements. These calculated light levels are applied uniformly to the total area of the particular element. For grid elements that lie close to the windows (where the initial light level distribution changes rapidly), this assumption of uniformity over the element may create calculation errors, depending on the size of the grid elements, their orientation, and the distance between them.

* The initial flux distribution incident on each surface from the window(s) serves as the starting point for further calculations of the internally reflected component. The program's algorithms assume the surfaces to be perfectly diffuse (lambertian reflectors). Light-exchange factors are calculated between each pair of grid elements on surfaces that "see" each other.

* The light flux bounces between the surfaces many times. The amount of flux remaining after each bounce declines exponentially according to the coefficient of reflectance. To control execution time, the user limits this process by defining the number of iterations, or bounces to be calculated. This limitation is another source of possible error. In most cases, the higher the number of iterations the more precise the predicted reflected component, particularly for high-reflectance surfaces. However, the starting point for the iterative interreflection calculation is the incident direct flux from the windows. If that value is incorrect, increasing the number of iterations for the interreflected calculation may lead to an incorrect final answer. We conclude that:

1) Calculated values may over- or underestimate light levels; the calculation procedure has no obvious bias in this respect.

2) Increasing the number of grid points and iterations improves calculation of the interreflected component and usually, but not always, provides an answer that more closely approximates the correct value.

IV. RESULTS AND DISCUSSION

Direct Component

We first compare measured and calculated results for the direct component in a simple room enclosure. Model A was designed to reduce as much as possible the relative magnitude of the reflected component in the overall illuminance readings from the interior photocells. Interior surfaces were covered with a diffuse low-reflectance ($\rho \simeq 1.5\%$) coating. The dimensions of the upper enclosure were enlarged (21 x 28 x 21 volume, representing a 7 x 28 x 7 space). The window is 4 x 5, which represents $\simeq$ 40% open area, relative to 7 x 7 facade. No glazing was used in this or any model (see figure 2, Model A).

We used the SUPERLITE program to estimate the magnitude of the remaining reflected component. Although this program is also used for the comparative evaluation, we use it because there is no practical way, in

scale model photometry, to completely eliminate a reflected component. However, we expect the reflected component to be very small because even the first bounce of internal visible flux is of an extremely low magnitude due to the low surface reflectivity.

The results of evaluating the residual reflected component are presented in figure 3a. The logarithmic vertical scale makes this calculated reflected component visible in spite of its small magnitude. We observe that at the deep end of the space there is less than 0.0001 daylight factor (DF), which corresponds to a measurement of 0.005 lux, less than 0.1% of the total measured illuminance at this point.

Those absolute values are well below the resolution of our instrumentation; we conclude that for this study the internally reflected component is negligible throughout the model. In practical terms, we may say that our scale model set-up has no measurable reflected components, providing an almost perfect measurement of the direct component.

With the same experimental set-up (with absorptance ρ = 1.5% for inner surfaces), in figures 3 and 4 we subtract the reflected calculated component, although clearly it has only symbolic meaning. Figures 3a and 3b show good fits between calculations and measurements of the direct component. The primary difference is in the front part of the space adjacent to the window, where measured values exceed the calculated by as much as 2% DF, a subject for future investigation.

We frequently provide results twice, using a logarithmic scale in addition to the linear scale, to make small differences more visible. However, we also magnify small "local" differences between the measured and calculated data sets by providing the relative local differences between these two data sets. The relative difference (RD) of the direct component in this case is defined at each measurement point in the space as

$$RD = \left[\frac{DM - DC}{TM} \times 100\right] \%$$

where:

RD = relative difference,

TM = total measured,

DM = direct measured, and

DC = direct calculated.

(Note that the normalization is to the total measured daylight factor.)

Figure 3c shows the relative difference between the measured and calculated data. Except for the two first photocells, the range of deviation is bounded within +12% and -15%. We assume that the relative difference is a combination of some degree of systematic error in the computational portion and random and/or systematic error in the measurements. Some of the seemingly random fluctuations that are superimposed on what should be a basically smooth function appear to be consistently repeated in other measured results. These might be due to two features of the

experimental set-up, since we know that in the case of the direct component, SUPERLITE-generated results are the absolutely correct reference:

* Small misalignments in the horizontal leveling of the photocell faces either because of imperfect mounting or imperfections in the photocell geometry. As surface illuminance is proportional to the cosine of the angle between the incident visible flux and the flux perpendicular to that surface, illuminance readings deep within the space are particularly sensitive to horizontal misalignments because flux from the distant window reaches the photocell surface from low angles. For examples, for an incidence angle of 85° a misalignment of $\pm 2°$ will result in an error of $\pm$ 40%. For an incidence angle of 65° the situation is less critical, but $\pm 2°$ misalignment will still create an error of $\pm$ 7.5%.

* Individual calibration factors for the photocells. As the silicon photocells in the Licor sensor are not identical, they must be calibrated individually. The calibration factors for the photocells are not perfectly linear over the full range of response, so the linear fits that were chosen are slightly off from the true values. However, these errors are consistently less than 3% except at the lowest end of the measurement range (< 5 lux).

If we use a smooth curve to approximate the relative difference based on actual measured data, as shown in figure 3c, the calculated results underpredict the measured data in the front of the room (the first four units), overpredict in the center of the room, and agree within a few percent in the back third of the room. Because the function of direct illumination changes so rapidly in the front third of the room, a slight shift in the measurement location relative to computational points could explain portions of these discrepancies.

In the back of the room, we note that the relative differences of ± 10 - 12% represent absolute measurement differences of less than 1 lux in a model in which illuminance levels in the front of the room exceed 600 lux. Approximation of curves of constant Δ illuminance are superimposed on figure 3c. We are thus looking at: a) differences that approach the calibration factor deviations explained previously, and b) differences that have little or no effect on the practical lighting design of a real daylighted space.

In future work, we will try to unequivocally establish the sources and magnitudes of the possible errors in these comparisons. We note once again that this pursuit is of largely academic consequences; the differences are small in the context of most practical applications.

Changing Window Dimensions

Figure 4a and 4b show measured and calculated results for a very small window (1 x 1, or 5% of the area of the 4 x 5 window), and a larger window (7 x 10, or 3.5 times larger than the 4 x 5 window). The curve for the 7 x 10 window has a monotonically decreasing negative slope because the window begins at the level of the photocell. Both the 1 x 1 and 4 x

5 windows have sills 2 units high, causing the function for illumination levels to reach a maximum before starting its decline towards the deep part of the space. Figures 4a and 4b show good agreement between the measured and calculated light levels. In figure 4c, we show absolute differences between calculated and measured results for the three windows. The small window shows good absolute agreement over the entire room. The large window shows differences in the front quarter of the room that have a maximum deviation of -1.3 DF%, while the deviation for the intermediate-sized window ranges from +2.2 DF% to -0.6 DF%. These deviations will be studied in depth when we investigate the responses of the front photocells. In the back half of the room, the agreement for all windows is good, never exceeding a difference of 0.2 DF, or about 10 lux.

We conclude that, from a practical perspective, the computer model does a good job of predicting the direct component of illumination from a window of variable size in a simple rectangular room. The experimental set-up also performs well except for the front photocell deviation, an issue that will be further explored before proceeding with the rest of this study.

Addition of Outside (Nonreflective) Overhangs

In many building designs, exterior shading elements are utilized to control daylight and sunlight. Nonreflective (ρ = 1.5%) overhangs, fins, and louvers partially obstruct the view of the sky from interior points. Using the 4 x 5 window in a room having nonreflective surfaces, we examined the magnitude of the reduction in the intensity of the direct component.

In figures 5a and 5b the measured data demonstrate that adding outside devices significantly affects the direct component of interior light levels. (Compare results with those shown in figure 3.) We plot the base case room with the 4 x 5 window and no shading devices. The remaining four curves show the results for each shading system. We show measured results (figures 5a and b), calculated results (figures 5c and d), and the absolute difference between measured and calculated results (figure 5e). Several conclusions can be drawn from the data.

In both measured and calculated results, the curves for systems A and C track each other very closely. This is expected since the shading elements are not reflective and the photocells in the models have no direct view of the lower shading element. Recall that only light incident from the upper hemisphere should affect the photocell reading. The curves for systems B and D lie together in the measured case and the calculated case. Both B and D have substantially lower light levels than the first two.

The absolute difference shown in figure 5e suggests that the four shading systems follow the pattern of the bare window: the calculated data underpredict results in the first four to six modules of the space (by less than 1.5% DF), unpredicts by a smaller (less than 0.6% DF) amount over the next five modules, and shows close agreement over the back two-thirds of the space. This suggests that the computer model does a

good job of predicting the obstruction effects of black shading elements. The next step is to raise the reflectance of the shading elements to more realistic levels. In this case, the measured data (not shown here) are increased, but never (with a diffuse sky) beyond the value associated with the bare window. To adequately model higher-reflectance shading systems, a computer model must determine interreflections between the elements. These calculations are in progress.

Reflected Component

To study the interior reflected component, we use model B (see figure 2) with the 4 x 5 window, but install interior surfaces having much higher reflectances. In one case all interior surfaces have ρ = 86%, and in a second case have ρ = 50%. The measured reflected components were derived by subtracting the direct measured from the measured total. For reflective interiors, the SUPERLITE program was run with various numbers of iterations. Results show that the accuracy of the calculation depends on this user-defined input. This input also affects the computer-run time and required memory.

The number of iterations required to converge to the correct solution is sensitive to the design features of the analyzed case, as can be observed in the following example. Figure 6a (with a 4 x 5 window and ρ = 86%) shows a small but noticeable change when the number of iterations is increased from 15 to 20. However, when the reflectances of interior surfaces decrease (as in figure 6b for a 4 x 5 window with ρ = 50%), as few as five iterations are sufficient. The difference is insignificant when we increase the iterations from 5 to 10, as shown. This tendency was expected because as reflectance drops, the remaining flux after each bounce declines ever faster, so the number of bounces that must be calculated to provide the same level of accuracy also declines. In realistic room designs having low floor reflectances the results will converge even more quickly.

Based on additional measurements of this type, we expect to make recommendations as to the number of calculation iterations required to achieve a given level of accuracy for reflected component as a function of model features and interior reflectances. Comparing figures 6a and b to figure 3b illustrates the relative importance of the reflected component. With 86% reflectance, the reflected component dominates throughout and represents 80-90% of the illuminance in the back two-thirds of the space. (Recall again that the window is illuminated by a uniform sky and ground, and that ρ = 86% for all interior surfaces). With 50% reflectance, the direct and reflected components have approximately the same magnitude throughout the space.

The relative differences between the calculated and measured data are shown in figures 6c and d. We observe a randomly fluctuating component, which appears in a similar pattern for the two cases. This suggest that the random component is due in part to the imperfections in the measurement procedures mentioned earlier. When a smooth function is fitted to these data, it is easier to observe trends (figures 6c and d). As the reference point is moved back from the window, the smoothed functions have a similar slope. These results suggest that the calculations tend

to overpredict illuminance near the front of the room, but improve deeper in the space. The overall agreement in the high-reflectance case, usually the most difficult problem, is very good, in the range of -10% to +4% relative difference. The somewhat greater difference is with 50% reflectance. The fluctuating pattern of this difference is similar to the one for the direct component (see figure 3c). This again indicates a consistent imperfection in our experimental set-up. The smoothed function here indicates that the calculation tool overestimates the reflected component range by 8 to 16%, an acceptable range for most design applications.

Models Having Partitions

To create additional geometric complexity in our design base case, we added various partitions within Model B. The three partition designs and the corresponding reflected component of the illumination level are shown in figures 7a, b, and c. Observed results indicate that the calculated values of the reflected component agree nicely with the measured values in the deeper part of the space behind the partition.

Since this model and its details are the same in front of the partitions as in the model analyzed in figures 6b and d, the front part of the space responds photometrically in almost the same way. The calculated reflected component values consistently overestimate the measured value by about 5 to 15% (figures 7d, e, and f). In the deep part of the space beyond the partition, the agreement between the calculated and measured value is surprisingly good. The absolute and relative differences can be seen in figures 7g and h. The presentation in figure 7h magnifies the small differences shown in figure 7g. With the exception of the points adjacent to the partitions, most of the data lie within the range of 20% relative difference, including the random fluctuations discussed previously. As the basic function in this region is almost constant, we may easily evaluate the corresponding deviation (in terms of measured illuminance levels) to be typically less than $\pm$ 3 lux. Modeling interior partitions is usually difficult for an illuminance calculation. In the future, we will extend these investigations using a larger variety of partition types and reflectances. However, at this point the results seem to indicate that the calculation tool evaluates the reflected component well in these difficult circumstances. Note that with all three partitions no direct illuminance component reached the deep reference points.

Skylights

We briefly examine measured results for rooms having skylights (Model C, figure 2). Our base case was a square room with a centrally located square skylight (4 x 4) occupying 6.3% of the ceiling area. Three other cases with lightwells of depth 2, 4, and 6 were also measured. The interior reflectances of the room and lightwell surfaces were 86%. In this case the incident visible flux goes through two major stages of interaction in the model, first passing through the skylight well, then entering the room beneath the skylight.

As the depth of the lightwell increases, the direct illuminance component in the space is reduced, and interreflectance from the lightwell walls becomes increasingly important. Figure 8 compares measured results under uniform sky conditions as a function of lightwell depth. As expected, the fractional reduction is largest at the edges of the space located farthest from the skylight opening. For the case with reflective lightwells, a computational model must accurately evaluate the interreflected flux that eventually penetrates the lightwell system. This generally is a difficult test for a lighting design computer model. Scale model photometry also allows one to investigate specular surfaces as part of lightwell design. Measured data for collimated illumination (not shown here) indicate a much greater variation in interior light level distribution in such cases.

Exterior Reflected Component in Spaces Facing Courtyards

In model tests and in simulation it is important to consider cases in which the externally reflected component becomes a significant factor in the daylight admittance to a built space. We first examine the situation in which the exterior ground, in front of Model D with a 3 x 7 window (figure 2) has different reflectance properties (ρ = 2.5% vs. 50%). Second, we compare the effects of the exterior ground which does not "see" the workplane directly, as interior reflectance is changed (ρ = 86% vs. 50%). We show the importance of interior reflectance to illuminance levels deep within the space. Both the absolute and relative changes, as a function of interior reflectance, are largest at the back of the space. Finally, we examine the case where exterior overhangs partially obstruct the sky component.

Figure 9 compares total interior illuminance distribution under a uniform sky with a black courtyard (ρ = 2.5%) for cases with different interior reflectances (ρ = 50% and 86%). The change in interior reflectance makes a moderate difference in the front of the room (increasing light levels about 25%) and a large difference in the back of the room (increasing light levels by a factor of almost 4). Note that this room is not as deep as those used in previous examples (e.g., figure 2).

We now change the courtyard reflectance from 2.5 to 50%. Figures 9b and c show interior illuminance levels for two values of interior reflectances, 86% and 50%, respectively. Comparing figure 9b with the 86% reflectance case in figure 9a, we note that the reflective ground raised interior levels by about 5% DF uniformly throughout the space. For 50% interior reflectance, the reflecting ground raises interior levels by about 1 to 2% DF. Figure 9b (50% ground reflectance) compares measured and calculated data for the window without an overhang. Note the good agreement between the two kinds of results.

The measured data in figures 9b and c show the effects of adding overhangs to windows. Each successive overhang element reduces illuminance levels by about the same amount. In the high-reflectance room, a window viewing a 50% reflective courtyard even with a large overhang will provide more light deep within the space than a bare window receiving no ground-reflected component. In the 50%-reflectance room, these two cases produce about equivalent results. Thus ground reflectance can

be an important contributor to interior illuminance levels. Initial comparison of our computer code to measured data indicates good agreement for the case with a bare window.

V. CONCLUSIONS

This paper presents an overall outline and initial results in an effort to use scale model photometry to validate daylighting prediction tools. Our ultimate objective is to produce a detailed photometric data base, which we propose to generate using a combination of scale model measurements and computer simulations.

This work demonstrates the beginning effort to validate a daylight prediction tool for each major illuminance component. Once such procedures have been established for one tool and a range of sky conditions, illuminance components, and design cases, the tool itself may then be used to generate a more detailed validation data base, provided it is applied within the domain of design cases bounded by the nature of the initial scale model comparisons.

For this study we utilized the SUPERLITE computer code. We have demonstrated the importance--and difficulty--of fine-tuning the scale model photometric procedure to produce usable results. The comparison is itself complicated. The differing importance of absolute and relative differences between measured and calculated results has not been fully resolved. A detailed examination of our results to date suggests several areas that require changes and improvements in experimental technique prior to the next phase of data collection. We have noted the importance of specifying the number of iterations to be used with a daylight evaluation computer code. Similar information related to the accuracy of calculation tools should be included in the manual of any newly released evaluation tool.

Although the initial goal of this work was to provide a measured photometric data base as a validation reference for simulation models, this study has enhanced our interest in using SUPERLITE to help calibrate the experimental facilities themselves. The comparison process has identified several improvements needed in the model testing. We believe that the revised scale model testing infrastructure that will be created will enable us to produce a reliable data base for the internal direct component, the internal reflected component, and the outside ground reflected component.

This systematic comparison of parametric measurements and detailed computer simulations will produce a more complete daylight performance data base. At the same time, more detailed studies of comparative results should provide additional useful insights regarding the potential of daylight utilization in buildings.

ACKNOWLEDGEMENTS

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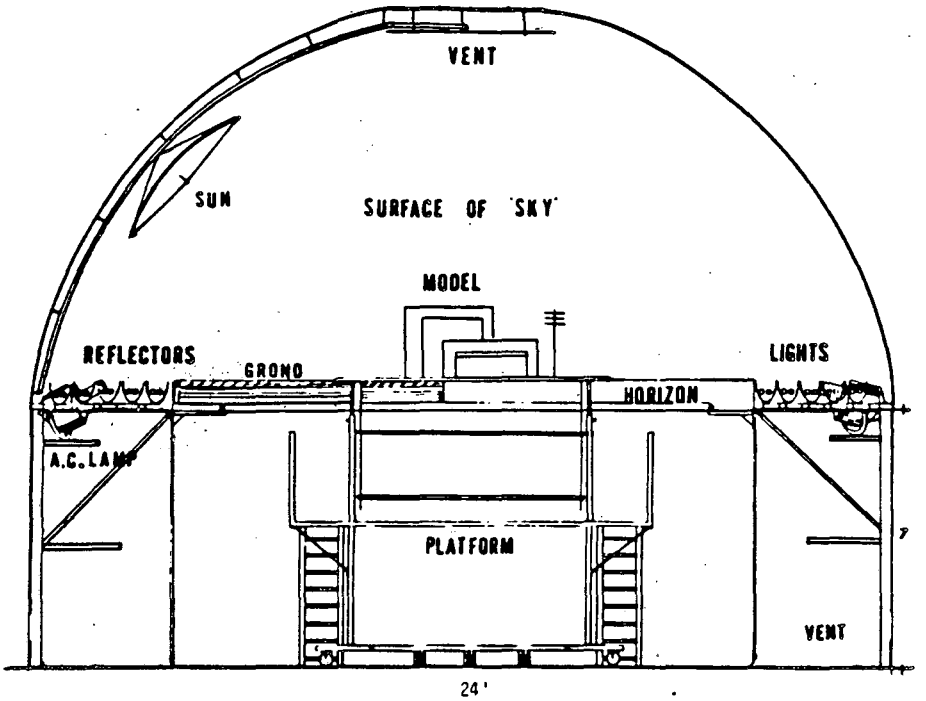

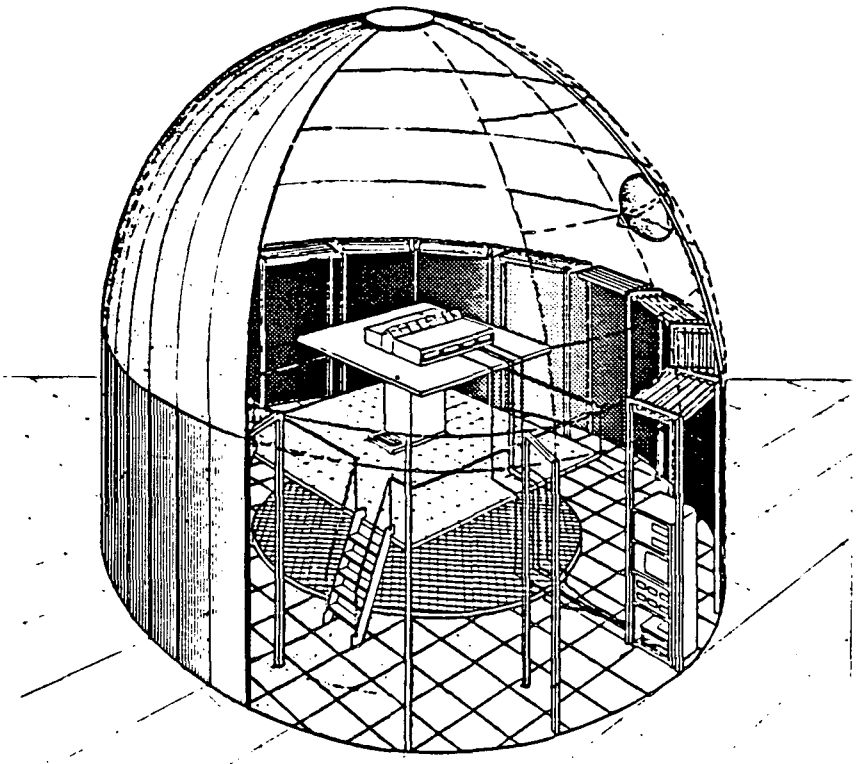

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Figure 1. The experimental facility, the LBL sky simulator.

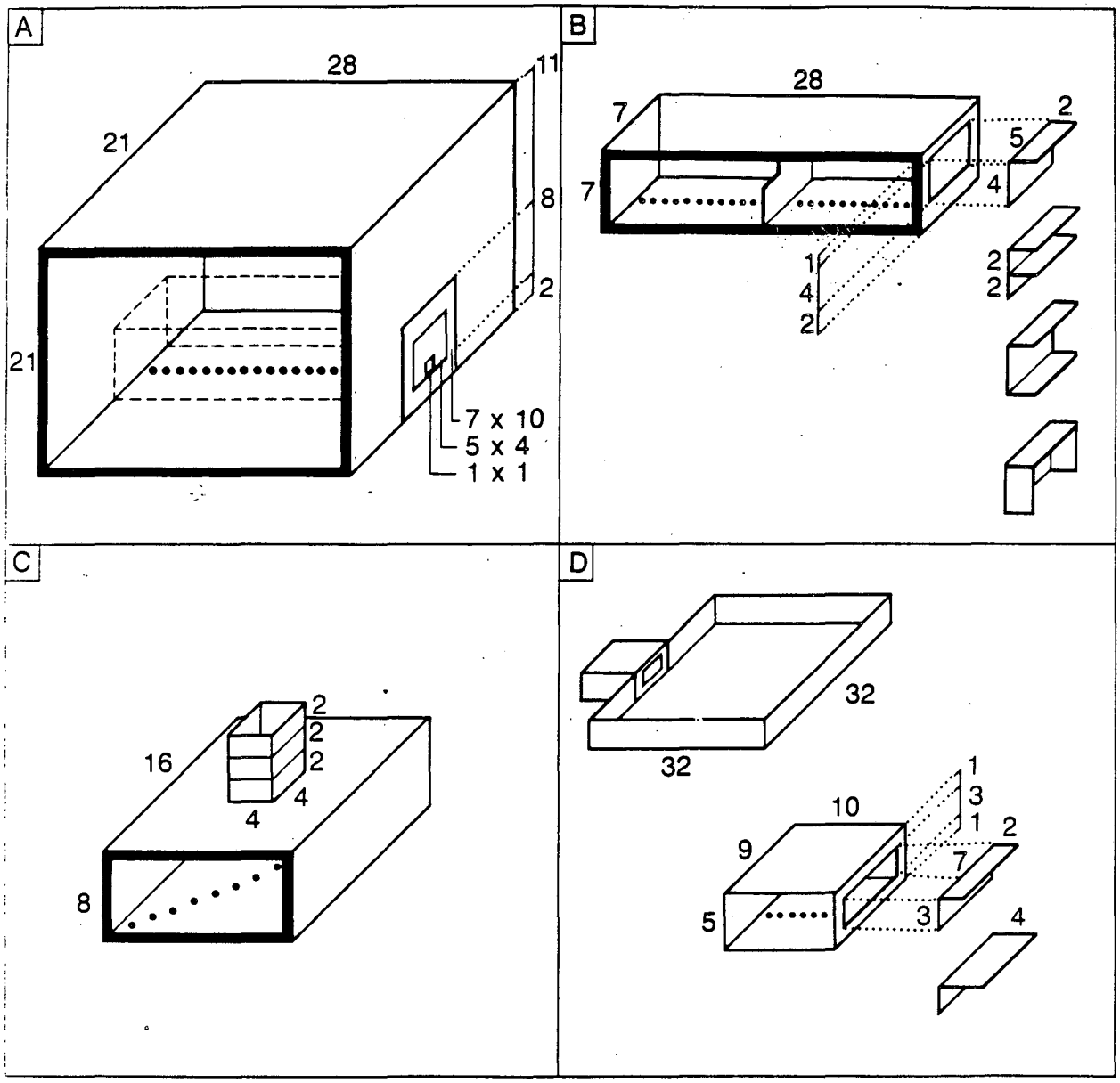

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Figure 2. Photometric scale models; dimensions are given in modules (1 module = 3.5 cm)

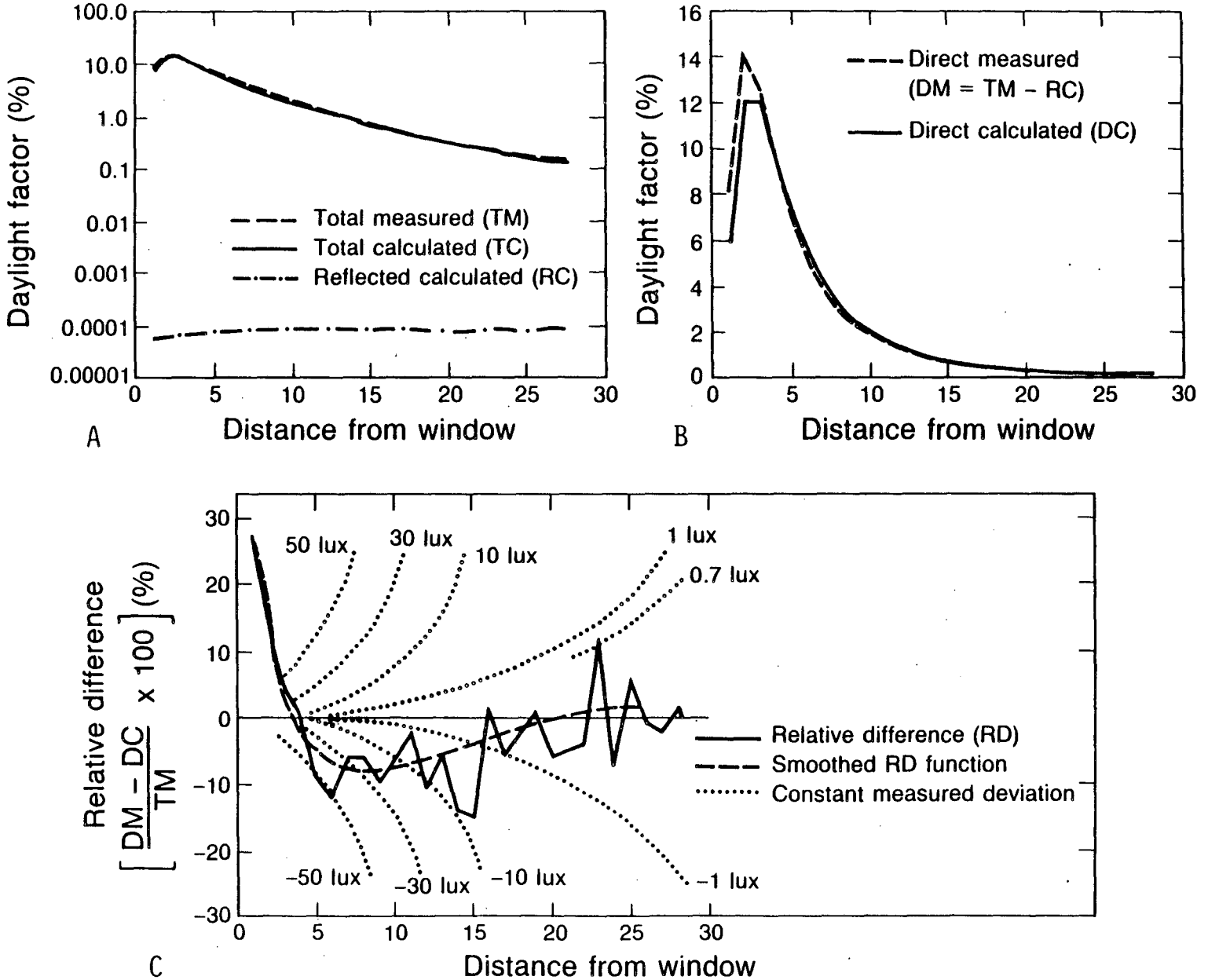


Figure 3. Validation of the direct component of illumination versus SUPERLITE program calculations. Measurements inside Model A with black texture (ρ = 1.5); 4 x 5 window.

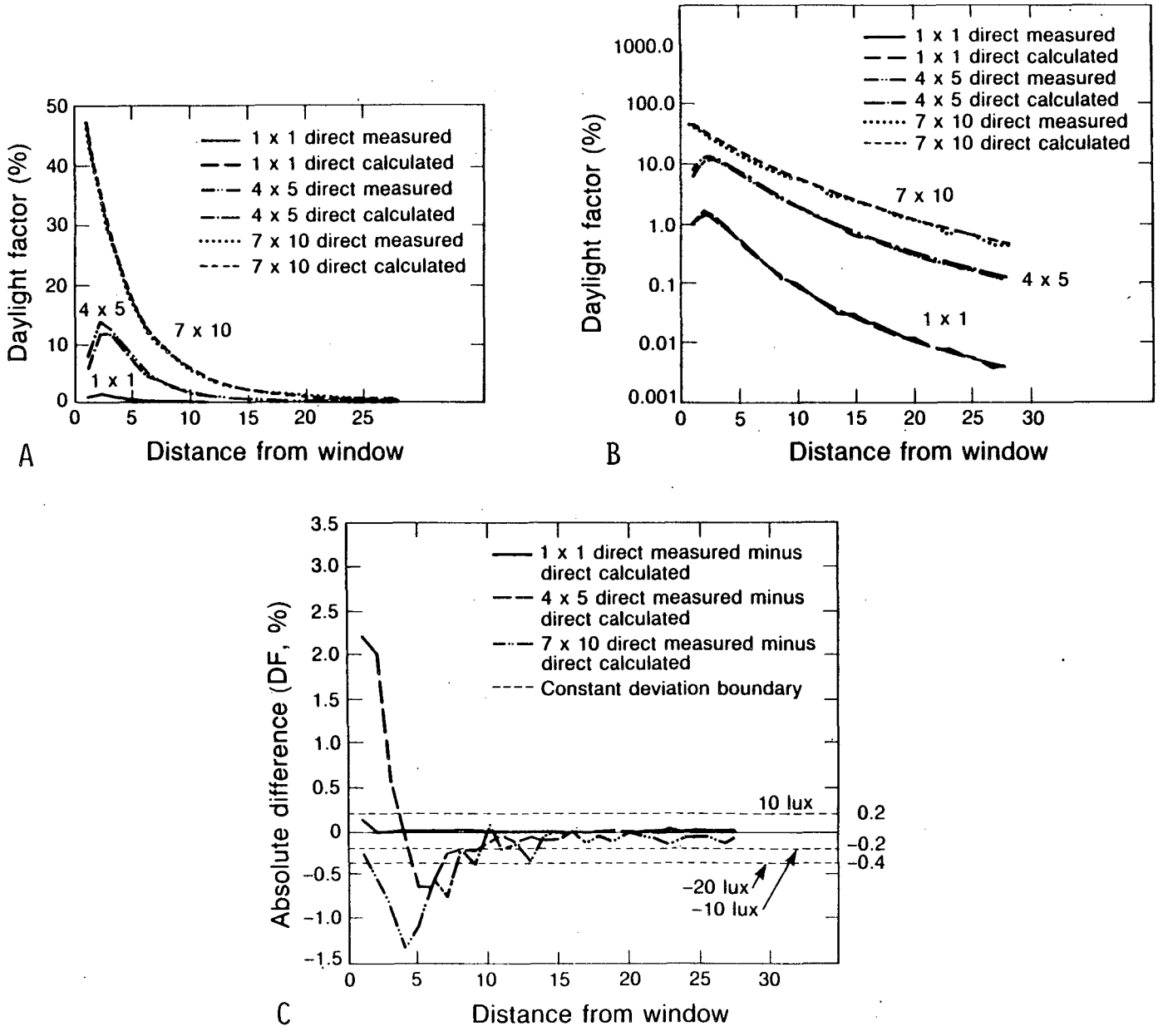


Figure 4. Validation of direct component for different window sizes, Model A.

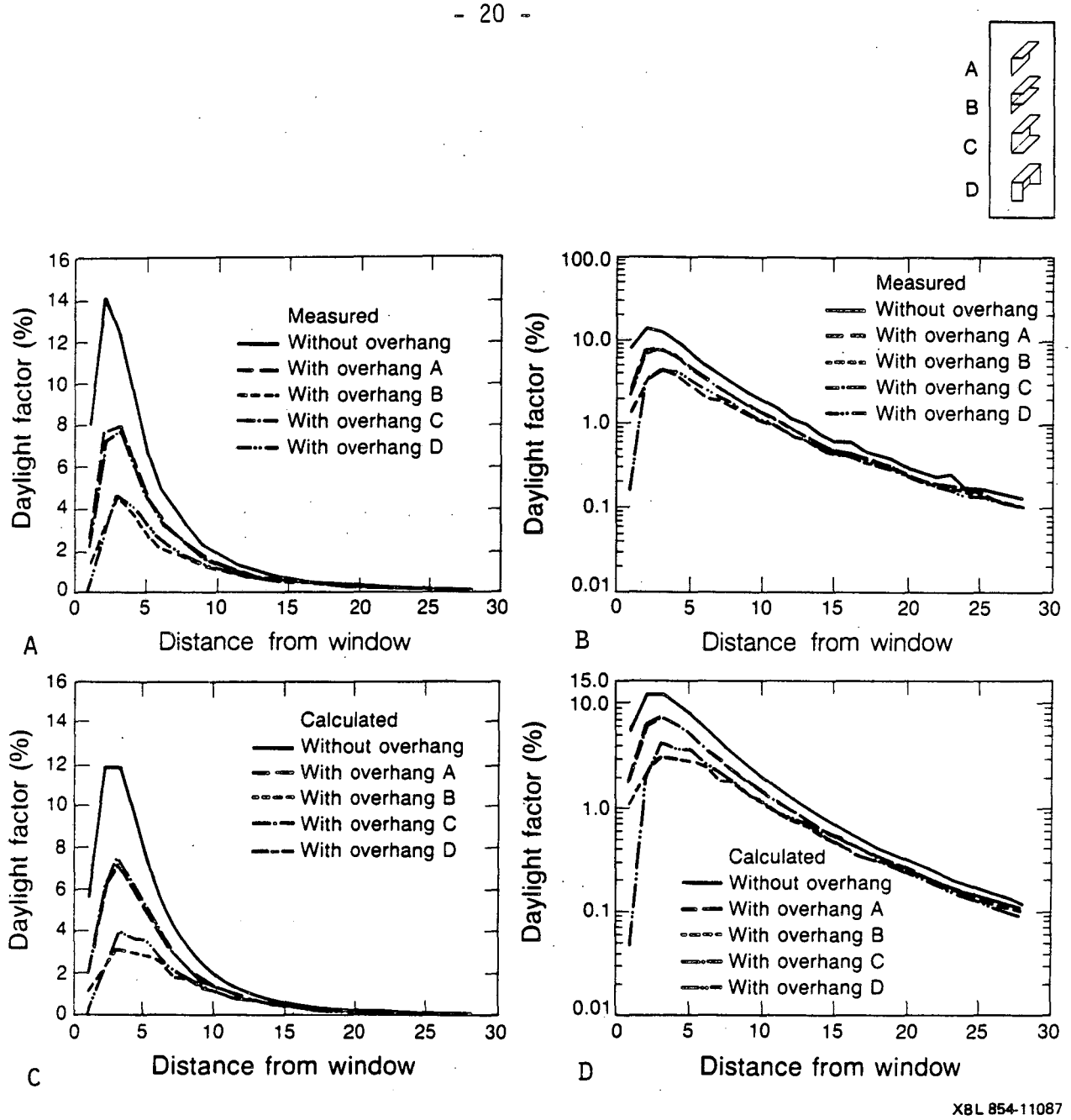


Figure 5. The impact of external overhangs (diffusive, ρ = 1.5%) on internal illumination distribution (direct component only). Measured and calculated results; Model B; 4 x 5 window.

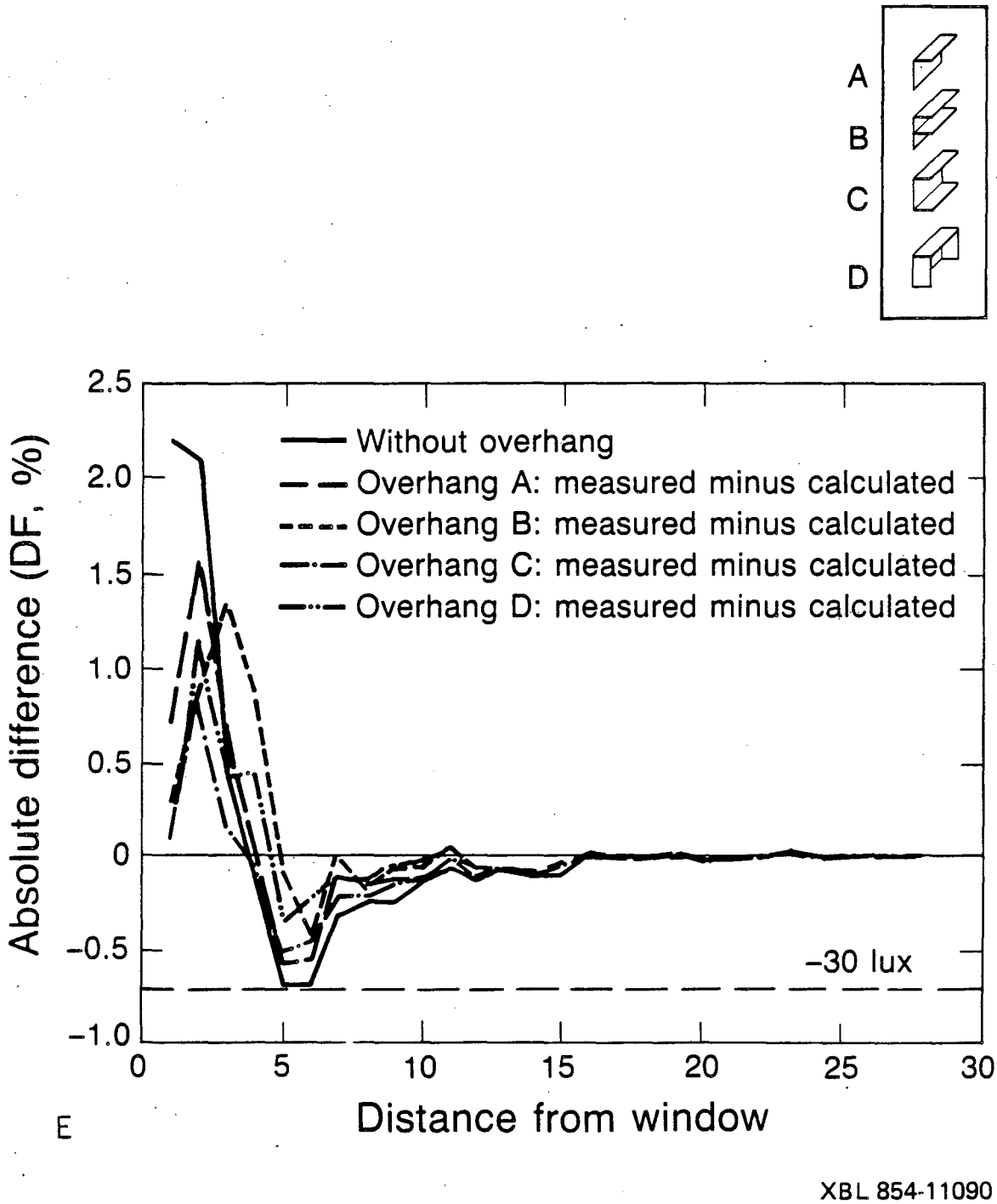


Figure 5 (continued): The impact of external overhangs: the reduction in direct component of illumination due to various overhangs. The difference between measured and calculated results; Model B; 4 x 5 window; ρ = 1.5%.

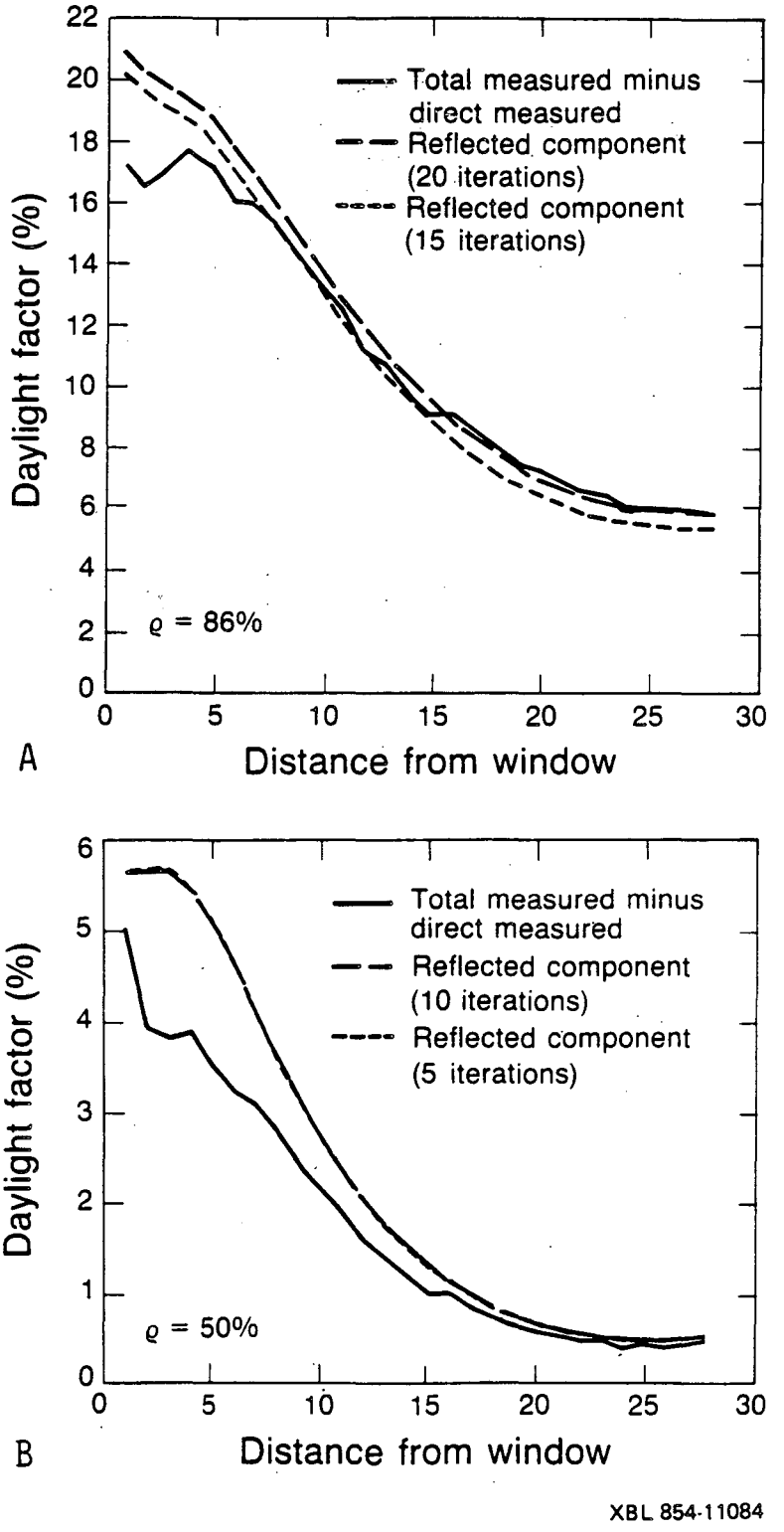
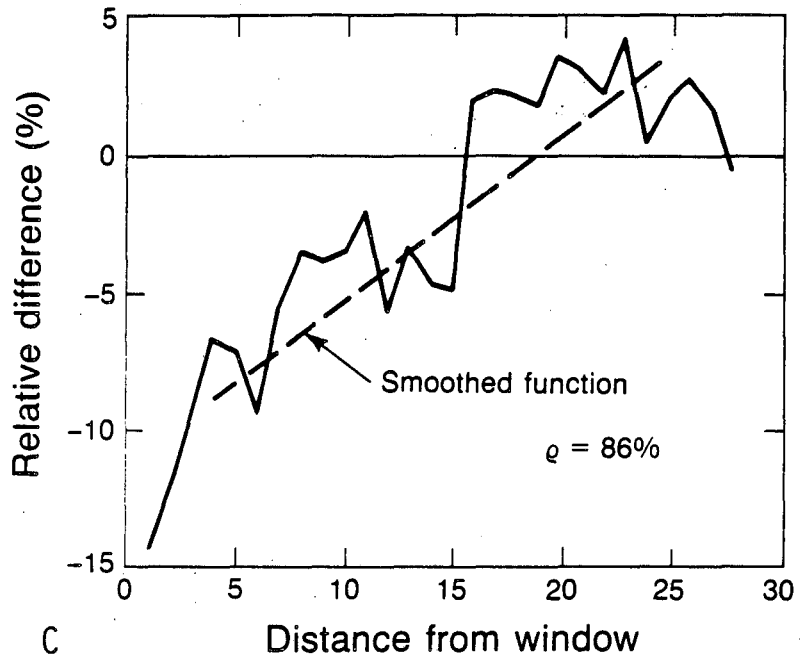


Figure 6. Illumination levels: reflected component only for interior textures of 86% (Fig. 6a) and 50% (Fig. 6b). Measured versus calculated values using different numbers of iterations for the calculations; Model B; 4 x 5 window.



Relative Difference — RD
Total Measured — TM
Direct Measured — DM
Reflected Calculated — RC

$$RD\ \% = \frac{(TM - DM) - RC}{TM} \times 100$$

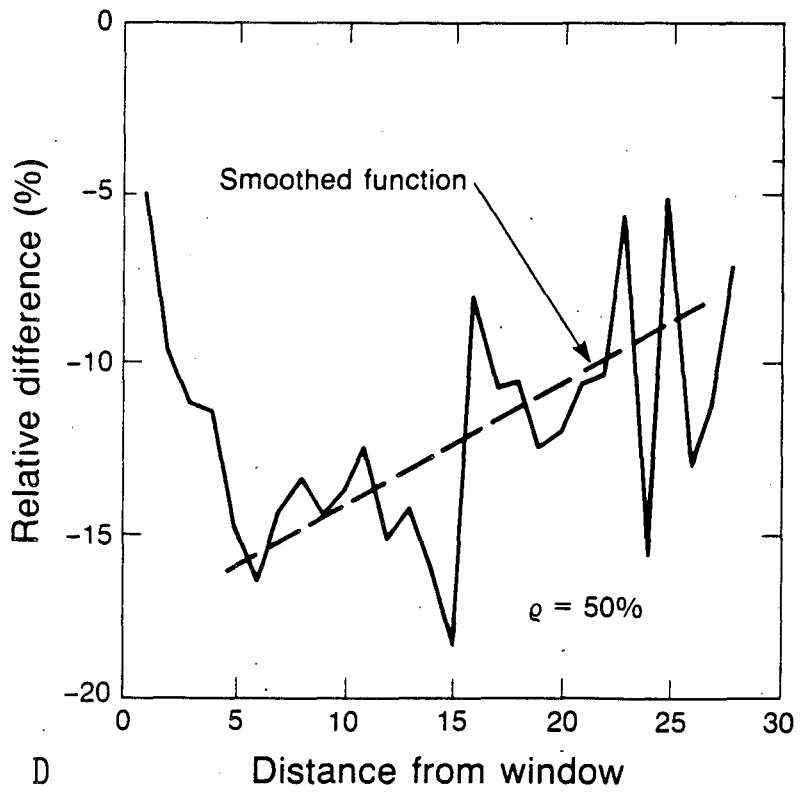


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Figure 6 (continued). The relative difference between the calculated and the measured reflected illumination as a percentage of the total measured light level (at that point). Interior textures of 86% (Fig. 6c) and 50% (Fig. 6d); Model B; 4 x 5 window.

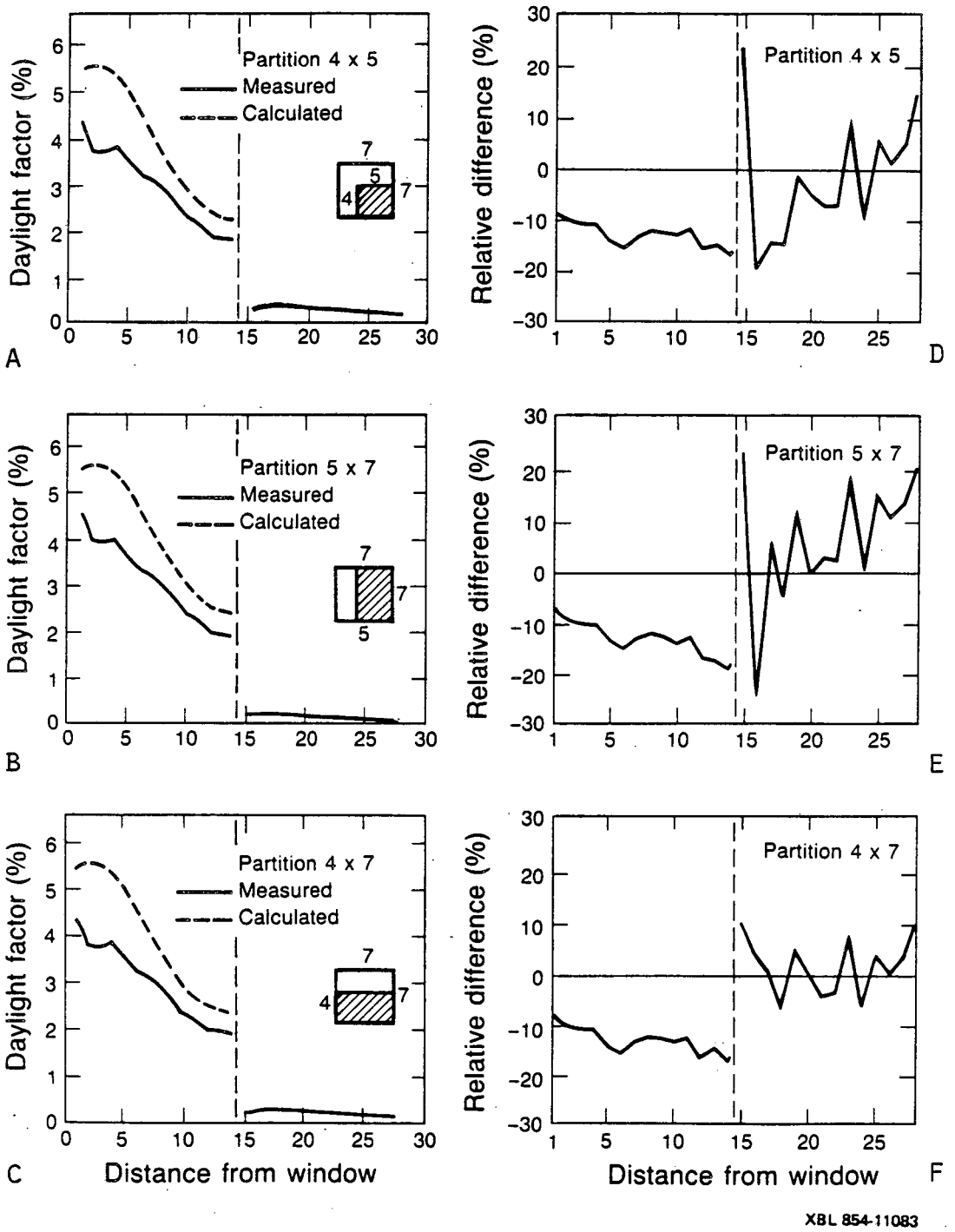
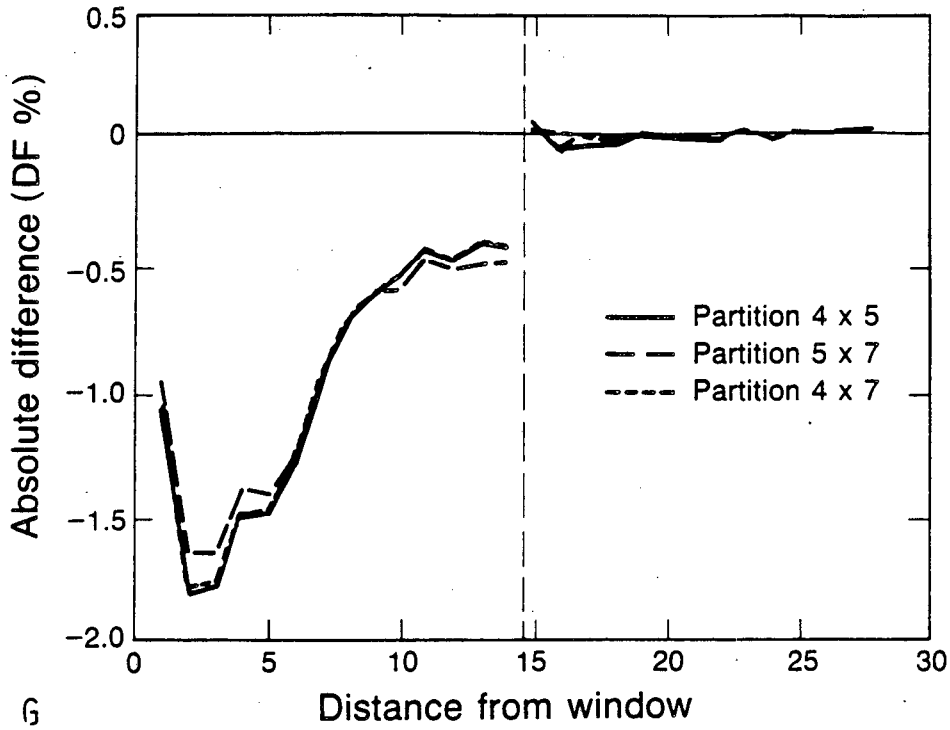
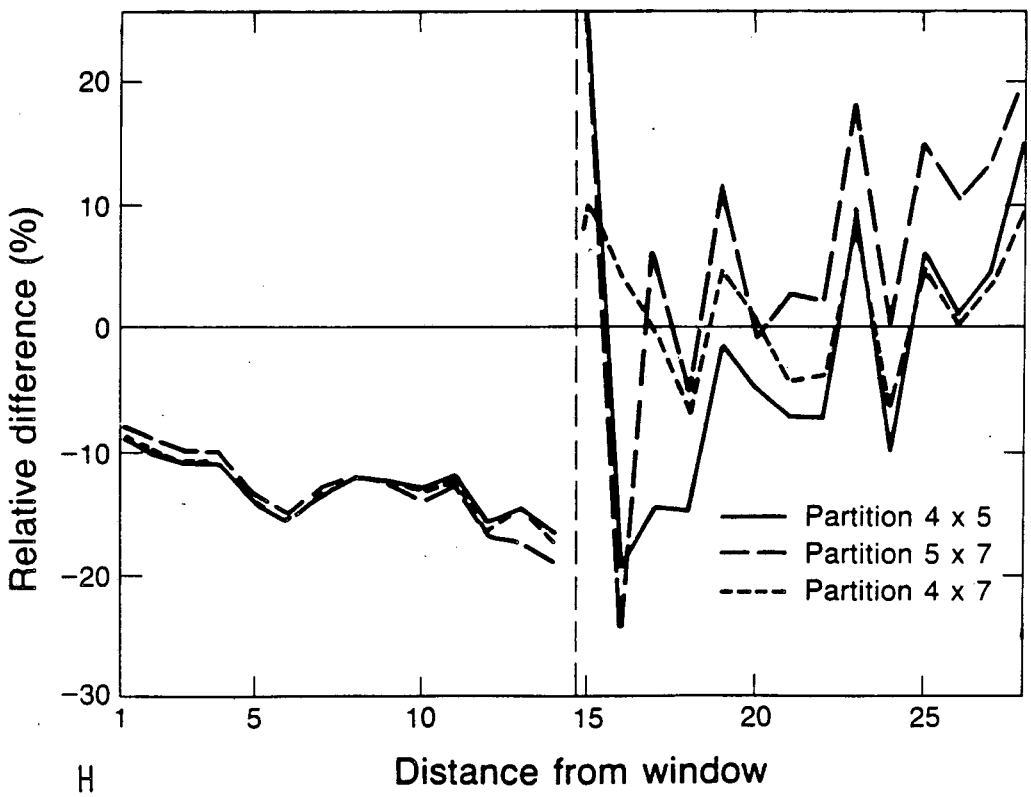


Figure 7. Illumination levels for different partitions in mid-depth of the space, reflected component only. Measured versus calculated results; Model B; 4 x 5 window; ρ = 50%.



G



H

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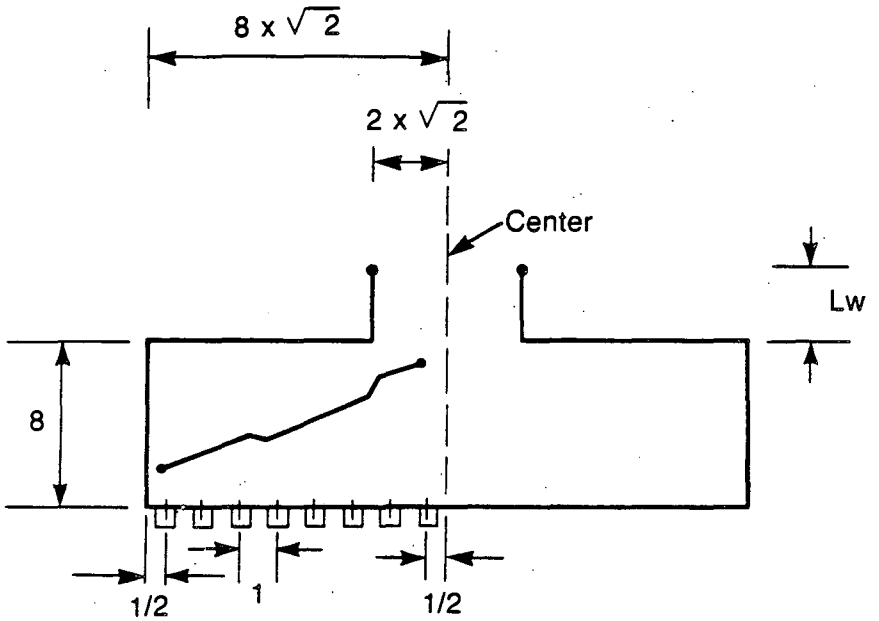
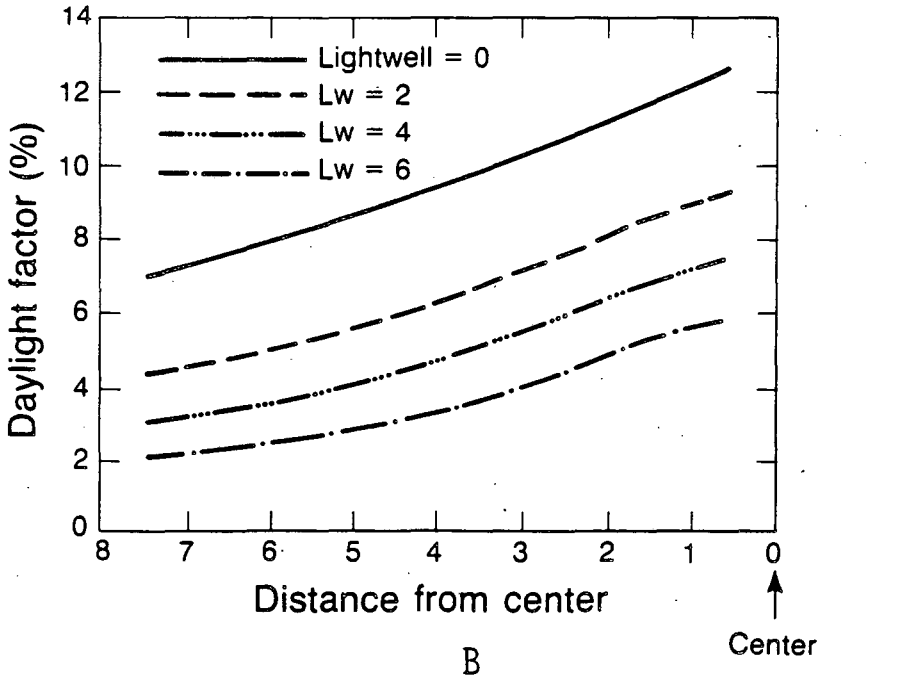
Figure 7 (continued). Illumination levels for different partitions in mid-depth of the space, reflected component only. Difference between measured and calculated results; Model B; 4 x 5 window; ρ = 50%.



A



B

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Figure 8. Top: Diagonal section through the scale model. Bottom: Measured total light levels underneath different well-type skylights. Model C; skylight 4 x 4; ρ = 86%.

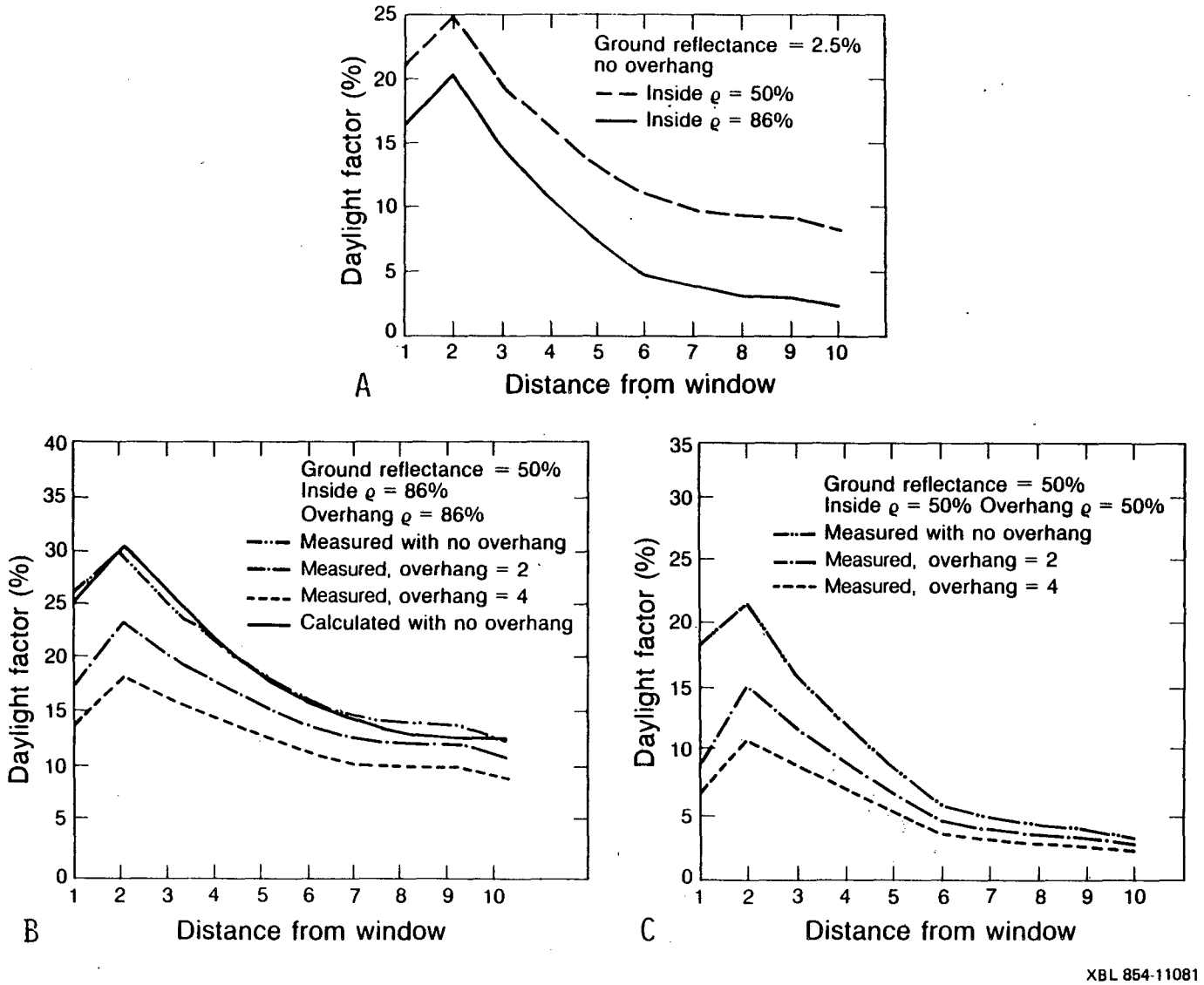

Figure 9. Measurements and calculations of total light levels for different overhangs in a courtyard design. Model A; 32 x 32 courtyard; 9 x 10 x 5 space; 3 x 7 window.

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