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DAYLIGHTING AND URBAN FORM: AN URBAN FABRIC OF LIGHT

Mark DeKay

This article attempts to answer the question, "What would the form of the city be like if we were to take seriously the provision of daylight to all buildings?" Previous work by this author reviewed existing daylight planning tools and found that they do not assure a predictable level of daylight. Previous work also identified an empirical relationship between daylight levels inside buildings and the street canyon ratios[1] — the DAYLIGHT ACCESS RULE *— as an objective basis for establishing development guidelines. This study identifies the important parameters available to designers and regulators that are necessary for urban daylighting. The results of the new* DAYLIGHT ACCESS RULE*, along with* ATRIUM BUILDING *type studies, are used to establish urban patterns of* ATRIUM BLOCKS *and* DAYLIGHT ENVELOPES *that support daylighting as an urban design strategy. Beyond defining the patterns of building massing, such that one building will not unduly block the access of another building to light from the sky, urban form can be generated from a consideration of daylit building forms used as increments for determining block sizes. An example application to downtown Chattanooga, Tennessee, is explored to evaluate existing development patterns and to propose alternatives to better support daylighting.*

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INTRODUCTION

Buildings built today will outlive supplies of oil and natural gas. Where I live, most of our power comes from burning coal, which produces sulfur dioxide, causing acid rain and severely damaging the most biodiverse ecosystem in the country, the Great Smoky Mountains. We in the Tennessee Valley burn coal lamps. Buildings today are responsible for one-third of both energy use and the global warming contribution of the U.S. The single most cost-effective way to reduce energy use in nonresidential buildings is the replacement of electric light, which contributes about one-third of commercial building energy use, with daylight. For any building to use daylight, it first needs access to it. This means that windows must be able to see the sky.

We know a lot about how to design buildings that are daylit. Given how much we know about daylight building design, it is surprising how little we know about creating city form in such a way that light is allowed to reach buildings.

There are many reasons to daylight buildings, both subjective and objective. Though the measurable energy savings, light quality, and environmental benefits of daylighting in buildings are undisputed, there are other equally compelling reasons supporting daylighting. Light is not merely the revealer of form. Its rhythms are fundamental to life. Light resets our biological clocks every day and plays a role in many human biological and psychological processes. The way architecture admits light places us in relationship with sky and horizon, giving rise to varieties of human interpretation and meaning. Light's cycles — the day's length, the sun's intensity, the seasonal patterns of sky cover, the dawn-to-dusk solar arc — are the most fundamental presence of nature in our lives.

THE FORM OF ATRIUM BUILDINGS

Let us begin by asking the question, "How might the massing and footprints of buildings designed for daylighting impact the form of the city?" In particular, we will examine the basic massing determinants of atrium buildings as a possible rational element for urban layout that could be used for determining property divisions or sizing blocks.

Most available daylight design tools are intended to provide information about the levels and distribution of light within a single room. Very few studies have addressed the impact of daylighting on the building as a whole, in terms of either quantifying basic massing and form decisions or the implications for other important efficiency and economic decisions, such as gross-to-net planning ratios, floor-area ratios, or the daylit fraction of floor area.

This part of the article establishes an ATRIUM BUILDING THICKNESS RULE for building dimension from outside wall to atrium and shows the relative impact of atrium sizing on massing, floorplan efficiency, structural spans, and percentage of RENTABLE AREA DAYLIT (%RAD) for variations in latitude and building height. The ATRIUM BUILDING THICKNESS RULE may be used to size the dimensions of building wings adjacent to an atrium. The plan implications, presented graphically, can be used to assess economic, schematic daylighting, and structural implications of building height and thickness.

Historically, buildings were designed with shallow plan depths to allow the penetration of daylight and cross ventilation to all rooms. In dense urban contexts, buildings took on "alphabet" plan configurations as large buildings intersected with street grids. The most land-efficient of these forms was the O-shaped building, which developed into the modern atrium type. Atria and light courts can be used to admit light deep into buildings and achieve high development densities. If the design intention is to use daylight as the building's primary light source, atria impose functional constraints on building form and bulk. For a given building height, two major elements of atrium buildings determine their form:

- The size and proportion of the atrium.
- The thickness of the building's wings.

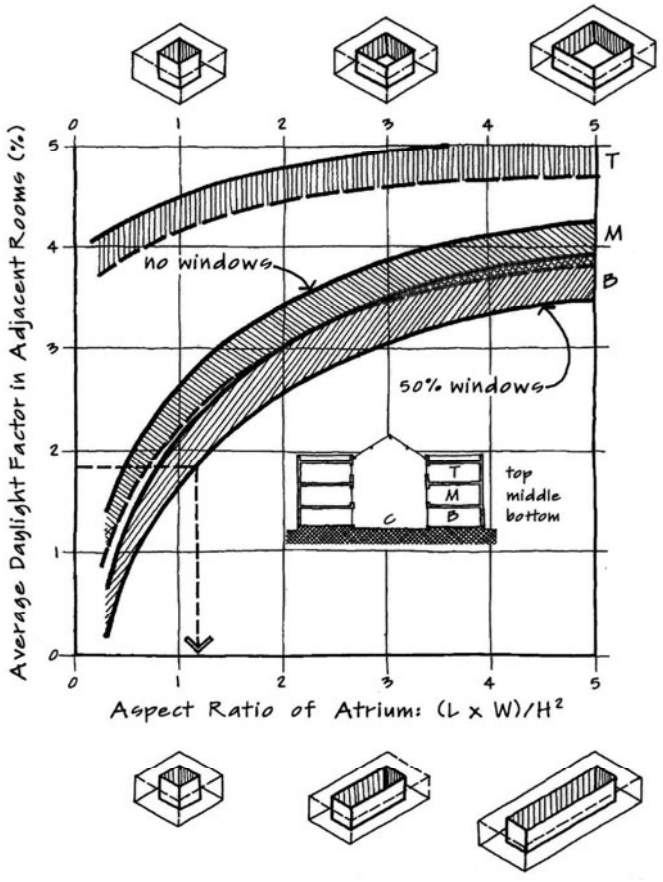


FIGURE 1. Sizing atria for daylight in adjacent rooms. Source: Brown and DeKay (2001), developed based on results from Baker, *et al.* (1993).

QUANTIFYING PRIMARY ATRIUM MASSING DETERMINANTS

Atria Size and Proportion

When the atrium is used as a lighting device for adjacent spaces, it must be proportioned carefully. Cartwright (1986) developed a simple ATRIUM SIZING rule-of-thumb (R/T) for this purpose. Since then, others have achieved similar results (Szerman, 1992, also in Hastings, 1994; Willbold-Lohr, 1989, also in Baker, *et al.*, 1993) (see Figure 1). By this method, the designer can determine the rough size of an atrium in the early phases of the building's design. The ATRIUM SIZING RULE is presented as a graph, plotting the daylight factor (DF) in the adjacent ground-floor space against the height-to-length ratio (H/L) of the atrium.

In addition to climate, the following variables determine the daylight available to lower floors:

- The type of roof system (glazing, apertures, structure).
- The height/length proportion of the atrium.
- The reflectance of interior materials.
- The size and placement of interior openings.

Atria H/L varies with the DF desired in interior rooms. For equal interior illumination levels and building height, higher DFs, and thus wider atria, are required at high latitudes due to lower overall daylight availability.

Building Thickness

Once the general building size and height are known, the atrium may be sized. The other major massing determinant, the thickness of the building between the atrium and the exterior wall, must also be determined. From a daylighting perspective, these two elements determine the atrium building's basic form.

The penetration of daylight from the atrium and the street side will generally be limited to about 2.5 times the height (*h*) of the daylight opening above the floor (Flynn and Segil, 1970). Therefore, the building's minimum thickness (T) is 5*h*, being 2 x 2.5*h*.

The 2.5H RULE is a generalization. The depth limitation of sidelit rooms is based on light distribution uniformity in order to keep illuminance ratios within the range that minimizes the perception of glare. Room dimensions, proportions, and reflectances all affect allowable depth, which can be greater or less than the 2.5H RULE, a strategy known as DAYLIT ROOM DEPTH, as can be seen in Figure 2 (Brown and DeKay, 2001: 201-202).

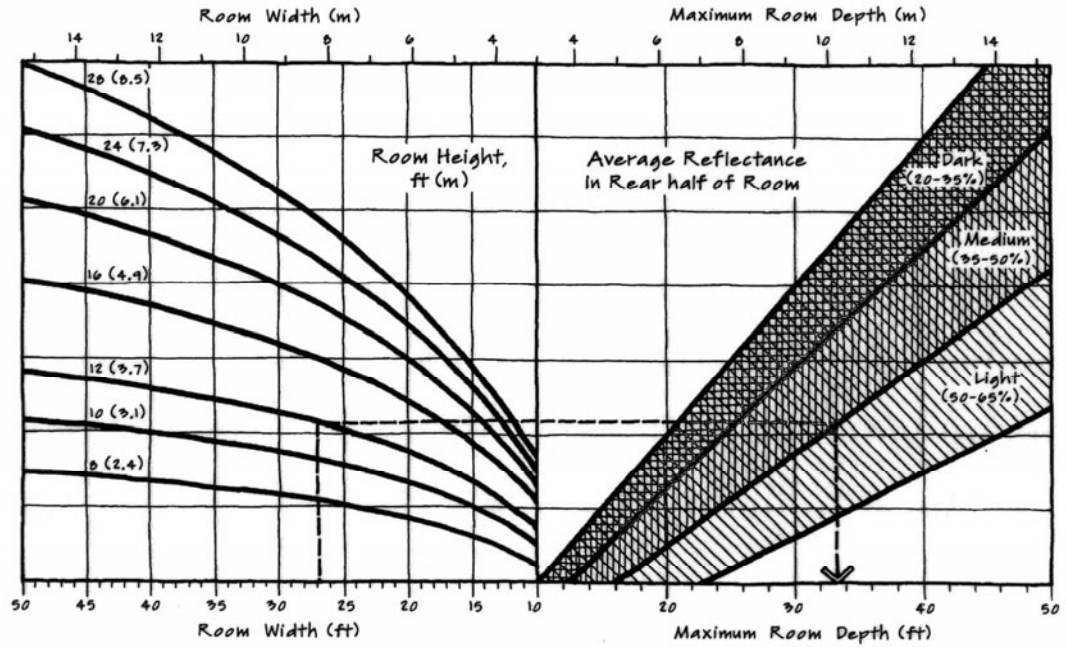


FIGURE 2. Estimating maximum room depth for daylight uniformity.
Source: Brown and DeKay (2001).

Assuming that the building has an internal circulation and service core between a daylit perimeter space and a daylit interior space adjacent to the atrium, a building with a 5*h* thickness provides light to this circulation and service core, where illumination needs and occupancy are low. While this is not undesirable from a daylighting or aesthetic point of view, it may reduce the site's development potential more than necessary and produce plans with high proportions of circulation.

Furthermore, there are usually storage and other service spaces within the occupied areas that do not require daylighting. The portion of the occupied space devoted to storage and service could be electrically lit, especially if it is an intermittent occupancy space.

Thus, to increase the plan efficiency and provide daylighting only where it is really needed, the building thickness could be increased above 5*h*. The question then arises, "How much can building thickness be increased above 5*h* while still providing daylight to most of the rentable space?"

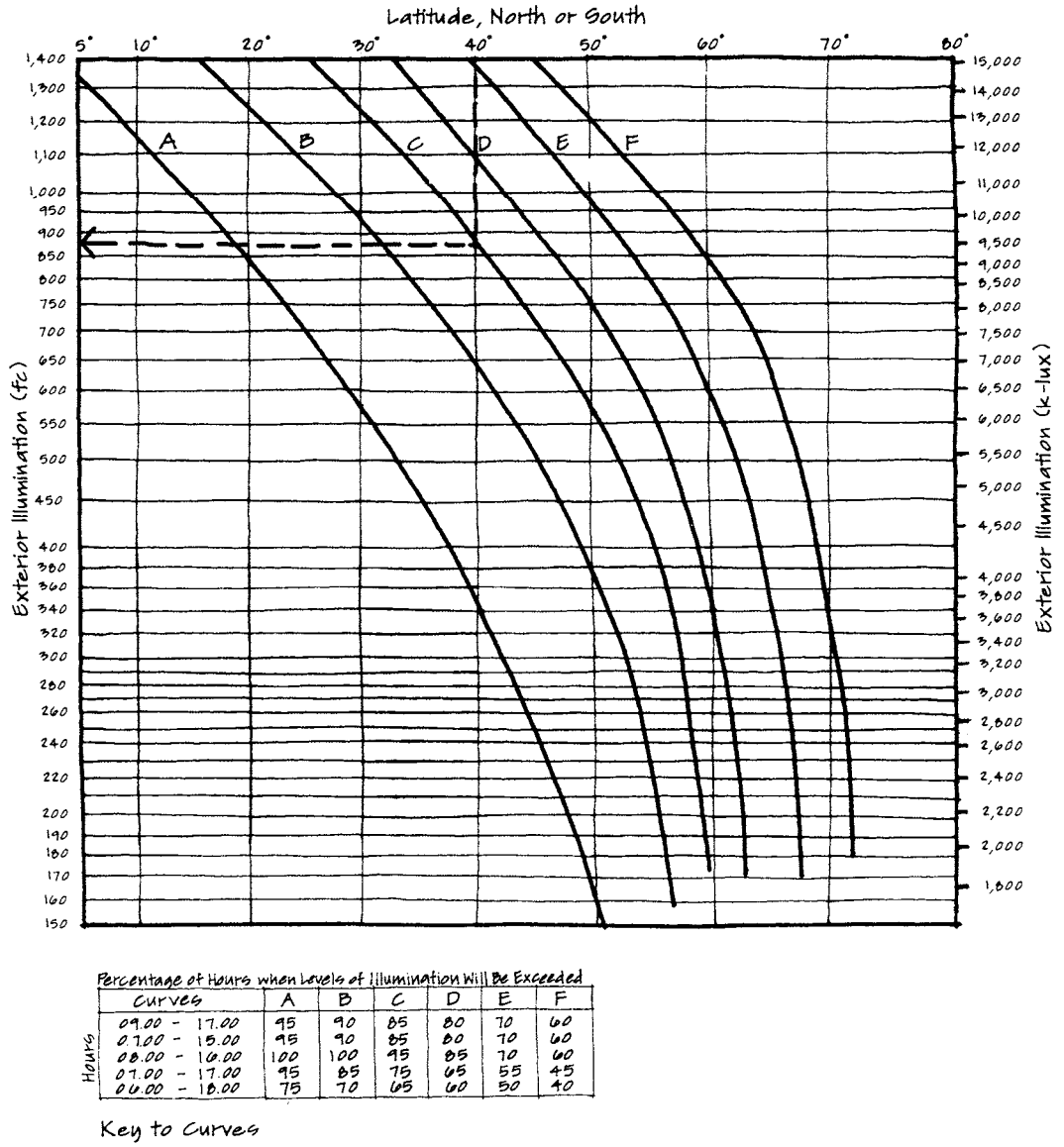
For the method explored here, three variables are important when the designer is determining this dimension:

- The building's gross floor area to net rentable floor area ratio (FAR) (G/N).
- The target percentage of the RENTABLE AREA DAYLIT.
- The reasonable fraction of occupancy (usually working hours) during which a minimum standard of illumination can be achieved.

METHODS

Atria Sizing

To size an atrium for daylight, a target *design daylight factor* is first required. The DF is defined as the ratio of interior horizontal illumination to exterior unobstructed horizontal illumination, expressed as a percentage.



Percentage of Hours when Levels of Illumination Will Be Exceeded

Hours	Curves	A	B	C	D	E	F
	09.00 - 17.00	95	90	85	80	70	60
	07.00 - 15.00	95	90	85	80	70	60
	08.00 - 16.00	100	100	95	85	70	60
	07.00 - 17.00	95	85	75	65	55	45
	06.00 - 18.00	75	70	65	60	50	40

Key to Curves

FIGURE 3. CIE daylight availability chart. Daylight availability under overcast skies, by latitude and percentage of hours.
Source: Brown and DeKay (2001), based on CIE (1970).

To calculate a target DF, two things are needed: the desired *interior illuminance* and the available *exterior illuminance*.

The required DFs under overcast sky conditions for latitudes from 28° to 54° were estimated for 10, 20, and 50 foot-candle (fc)[2] (100, 200, 500 lux[3]) interior illumination levels, representing IES[4] ILLUMINANCE CATEGORIES of C and D. For a given interior illumination level, the required DF increases with higher latitude because of decreasing exterior daylight availability. The CIE[5] DAYLIGHT AVAILABILITY CHART[6] (see Figure 3) was used for this purpose. Required DFs are shown in Table 2.

The required DF figures for providing a 20 fc minimum level of interior illumination were then grouped by latitude, allowing a maximum of 1% DF range between groups, as shown in Table 1.[7]

TABLE 1. Required average daylight factors, grouped by latitude.[7]

Latitude	Required DF
28°-38°	1.5-2.0
40°-48°	2.5-3.0
50°-52°	3.5-4.0
54°	4.5

TABLE 2. DF and atria proportion required under overcast sky, by latitude (for 20 fc, 85% of daily working hours).

	DF required		Atria			
	IES C	IES D	H/L*		Length (L)**	
°Latitude	10-20 fc	20-50 fc	Ratio	4-story	6-story	10-story
28	1.0-1.5	1.5-4.0	1.60			
30	1.0-1.5	1.5-4.0				
32	1.0-1.5	1.5-4.5	1.60	30 ft.	45 ft.	75 ft.
34	1.0-2.0	2.0-4.5				
36	1.0-2.0	2.0-5.0				
38	1.0-2.0	2.0-5.5	1.35	*36 ft.*	*53 ft.*	*89 ft.*
40	1.0-2.5	2.5-5.5	1.20	40 ft.	60 ft.	100 ft.
42	1.0-2.5	2.5-6.0				
44	1.5-2.5	2.5-7.0				
46	1.5-3.0	3.0-7.5				
48	1.5-3.0	3.0-8.0	1.10	*44 ft.*	*65 ft.*	*109 ft.*
50	2.0-3.5	3.5-9.0	0.95	51 ft.	76 ft.	126 ft.
52	2.0-4.0	4.0-10.0	0.85	*56 ft.*	*85 ft.*	*141 ft.*
54	2.0-4.5	4.5-11.5	0.75	*64 ft.*	*96 ft.*	*160 ft.*
56	3.0-5.5	5.5-14.5	0.65			
58	4.0-8.0	8.0-20.0	0.40			
60	5.5-11.5	11.5-28.5	N/A			

Notes.
* Atria proportions are for roughly square atria, determined by the Cartwright ATRIUM SIZING RULE.
H = height of atrium. L = length (or width) of atrium.
** Italicized figures are used to size atrium plans in Figures 15 and 17. Floor-to-floor height = 12 ft. per story.

Using the Cartwright ATRIUM SIZING RULE (Cartwright, 1986), atria proportions were determined for buildings of four, six, and 10 stories using DFs at each end of the range within each latitude group. These results are shown in Table 2. The most restrictive of the atrium H/L proportions within each latitude group are shown in italics; these are used to create the graphic matrices that follow.

Comparative Plans and Analysis

Three matrices were developed, one each for plan variations of building thicknesses of 5*h*, 6*h*, and 7*h*, where *h* is the window-head height above the floor. Building plans varied by latitude category and building height. These plans were then analyzed for the following factors:

- Atria length (structural span).
- Atria area as a percentage of building footprint.
- FAR, assuming site area = building footprint.
- Percentage of RENTABLE AREA DAYLIT (%RAD).

The matrices for T = 6*h* and T = 7*h* are shown in Figures 4 and 5. Volumetric implications for T = 7*h* are illustrated in Figure 6. FAR[8] shows the development efficiency of the building as a multiple of its footprint. Taller buildings at higher latitudes occupy larger footprints than shorter buildings at lower latitudes.

The %RAD is determined assuming a G/N ratio of 1.35.[9] Typical G/N ratios for office and apartment buildings are in the range of 1.25-1.35.

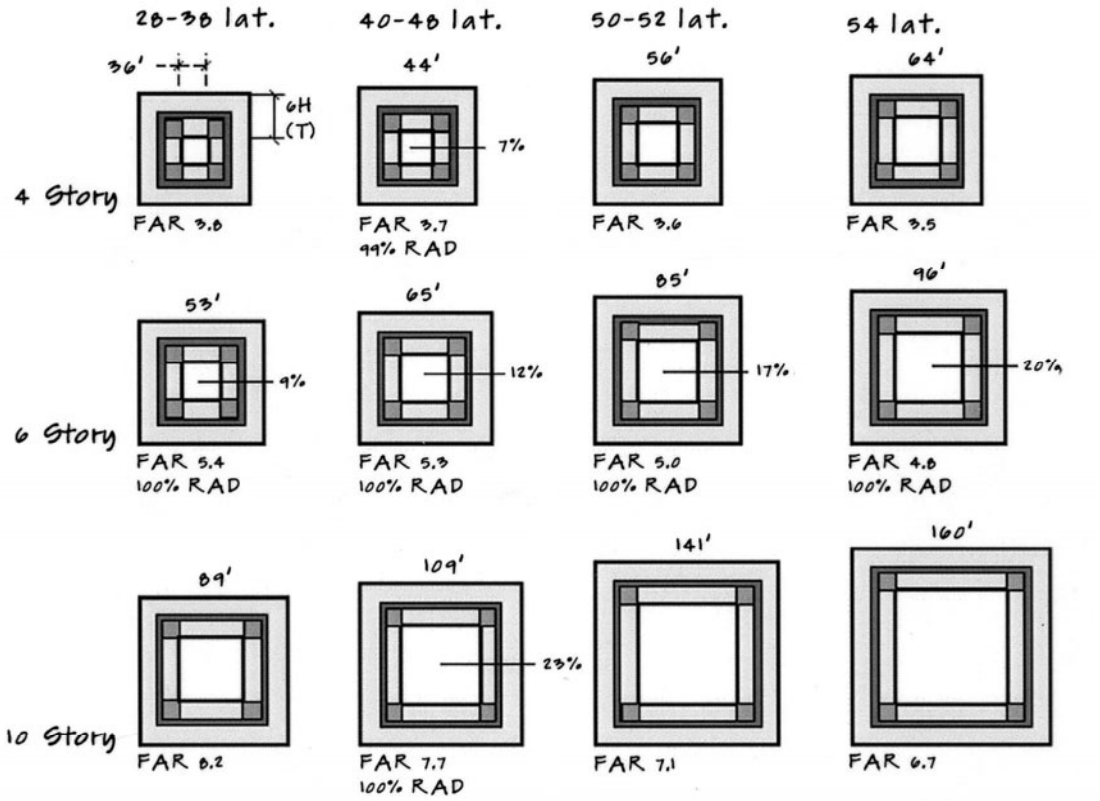


FIGURE 4. Atria building plan sizes for T = 6*h*. The center white square is the atrium. The light-toned areas represent daylit floor area. The dark zone is entirely electrically lit, and the medium-toned zones in the corners may borrow light from other spaces but have no direct access to daylight openings. They are considered service space. The dimensions shown above each plan indicate the length of the atrium in the plan. Atria lengths were determined using the building height (in this case, multiples of the 12 ft. floor-to-floor height), along with the predetermined H/L ratio from Table 2.

RESULTS CONCERNING ATRIUM BUILDING FORM

Required atrium size increases with latitude. Required DFS[10] range from 1.5% at 28°-30° latitude to 4.5% at 54° latitude. H/L ratios for the four latitude groups range from 1.6:1 at 28°-30° latitude to 0.4:1 at 56°.

Ten-story atria have serious structural consequences above 38° latitude, where spans exceed 100 ft. Spans for four- and six-story atria are less than 100 ft. at all latitudes.

Atrium area as a percentage of a typical floor area or building footprint increases with building height and with latitude. For the 40°-48° U.S. latitudes, where overcast conditions are most common, the light court for a four-story building requires 6% of the typical floor's area; for a 10-story building, 19%. For a six-story building, the light court as a percentage of the typical floor increases from 8% at 28°-38° latitude to 17% at 54° latitude.

Footprint FAR also increases with building height but decreases with latitude. The change in maximum footprint FAR as a function of latitude is less significant than that for building height. At T = 7*h*, footprint FAR ranges from 3.8-8.1 for the 40°-48° category. For a six-story building, the range is 5.0 at 54° to 5.6 at 28°-38° latitude.

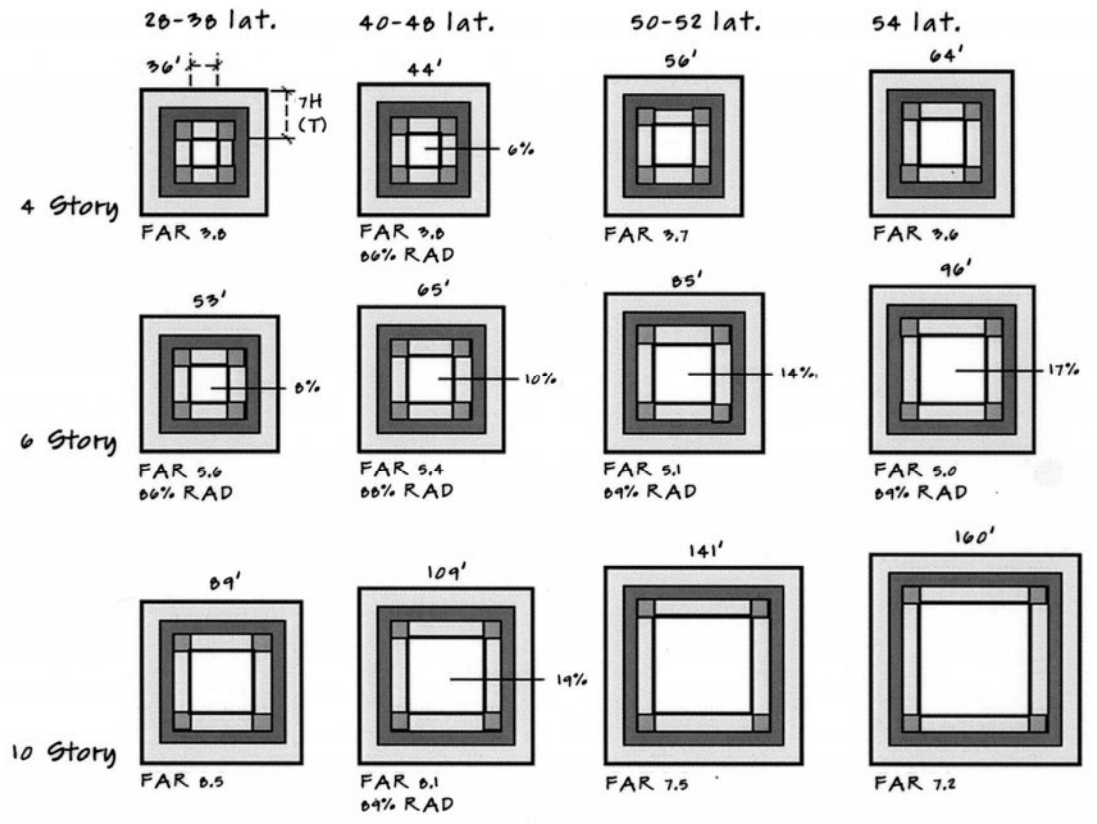


FIGURE 5. Atria building plan sizes for T = 7*h*.

The results clearly show that for a typical office or apartment building,[11] 80-100% RENTABLE AREA DAYLIT can be achieved with a building thickness of 6-7*h*. Below 6*h*, no gain in efficiency or increase in daylit area is achieved, assuming that the designer is not interested in attempting to daylight the internal service zones. Above 7*h*, the %RAD falls below 80%. These findings hold true for all latitudes and building heights tested.

The Building Thickness Rule

The results suggest a design guideline, given here as an ATRIUM BUILDING THICKNESS RULE (for G/N = 35), as follows:

> *Use a dimension between outside wall and atrium of 6h to achieve 90-100%* RENTABLE AREA DAYLIT, *and use 7h to achieve 80-90%* RENTABLE AREA DAYLIT.

Or, put more succinctly:

> *If T = 6h, 90 < %RAD < 100*
> *If T = 7h, 80 < %RAD < 90*

Of course, different daylight criteria will yield variations in this guideline. Because this relationship holds true for all building height and latitude combinations tested, and thus for a range of H/L proportions, the rule is independent of interior illumination level. %RAD, then, is a function of both building thickness and the G/N ratio. This becomes apparent when examining Figures 5 and 6 — there is only a small degree of variation in %RAD for a given value of T.

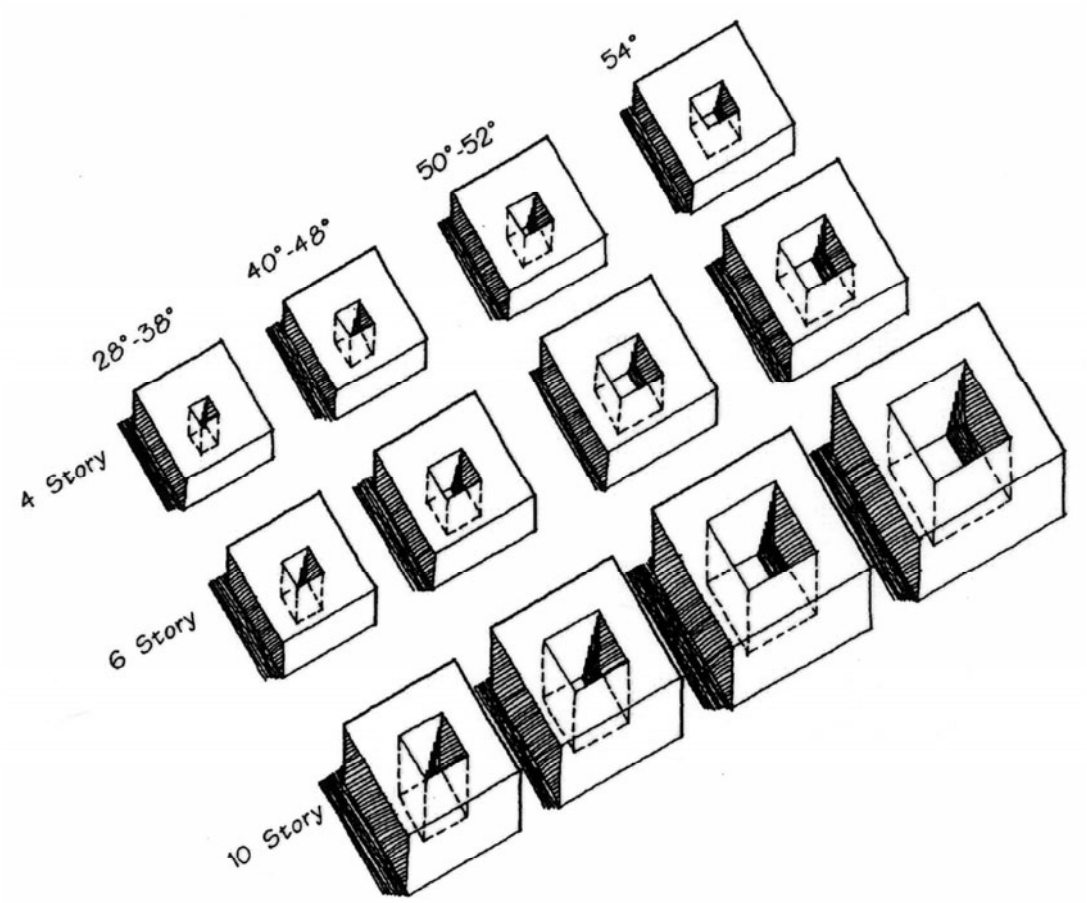


FIGURE 6. Axonometric projections of atria buildings for T = 7*h*.

CONCLUSIONS ABOUT ATRIUM BUILDING FORM

The findings suggest a simple, approximate relationship between building thickness from light court to outside wall and the fraction of tenant space daylit. This ATRIUM BUILDING THICKNESS RULE can be used in conjunction with an ATRIUM SIZING RULE to establish building massing for planning purposes.

The results further show that the design of atria as lighting fixtures has serious implications for the most basic concept of the building's form, especially for tall buildings and buildings at high latitudes. For instance, the ground floor area and volume of a light court for a six-story building at 54° latitude is 3.3 times that for a six-story building providing the same DF at 28°-38° latitude. This has obvious cost, maintenance, and mechanical-system ramifications. The same observations for building height can be made. For instance, at 40°-48° latitude, a 10-story building requires 6.1 times the light-court area per floor as does a four-story building providing the same DF.

Atrium size increases with building height at a much faster rate than does floor area since the building thickness is limited to a constant, as discussed above. The 10-story building area per floor is only 1.6 times that of the four-story building, but it incurs the cost of a six-fold increase in atrium volume per floor. There may be economic incentives to develop at a higher FAR by increasing the number of floors, but this benefit comes at an increasingly high price.

Generalizations about matching DF recommendations to tasks or occupancies can be very misleading given wide variations in daylight availability under different sky conditions and at different latitudes. These generalizations can result in undersized atria, and thus underlit spaces, or in oversized atria, leading to excessive thermal transfer and capital investment.

For atrium buildings, the BUILDING THICKNESS RULE can be used to ensure that an adequate fraction of the occupied space will be daylit. One basic measure of both market and aesthetic potential is the %RAD. Marketability of tenant space is an important consideration in any new commercial or residential building. Well daylit space often has a market advantage and almost always has an aesthetic advantage over predominantly electrically lit space.

URBAN DEVELOPMENT PATTERNS

In the following text, land use and density implications of daylighting are explored through reasoning from the massing characteristics of daylit buildings and applying the DAYLIGHT ACCESS RULE. Following this, we explore the idea that blocks and streets can be laid out to support daylighting as a design strategy from generalizations about the form of atrium buildings.

First, we determine the most efficient (highest density) atrium buildings that can be built on an open site. Then, we intersect those buildings with actual patterns of streets and blocks from three existing cities. The resulting analysis suggests a limited set of building/block patterns for grid cities.

The relationships between the DF inside a room and the ratio of street wall height to street width were used to determine allowable prescriptive DAYLIGHT ENVELOPES. The building bulk allowed by these envelopes was then calculated.

DeKay (1992, n.d.) has shown that most daylight planning tools are designed in some way to control sky exposure by limiting street wall height or spacing between buildings, yet their STREET CANYON RATIOS, allowable volume, and FAR recommendations vary dramatically. In response, we developed an objective method of determining daylight access that insures a quantifiable daylight level within buildings. This DAYLIGHT ACCESS RULE determines the relationship between H/W and DF, and is applied subsequently to determine appropriate limits to development envelopes and their implications for maximum urban density.

We have already addressed atrium building form, including the variables of building height and thickness, latitude, and interior light levels. We are now ready to use the results about atrium buildings to develop suggestions for block sizes and daylit building types.

BLOCK FORMS FOR GENERIC ATRIA BUILDINGS

Minimum plan sizes for atrium buildings were proposed in matrices that varied by building height and latitude (Figures 4 and 5). These plans were used as increments of development to set block sizes that were supportive of atria as a daylighting design strategy. Figure 7 shows combinations of four, six, and 10-story ATRIUM BUILDING MODULES for latitudes between 40° and 48°. It is important to note that in buildings with multiple atria, the occupied area between atria is the same dimension as the basic BUILDING THICKNESS between an atrium and an outside wall. This means that the basic plan module that can be multiplied to form a building with multiple atria is the sum of the atrium length (L) and one building thickness (T):

Atria Building Module = L + T

Using this ATRIUM BUILDING MODULE, blocks were sized for patterns with and without alleys. On blocks with alleys, the building mass shown will have to be reduced on upper floors along the alleys to allow access to daylight for the lower floors.

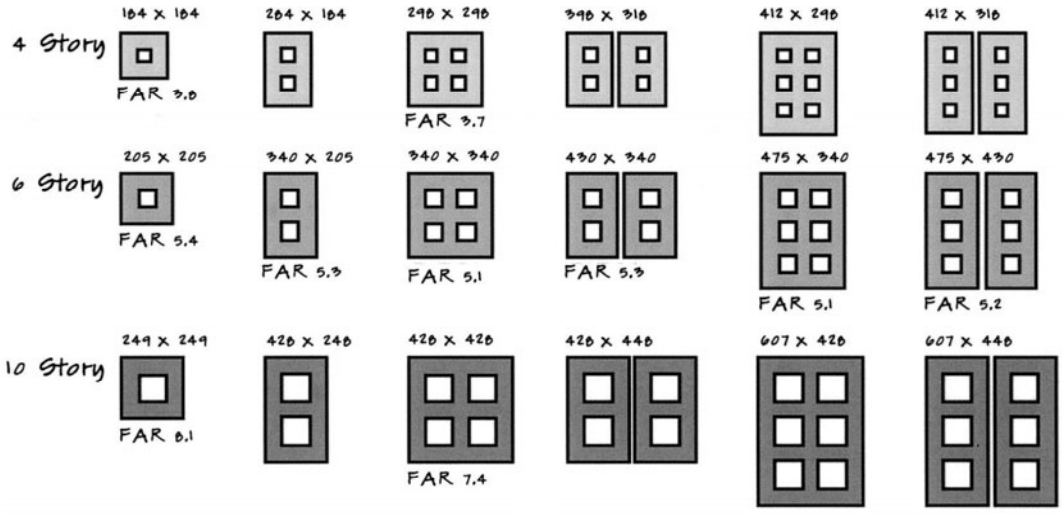


FIGURE 7. Atrium blocks: minimum block sizes for 40°-48° latitude (assumes a 20 fc (215 lux) minimum illumination level during 85% of working hours annually).

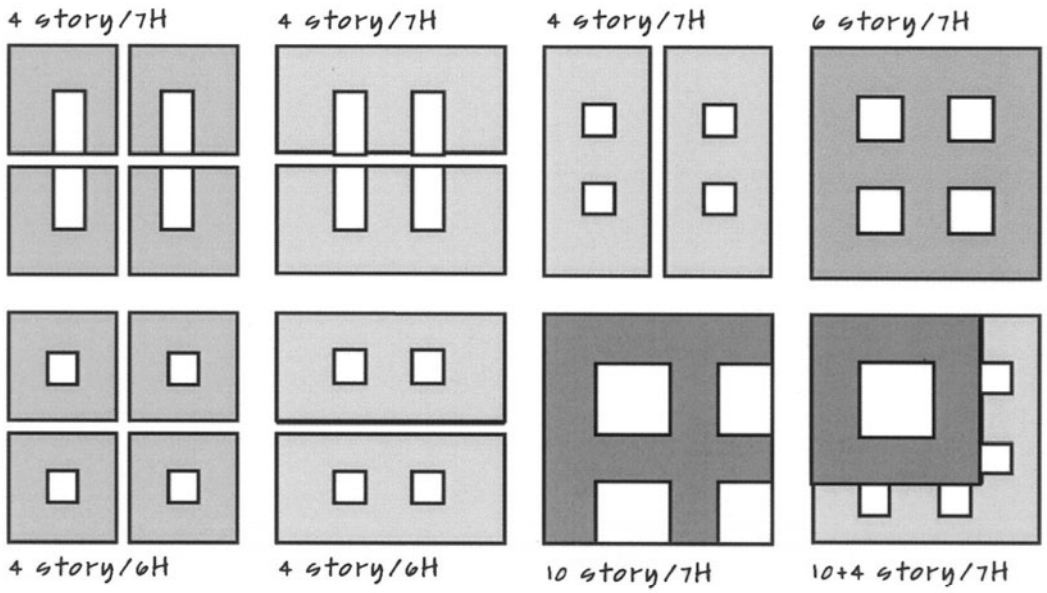


FIGURE 8. Atria buildings for blocks in Eugene, Oregon (340 ft. x 340 ft.; alleys either or both ways; 60 ft. ROW).

These patterns of ATRIUM BLOCKS can be combined with variations in street width and then modified using a DAYLIGHT ACCESS RULE. This process yields the theoretical maximum building envelope for daylight-sensitive development.

In an existing city, the block dimensions are usually already set, thus only certain buildings can be built efficiently on them. Some (perhaps a tall building at a high latitude) will be too large and will not fit on the block. Others will be too small and will not make efficient use of the available land.

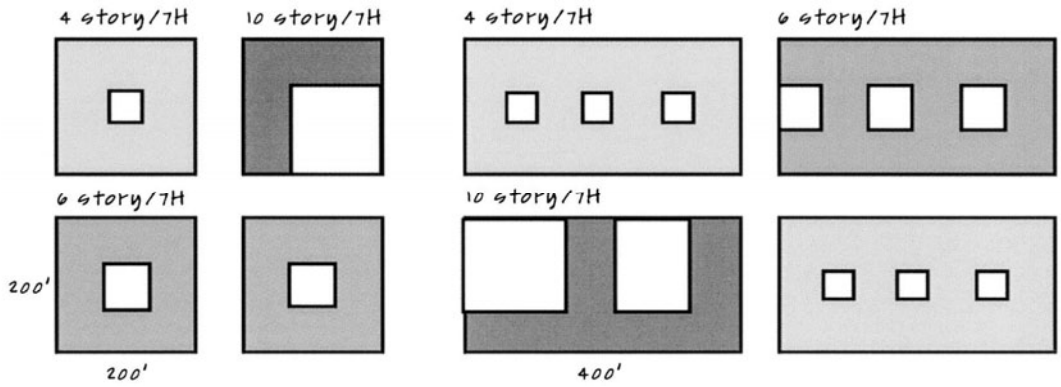


FIGURE 9. Atria buildings for blocks in Portland, Oregon
(200 ft. x 200 ft. and 200 ft. x 400 ft.; 60 ft. typical and up to 100 ft. ROW arterials).

ATRIA BUILDINGS FOR EXISTING CITY GRIDS

In order to study the patterns generated by the intersection of atrium building forms with non-ideal (for atria) city grids, urban patterns of blocks and streets from three cities were documented and overlaid with combinations of ATRIUM BUILDING MODULES. The major atrium building types possible in these cities are shown in Figures 8-10.

Atria Buildings in Eugene, Oregon

Eugene, Oregon, is platted on a 400 ft. (121.9 m) grid running the center of streets, thus the width of the street right-of-way (ROW) determines the dimension of the block face. Sixty-foot wide (18.3 m) streets are the most common, leaving a 340 ft. (103.6 m) typical block face. Alleys may run either or both directions, the latter being more common in the city center. Eugene's block sizes work best for four- and six-story buildings. Divisions of the block with alleys create plots undersized for both six- and 10-story buildings. Gridded center city blocks with cross-alleys are well sized for four single-atrium buildings, one in each quadrant. Blocks divided with a single alley are also well suited for four-story buildings. Blocks with no alleys are used efficiently by six-story buildings with multiple atria. See Figure 8.

Atria Buildings in Portland, Oregon

Typical blocks in Portland, Oregon, are 200 ft. x 200 ft. (61 m x 61 m) in the older part of the city, but 200 ft. x 400 ft. (61 m x 121.9 m) blocks are also common. The most common ROW is 60 ft. (18.3 m), with arterials up to 100 ft. (30.5 m). The small center city blocks are large enough for four- and six-story single-atrium buildings, but not for 10-story buildings. The larger blocks, still limited by the 200 ft. (61 m) dimension, are best suited for four-story multiple-atria buildings. Six-story multiple-atria buildings on these blocks intersect inefficiently with the street grid. See Figure 9.

Atria Buildings in Seattle, Washington

Seattle, Washington's blocks are 256 ft. x 240 ft. (78 m x 73.2 m) and 256 ft. x 360 ft. (78 m x 109.7 m). The 256 ft. (78 m) face typically fronts 90 ft. (27.4 m) ROW north/south avenues, while the 240 ft. (73.2 m) and 360 ft. (109.7 m) faces typically front 66 ft. (20.1 m) secondary streets. Alleys are typically 16 ft. (4.9 m) running north/south. The 240 ft. (73.2 m) square blocks yield hybrid atrium/sidelit forms at four and six stories. A single 10-story atrium building fits the block well but covers the alley. The lot size generated by crossing a narrow block with an alley is too small for any efficient atrium building. Multiple-atria buildings covering the alley or E-type sidelit buildings are the best daylight building-form alternatives in Seattle. See Figure 10.

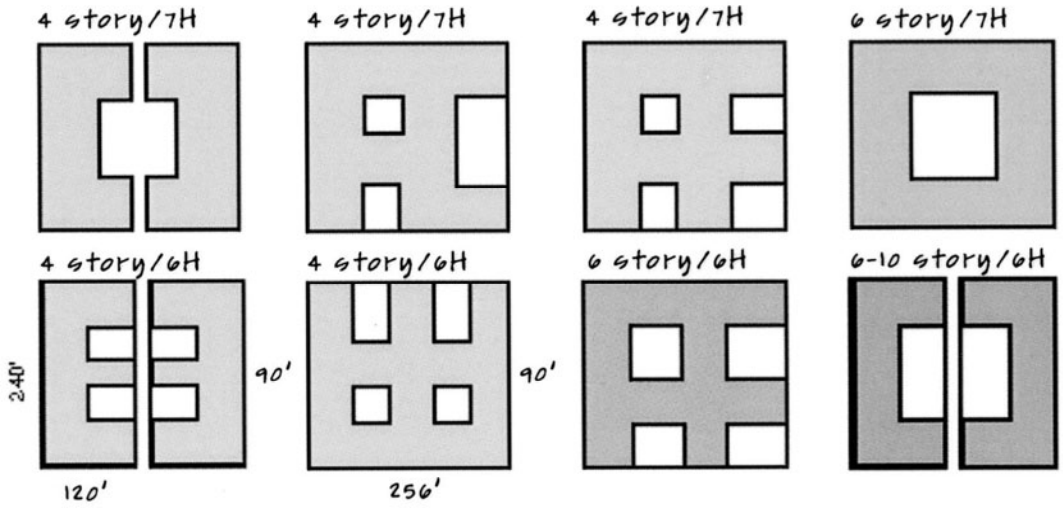


FIGURE 10. Atria buildings for short blocks in Seattle, Washington (256 ft. x 240 ft.; alleys at 16 ft.; 66 ft. and 90 ft. ROW).

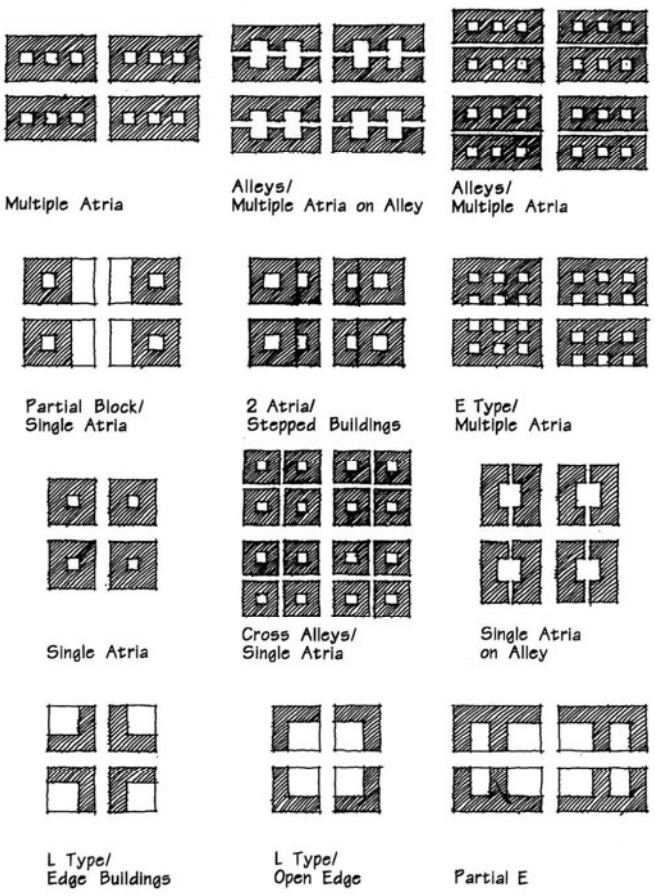


FIGURE 11. Urban atrium types.

DAYLIT BUILDING TYPES IN GRID CITIES

The foregoing analysis of block patterns for atrium buildings in existing cities suggests a limited set of URBAN ATRIUM TYPES. Similar analysis could also be done for sidelit buildings. Sidelit building plans are most often laid out in thin wings and generate several characteristic building types when limited by and intersected with the city grid (Holl, 1980). Urban block/building patterns for atrium buildings are shown in Figure 11.

Three basic patterns are evident for atrium buildings in grid cities:

(1) Buildings that fill an entire block, with either single atrium or multiple atria.
(2) Buildings that fill a partial block, leaving open space.
(3) Hybrid buildings that combine atrium and sidelit or shorter atrium forms to fill an entire block.

Atrium buildings can fill an entire block, sometimes with multiple atria in the same building (full block/multiple atria). On narrow blocks with alleys, the atrium can be located on the alley

(alley block/coincident multiple atria). For wider alley blocks, the half block between the alley and the street can be occupied by a full atrium building (full alley block).

Taller buildings requiring larger atria will often fill only a partial block (partial block/single atrium). The leftover space is not enough to repeat another ATRIUM MODULE of the same building height but may be large enough for a shorter building module (stepped height/multiple atria). Low rise, multiple-atria buildings on wider blocks can generate hybrid atrium/sidelit types, with E-type edges on one side (E-type/multiple atria).

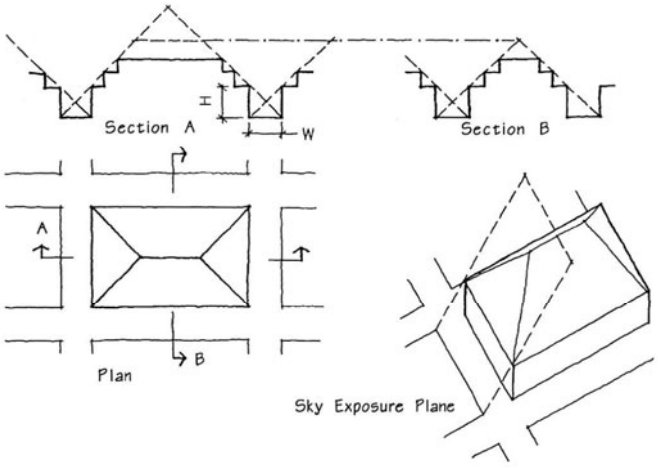


FIGURE 12. Construction of a daylight envelope.

Small, square blocks are ideal for single-atrium buildings (full block/single atrium). Square blocks divided by cross alleys require shorter single-atrium buildings (single atrium/cross alleys). Square blocks with an alley in only one direction generally require a single atrium coincident with the alley (alley block/single coincident atrium), except on very large blocks.

The lower three diagrams (L-type/Edge Buildings, L-type/Open Edge, and F-type (Partial E)) can be used for sidelit buildings, especially for taller buildings on blocks where the size of the block restricts atrium size.

DAYLIGHT ENVELOPES

When the DAYLIGHT ACCESS RULE is applied to an urban pattern of blocks and streets, a development envelope can be generated that describes the limit of building boundaries that will provide lower floors of opposite or neighboring buildings with sufficient daylight. The DAYLIGHT ACCESS RULE can be used to determine a maximum H/W for a given DF goal. If street width is fixed, a maximum street wall height can be calculated. A SKY EXPOSURE PLANE can then be defined by striking a line from the opposite side of the street at ground level through the top of the street wall, as illustrated in Figure 12. When applied on all four sides of a block, a hip-roof-shaped pyramid is formed above the street-wall-defined rectangular volume. This is a DAYLIGHT ENVELOPE.

As has been shown, the height of atrium buildings affects atrium sizing and, thus, building footprint size. Blocks can therefore be sized to support the desired building height and DF planning goal. This block size must be matched to an appropriate street width if the same DF planning goal that is achieved by the atrium sizing is to be achieved in the exterior sidelit zones of the buildings.

Example: For buildings of four, six, and 10 stories with two atria, minimum block sizes, given in Figure 7, are 298 ft. x 184 ft., 340 ft. x 205 ft., and 428 ft. x 248 ft., respectively (90.8 m x 56 m, 103.6 m x 62.5 m, and 130.5 m x 75.6 m). To match these block sizes with an appropriate street width, we can use Table 2 to determine a maximum H/W ratio. For a 20 fc (215 lux) goal, an average DF of 2.5-3.0% is required in the latitude class of 40°-48°. Assuming an average exterior surface reflectance of 33% (representing an opaque material of 40% and 15% reflective windows) and a generous 50% of the facade on the lower floor as windows, the DAYLIGHT ACCESS RULE indicates that a 2.5% DF requires a maximum H/W ratio of 1, corresponding to a 45° exposure plane (DeKay, 1993, n.d.). Other daylight criteria and assumptions for surface and window characteristics would, of course, yield variations in the recommended sky exposure plane.

TABLE 3. Matching building height, block size, and street width.

Height	Block Size	Street Width
4-story	298 x 184 ft. (90.8 x 56 m)	60 ft. (18.2 m)
6-story	340 x 205 ft. (103.6 x 62.5 m)	80 ft. (24.4 m)
10-story	428 x 248 ft. (130.5 x 75.6 m)	120 ft. (36.6 m)

TABLE 4. Density implications of daylight access.

Development Pattern	FAR of Block	FAR including Streets	FAR of Block, w/ Atria Building
298 x 184 ft. blocks/ 60 ft. ROW (90.8 x 56/18.2 m)	8.0	5.1	3.8
340 x 205 ft. blocks/ 80 ft. ROW (103.6 x 62.5/24.4 m)	10.1	5.9	5.3
428 x 248 ft. blocks/ 100 ft. ROW (130.5 x 75.6/30.5 m)	12.5	7.2	7.6

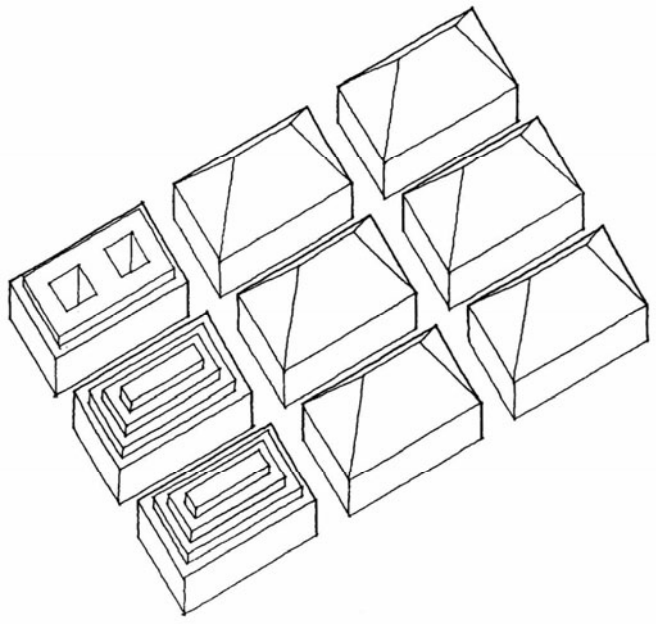


FIGURE 13. Daylight envelopes for 428 ft. x 248 ft. (130.5 m x 75.6 m) blocks with 100 ft. (30.5 m) wide streets.

Using this H/W ratio of 1 and assuming a story height of 12 ft. (3.7 m), the associations of block size, street width, and building height shown in Table 3 can be made. A 10-story building with 12 ft. (3.7 m) story heights would be 120 ft. (36.6 m) high and for H/W = 1, would require a major boulevard of 120 ft. (36.6 m) in width. Since 100 ft. (30.5 m) is about the widest arterial commonly used in the U.S., eight stories should be the maximum street wall in most cities. For each of these three development patterns, a DAYLIGHT ENVELOPE was generated. Figure 13 shows one such pattern. Hip-roof type forms indicate the envelope. Stepped forms indicate the maximum building within that envelope, shown in two-story increments. A generic flat-roofed atrium mass is also shown for comparison. It is obvious that an atrium building would not fill the entire envelope. Remember also that the envelopes are illustrated at the scale of the block and that several buildings may fill a block, but collectively, they should not penetrate the envelope.

DENSITY IMPLICATIONS OF DAYLIGHT ACCESS

To get some idea of the limitations on density created by daylight access envelopes, building bulk and FAR were calculated for the development patterns described above. The calculated bulk is shown in Table 4.

From this comparison, several interesting conclusions can be drawn, while remembering that these results represent a particular set of variables. First of all, the 12.5 maximum FAR indicates that dense urban FAR limits of 15 or 18, as found in parts of Manhattan, cannot support daylighting to all buildings. The FAR for the atrium buildings alone are probably the maximum development potential for each of the respective development patterns, since sidelit portions of the building, which might fill the upper portion of the daylight access envelope, would require significant spacing between wings, similar to atrium sizing.

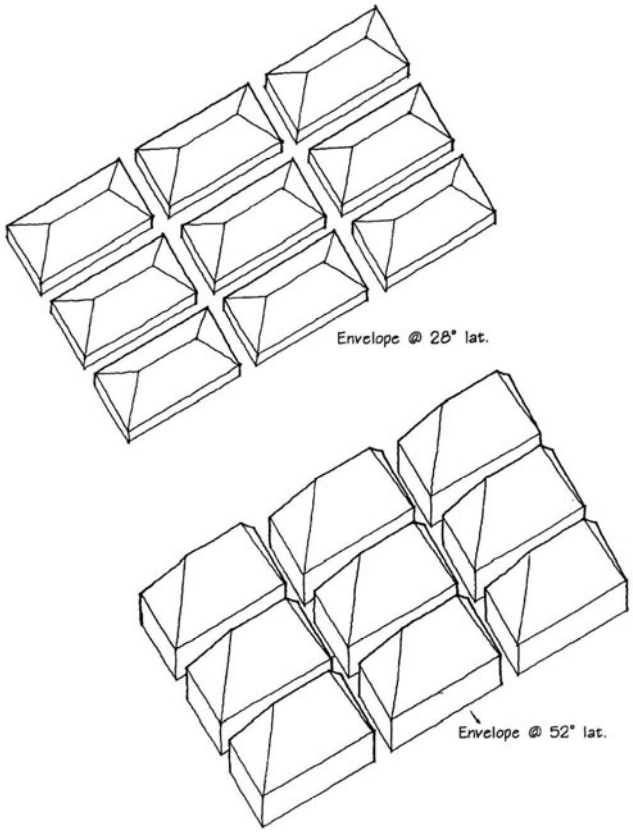


FIGURE 14. Daylight envelopes for the same block/street pattern at 28° and 52° latitude.

The above results suggest a maximum height limit of 100 ft. (30.5 m), or about eight stories on major arterials of 100 ft. (30.5 m) ROW. An eight-story building at 48° latitude has an atrium height-to-length ratio of 1:1 and a maximum FAR of 6.6 for a two-atria building (block size: 227 ft. x 384 ft. or 69.2 m x 117 m). This would seem to be the maximum development density that would support daylighting at this latitude. At lower latitudes, greater density and street wall height would be allowed. At higher latitudes, less density would be possible. Theoretically, in clear sky climates, higher density would be allowed because the higher available daylight outside requires lower DFS, thus lower atrium H/L ratios and lower building height/street width (H/W) ratios. Clear sky conditions have not been investigated in this study.

VARIATIONS IN DAYLIGHT ENVELOPES BY LATITUDE

Figure 14 shows daylight access envelopes generated on the same urban grid for 28° (Florida) and 52° (southern Alaska, Newfoundland) latitudes. For the same daylight goals,[12] a 1.5% DF is required at 28° and a 4% DF at 52°, and H/W ratio[13] is 1.5 at 28° and 0.5 at 52°. This means that the street wall must be no more than one half of the street width in a high-latitude city and can be up to one and a half times the street width in a low-latitude city.

CONCLUSIONS ABOUT URBAN DEVELOPMENT PATTERNS FOR DAYLIGHT

The results of atrium/block analysis show the importance of matching building height to block size if daylighting is considered important. The analysis suggests a limited set of atrium typologies, while three basic patterns are evident for atrium buildings in grid cities.

There are still no basic massing rules for reentrant C, E, F, and H types to ensure that the massing decisions intended to provide daylight are actually dimensioned within parameters that allow sufficient levels within the rooms of lower floors. This is clearly an unresolved subject for future research efforts.

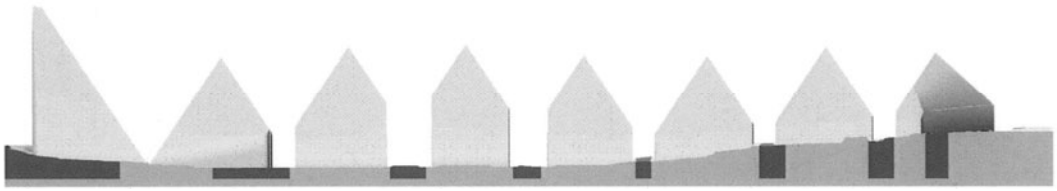


FIGURE 15. Downtown Chattanooga daylight envelopes (east-west section at 6th St. looking north).

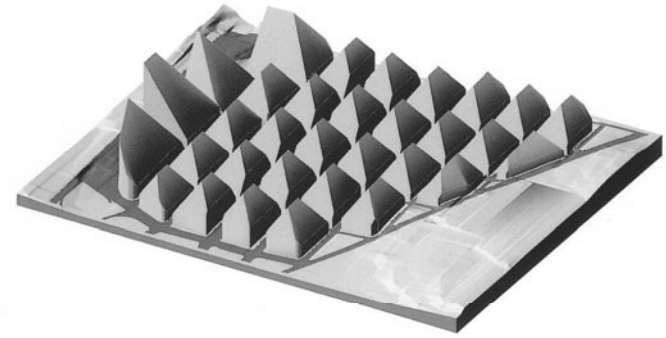


FIGURE 16. Downtown Chattanooga daylight envelopes (view from southeast looking towards northwest).

DAYLIGHT ENVELOPES offer a prescriptive development control. The method as presented allows the H/W ratio that defines the sky exposure plane, and thus the envelope, to be determined using the DAYLIGHT ACCESS RULE for the variables of latitude, exterior reflectance, window area, and daylight goal. The DAYLIGHT ENVELOPE, as developed herein, is more restrictive than necessary. The same results can theoretically be achieved with a performance tool such as BRADA (Bryan and Fergle, 1986), which measures the percentage of sky exposure, if it could be tied to interior light levels or to a clear standard at the building facade. What is helpful about the prescriptive approach is that it gives a base-line standard for use in interpreting the results of performance tools such as BRADA. As a development tool, the DAYLIGHT ENVELOPE will tend to produce street-oriented buildings of high site coverage and, when a site is developed to its full potential, stepped building forms.

Daylight Planning for Chattanooga, Tennessee

To show the potential impacts of daylight planning in a real city, this section shows the DAYLIGHT ENVELOPE applied to the core of downtown Chattanooga (Figures 15-18).

The site used is the densest district in the city.[14] The same methods, building characteristics, and daylight criteria described above were employed to build DAYLIGHT ENVELOPES for downtown Chattanooga. The very large parcels and the very wide right-of-way along U.S. Highway 27 create tall peaks in the DAYLIGHT ENVELOPE on the district's western edge. From the point of view of natural light, this is a good place for tall buildings. Taller buildings and parking garages along the highway could also help form an acoustic barrier to protect blocks farther east.

Existing Chattanooga Buildings and Daylight Access

We can now ask, "How does the existing development pattern compare to these theoretical daylight envelopes?" The drawing in Figure 17 clearly shows that the existing buildings were not designed to consider their neighbors' rights to light.

The worst problems are created by less than two dozen of the largest buildings. Regulating development for daylight and solar access would produce more buildings of smaller size distributed over more sites, a pattern more prevalent in inner-city districts prior to fluorescent lighting. Limiting height tends to drive buildings to cover more of the site, so there is less parking and less distance from the building to the street. Buildings would have stronger relationships to the street and would create more pleasant, climatically comfortable, and active streets and public spaces.

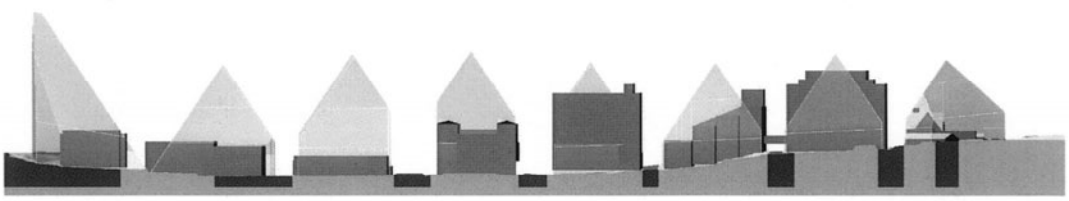


FIGURE 17. Downtown Chattanooga daylight envelopes with existing buildings (east-west section at 6th St. looking north).

Within the DAYLIGHT ENVELOPE, buildings can be taller on the wider streets. Relatively tall buildings, up to 14 stories, are possible along Broad St., while cross-streets allow for six stories. However, the section shows that an 11-story facade along Market St. violates the envelope, reducing light to its neighbors.

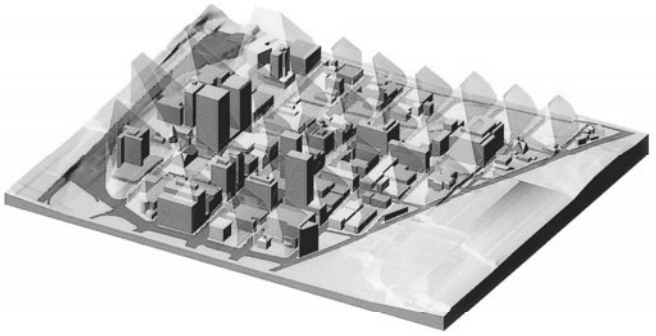


FIGURE 18. Downtown Chattanooga daylight envelopes with existing buildings (view from southeast looking towards northwest).

The Future Daylit City

Finally, we asked, "In 50 to 100 years from now, what form would Chattanooga's downtown take if daylight planning guided its development?" The drawings in Figures 19 and 20 show possible building configurations that satisfy composite climatic envelopes (both solar and daylight) and follow several design rules, allowing good natural lighting for most rooms, while attempting to maximize development potential.

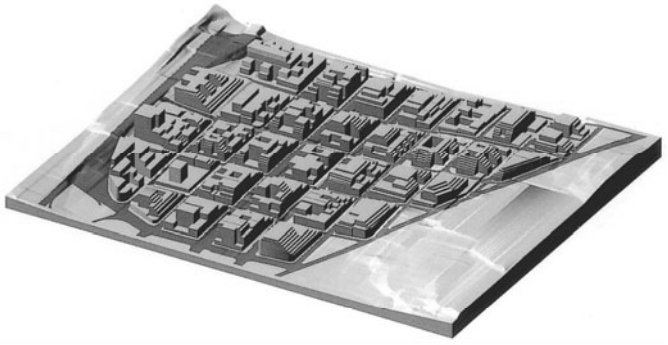


FIGURE 19. Hypothetical daylit development in Chattanooga (view from southeast looking towards northwest).

In this final set of images, the DAYLIGHT ENVELOPE has been intersected with SOLAR ENVELOPES (which protect winter direct-beam sun access) to create a composite CLIMATIC ENVELOPE that is the lesser boundary of their combined volumes. SOLAR ENVELOPES are well studied and documented elsewhere (for details on SOLAR ENVELOPES, see Brown and DeKay, 2001; Knowles, 1981). We generated both SOLAR ENVELOPES and DAYLIGHT ENVELOPES for each block and then created a new composite CLIMATIC ENVELOPE by taking only the volume included in both. This way, both solar and daylight access are insured. Within this CLIMATIC ENVELOPE, we generated hypothetical building forms following several well-known daylight design-massing patterns.

Because of the BUILDING THICKNESS RULE, the buildings shown follow one of two patterns: buildings with THIN PLANS of 50-70 ft. thick or buildings with LIGHT COURTS and ATRIA. The peaks of the envelope have been cut off where the size of the floor under the envelope was too small to be practically occupied. Light courts are shown without roofs, but in many cases could be covered in glass or partially glazed roofs to make an atrium.

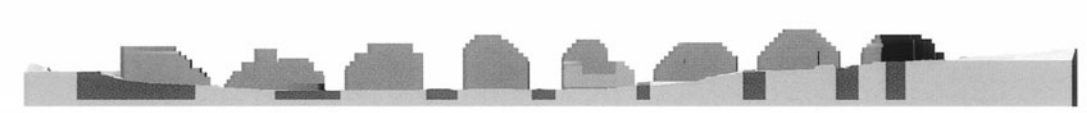


FIGURE 20. Hypothetical daylit development in Chattanooga (east-west section at 6th St. looking north).

Often, though not always, we have located light courts with an open side to the south. This allows an occupied roof garden to be sunny and wind-protected in winter. If the southern side of an atrium is lower than the north side, it also works better as a solar-heat collector for the building (a sunspace system). Finally, we have added a certain amount of randomness, based in part on the underlying parcel sizes and configurations and on the patterns of existing development. For instance, we have treated some blocks as a single large building, others as two large sites, and some as composed of several smaller parcels.

In creating this speculative CITY OF LIGHT, we have also attempted to maximize density (FAR) within the CLIMATIC ENVELOPE. We found that the existing downtown FAR is about 7.4, a large percentage of which is found in a few of the largest buildings. Maximum development filling the climatic envelopes would allow for a FAR of 15.3, while buildings with good daylighting, shown in Figure 19, still achieve a FAR of 10.8, an increase of 45% above the 2002 level. There is room for much growth while still providing access to the renewable resources of sun and light!

GENERAL CONCLUSIONS

Indications for Further Research

Thin towers set back from the street wall may have little effect on daylight access because they potentially intercept only a small fraction of the sky-dome as seen from a window of a building across the street. This hypothesis awaits systematic verification. Building shadows can have significant impacts on the performance of photovoltaic, solar domestic hot water, and passive solar heating systems. In the future, societal values for rooftop solar access may limit tall-building placement and form by new building restrictions to preserve rights to on-site sunlight resources.

Next, the study as a whole assumes overcast sky conditions. For cities in climates dominated by clear skies, it is expected that increased densities and larger DAYLIGHT ENVELOPES would be allowed, and that the daylight access envelope might become orientational, responding to sun path. In the same way, the methods for atrium building sizing assumed overcast conditions. Atria building form and its implications for urban planning should be explored for clear sky conditions. However, it should be noted that clear sky dominant climates are the exception in North America.

Finally, there are several questions related to projections and reasoning that follow from the studies of atrium building form. The assumption is made, based on prevailing wisdom and literature, that the atrium building maximizes land efficiency in large daylit buildings. This assumption might be questioned if more rigorous studies are done on the sizing of atria open on one or two sides, or for other C-, E-, and F-type buildings. In particular, atria with one or two sides glazed will usually provide much more light than toplit-only buildings. Therefore, building footprints and atrium width could decrease. Land efficiency aside, these building types should be considered for other reasons, including the provision for urban variety. This portion of the study could be recast using sidelit buildings as the dominant type.

The atrium sizing rule actually assumes unglazed light courts. This is a significant simplifying assumption because an atrium's roof glazing and structure can decrease light transmission by 20-80%, relative to an unglazed court. This means that a roof with a 50% light transmittance admits one-half the light and therefore would require a doubling of the target DF used in the ATRIUM SIZING RULE. This means a substantially larger atrium on larger blocks. Recommendations given herein may then be taken as the *minimum* sizes.

Conclusions

This article investigated the implications of daylighting for urban development patterns. It is a significant step in answering the question, "What would the form of the city be like if we were to take seriously the provision of daylight to all buildings?"

The results of urban design and planning decisions potentially last for centuries, the basic pattern of streets and blocks outliving a succession of buildings. If we are to shift over the next century to renewable forms of energy, then we must begin the transition in our cities now by building physical patterns that form the infrastructure for the provision of light to buildings. At this point in design history, we can begin to envision buildings that will elegantly sail late into this century when oil production has long peaked and the fossil fuel age waned. The buildings built today will outlive many of their energy sources and thus will be required to engage site-based energy sources of sun, wind, and light to meet their needs. This transition can be either easy or difficult. If cities continue to have development patterns driven primarily by real estate speculation, transportation planning, and corporate imagery, then much of the urban fabric may have to be reconstructed and reconfigured to facilitate design for ecological function. If however, cities take on the responsibility of creating physical patterns that support timeless ecological strategies, then their historic character and identities can be continuous and long-lived, facilitating the transition to the inevitable solar age.

NOTES

1. STREET CANYON RATIO is the proportion of street wall height to street width.

2. A foot-candle is an inch-pound measure of illuminance; specifically, the amount of direct light from one candle falling on a square foot of surface one foot away.

3. A lux is an SI measure of illuminance; 1 lux x 0.0929 = 1 foot-candle.

4. Illumination Engineering Society (IES USA). Illuminance categories are used for general recommendations about how much light to provide for a given task. Illuminance category C = 10-20 fc/100-200 lux; category D = 20-50 fc/200-500 lux (Rea, 1993:459-478).

5. Commission Internationale de l'Eclairage (CIE), an international lighting standards organization (CIE, 1970).

6. The DAYLIGHT AVAILABILITY CHART gives minimum maintained external illumination as a function of latitude for a given percent of the normal working day. Daylight for 85% of working hours was used as a reasonable design target. This figure is easily achievable in lower latitudes but is ambitious at far northerly latitudes. Larger DFS are required to provide the same minimum illuminance for a greater percentage of the day.

7. DFS are rounded to the nearest 0.5%. An average ambient illumination level of 20 fc, which falls between IES illuminance categories C and D, is appropriate for general illumination if electric task lighting is provided. For interior illuminance levels greater than 20 fc, the latitude groupings might vary from those given in the table.

8. FAR is established by the following relationship: FAR = *total floor area/footprint area*. Actual site FAR will usually be lower, since most buildings do not occupy their entire site.

9. Rentable area is assumed to be the net fraction of the total building floor area, and %RAD is the daylit fraction of the net area, assuming a 2.5*h* maximum penetration of daylight. Expressed another way, %RAD is found thusly: RAD = (A_d) … (G/N ÷ A_g)(100), where A_d = total daylit floor area; G/N = gross-to-net ratio; and A_g = total gross floor area of all floors. The area of the atrium should not be counted in the above calculation. The entire floor of the atrium, however, is assumed to be sufficiently daylit.

10. To provide the same 20 fc of illumination for 85% of working hours year round.

11. G/N ratio of 1.35.

12. Assuming average minimum 20 fc (215 lux) interior illumination level at 85% of working hours under overcast skies.

13. Assuming windows on 50% of the exterior wall of the ground floor and a 33% average exterior wall reflectance.

14. The study district is bounded by Martin Luther King Boulevard on the south, 4th St. on the north, U.S. Highway 27 on the west, and Georgia Avenue on the east.

REFERENCES

Baker NV, Fanchiotti A, Steemers K (1993) *Daylighting in architecture: A European reference book*. London: James and James.

Brown GZ, DeKay M (2001) *Sun, wind, and light: Architectural design strategies*, 2nd edition. New York: John Wiley.

Bryan H, Fergle RJ (1986) BRADA: A daylighting analysis technique for the Boston redevelopment authority. In S Zdepski and R McCluney (Eds.), *Proceedings of the 1986 International Daylighting Conference*, Long Beach, CA (4-7 November). McLean, VA: 1986 International Daylighting Organizing Committee, pp. 313-321.

Cartwright V (1986) Sizing atria for daylighting. Unpublished research paper, University of Oregon, Eugene.

Commission Internationale de l'Eclairage (CIE) (1970) *Daylight: International recommendations for the calculation of natural daylight* (Pub. CIE No. 16 (E3.2)). Paris: CIE.

DeKay M (1992) A comparative review of daylight planning tools and a rule-of-thumb for street width to building height. In SM Burley and ME Arden (Eds.), *Proceedings of the 17th National Passive Solar Conference, American Solar Energy Society (ASES)*, Cocoa Beach, FL (15-18 June). Boulder, CO: ASES.

DeKay M (1993) The relationship of building height to street width under overcast skies. In SM Burley and ME Arden (Eds.), *Proceedings of the 18th National Passive Solar Conference, ASES*, Washington, DC (22-28 April). Boulder, CO: ASES.

DeKay M (n.d.) Daylighting and urban form: Design and planning for daylight access. Forthcoming.

Flynn JE, Segil AW (1970) *Architectural interior systems*. New York: Van Nostrand Reinhold.

Hastings R (1994) Passive solar commercial and institutional buildings: A sourcebook of examples and design insight. In S Robert (Ed.), *International energy agency, solar heating and cooling: Task XI, passive commercial buildings*. London: James and James.

Holl S (1980) *The alphabetical city (Pamphlet architecture #5)*. New York: Princeton Architectural Press.

Knowles R (1981) *Sun, rhythm, form*. Cambridge: MIT Press.

Rea MS (Ed.) (1993) *Lighting handbook, reference and application*, 8th edition. New York: Illumination Engineering Society of North America.

Szerman M (1992) Daylighting in adjacent rooms connected to an atrium by artificial sky measurements. *Building Research and Information* 20(6):357-359.

Willbold-Lohr G (1989) Daylighting in glazed atria. In TC Steemers and W Palz (Eds.), *Proceedings of the Second European Conference on Architecture*, Paris (4-8 December). Dordrecht, The Netherlands: Kluwer Academic Publishers, pp. 16-20.

Additional information may be obtained by writing directly to Professor DeKay at the College of Architecture and Design, 1715 Volunteer Blvd., University of Tennessee, Knoxville, TN 37996, USA; email: mdekay@utk.edu.

AUTOBIOGRAPHICAL SKETCH

Mark DeKay is Associate Professor at the College of Architecture and Design, University of Tennessee, Knoxville. He received his B.Arch. from Tulane University in 1984, M.Arch. from University of Oregon in 1992, and became Registered Architect in 1992.

Professor DeKay specializes in ecological design theory and practice. He is a registered architect and has taught at the university level for 17 years. Prior to UT, he taught at Virginia Tech and Washington University in St. Louis.

Professor DeKay's research interest is in energy and environmental issues in building design and urban design, specifically, the impact of design decisions on environmental quality and the study of how to create ecological integrity through the form and organization of the built environment. He also has an emerging interest in integral theory and its applications to design.

His recently completed work focuses on multifunctional green infrastructure planning at the urban and landscape scales, including design studies for downtown Chattanooga, Tennessee, and the Beaver Creek Watershed in Knox County, Tennessee. His current writing projects include scholarly articles on daylighting, ecological design theory, and integral architecture.

The second edition of his book, *Sun, Wind, and Light: Architectural Design Strategies*, coauthored with G. Z. Brown, was published in 2001; it is a resource for designers to consider the form-generating potential of climatic forces. Other work includes knowledge-based mapping of climatic design and curricular projects on the technical education of architects.

Professor DeKay regularly teaches courses in graduate design studio, environmental control systems, and seminars in green design, climatic design, and architectural technology. He was the winner of the 1995 AIA Education Honor Award for the course "Environment and Buildings," a 2000 Fulbright Fellowship to India, and a 2005 AIA/Tides Foundation award for Ecoliteracy in Architecture Schools for his graduate design and technology courses.

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