Volumetric Implications and a Rule-of-Thumb for Thickness of Atria Buildings

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VOLUMETRIC IMPLICATIONS AND A RULE-OF-THUMB FOR THICKNESS OF ATRIA BUILDINGS

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ABSTRACT

Most tools available to designers 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 decisions or the implications for other important efficiency and economic decisions, such as gross to net planning ratios, floor area ratios, or the fraction of floor area daylit.

This study establishes a rule-of-thumb for building dimension from outside wall to atria and shows the relative impact of atria sizing on massing, floor plan efficiency, structural spans, and percentage of rentable areas daylit (%RAD), for variations in latitude and building height. During schematic design the rule-of-thumb may be used to size the dimensions of building wings adjacent to atria. The plan implications, presented graphically, can be used to assess schematic daylighting, economic, and structural implications of building height and thickness.

For a given building height, two major elements of atria buildings determine their form:

- The size and proportion of the atria.
- The building thickness.

The atrium building’s massing affects floor plan efficiency, structural spans, marketability, and the fraction of floor area daylit.

2. QUANTIFYING PRIMARY ATRIUM MASSING DETERMINANTS

2.1 Atria Size and Proportion

When the atrium is used as a lighting device for adjacent spaces, they must be proportioned carefully. Cartwright (2) has developed a simple atria sizing rule-of-thumb (R/T) for this purpose. By her method, the designer can determine the rough size of an atria in the early phases of the building’s design. The atria sizing R/T is presented as a graph, plotting daylight factor in the adjacent ground floor space against height to length ratio (H/L) of the atrium.

In general, the height/length proportion of the atria, the reflectances of interior materials, and the size of interior openings determines the daylight available to lower floors. Atria H/L varies with the daylight factor desired in interior rooms. For equal interior illumination levels and building height, higher daylight factors, and thus wider atria are required at high latitudes, due to lower overall daylight availability.

Since the atrium, or light court, requires a significant percentage of the area on each floor, the designer needs to be able to understand its impact on the maximum development potential of the site, usually measured in floor area ratio (FAR). Since many atria are conditioned spaces and must at least be sufficiently ventilated, the size of the atrium in relation to the rest of the building should also be considered. This can be approximated by considering the court area as a fraction of the building footprint. A larger atrium increases mechanical equipment requirements for the atrium itself.

Atria in tall buildings must be larger than in shorter buildings; with increased height comes increased structural spans to roof the court. The relationship between building height and the degree to which expensive long span structures must be employed is another critical factor to the designer in the schematic stage.

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2.2 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 atria and from the street side will generally be limited, as a rule-of-thumb to 2.5 times the height (H) of the daylight opening above the floor (4). Therefore, the building’s minimum thickness (T) is 5H (2 x 2.5H).

Assuming that the building has an internal circulation and service core between a daylit perimeter rental space and a daylit interior space adjacent to the atrium, a building with a 5H 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 leasable tenant areas that do not require daylighting. The proportion of the tenant 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 (T) could be increased above 5H. The question then arises, “How much can building thickness be increased above 5H while still providing daylight to most of the rentable space?” Three variables are important when the designer is determining this dimension:

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

3. METHODS

3.1 Atria Sizing

Since the daylight factor (DF) is defined as the percentage of interior illumination as a fraction of exterior illumination, for a constant interior illumination level, the required daylight factor increases with latitude, when under similar sky cover conditions, because of decreasing exterior daylight availability. The required daylight factor under overcast sky conditions for latitudes from 28° to 60° were estimated for 10, 20, and 50 foot-candle interior illumination levels, representing IES illuminance categories C and D.

The CIE daylight availability chart (1, 3), which gives minimum maintained external illumination as a function of latitude, for a given percent of the normal working day was used for this purpose. 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 DF’s are required to provide the same minimum illumination for a greater percentage of the day. Required DF’s are shown in TABLE 1.

The required daylight factor figures for providing 20 fc minimum of interior illumination were then grouped by latitude, allowing 1.0% DF range between groups as follows:

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Average DF</th>
</tr>
</thead>
<tbody>
<tr>
<td>28°-38°</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>40°-48°</td>
<td>2.5-3.0</td>
</tr>
<tr>
<td>50°-52°</td>
<td>3.5-4.0</td>
</tr>
<tr>
<td>54°</td>
<td>4.5</td>
</tr>
</tbody>
</table>

DF’s 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 illumination levels greater than 20 fc, the latitude groupings might vary from those given above.

Using the Cartwright atria sizing R/T (2), atria proportions were determined, using daylight factors at each end of the range within each latitude group, for buildings of four, six, and ten stories. A 12’ (3.7 m) floor-to-floor height and H = 10’ (3.1 m) were assumed. These results are shown in TABLE 1. The most restrictive of the atria H/L proportions within each latitude group are shown in bold face; these are used to create the graphic matrices which follow.

| TABLE 1. DAYLIGHT FACTOR AND ATRIA PROPORTION REQUIRED UNDER OVERCAST SKY FOR VARIOUS LATITUDES (for 20 fc, 85% of daily working hours) |
|-------|-------|-------|-------|-------|-------|
|       | IES Category | Atria |       |       |       |
|       | C      | D      | Ratio | Length (L)** |       |
| lat. | 10-20 fc | 20-50 fc |       |       |       |
| 28  | 1.0-1.5 | 1.5-4.0 | 1.6   | 36’   | 53’   | 76’   |
| 30  | 1.0-1.5 | 1.5-4.0 | 1.6   | 36’   | 53’   | 76’   |
| 32  | 1.0-1.5 | 1.5-4.5 | 1.6   | 36’   | 53’   | 76’   |
| 34  | 1.0-2.0 | 2.0-4.5 | 1.6   | 36’   | 53’   | 76’   |
| 36  | 1.0-2.0 | 2.0-5.0 | 1.35  | 36’   | 53’   | 76’   |
| 38  | 1.0-2.0 | 2.0-5.5 | 1.35  | 36’   | 53’   | 76’   |
| 40  | 1.0-2.5 | 2.5-5.5 | 1.2   | 40’   | 60’   | 100’  |
| 42  | 1.0-2.5 | 2.5-6.0 | 1.2   | 40’   | 60’   | 100’  |
| 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 | 1.1   | 44’   | 65’   | 76’   |
| 50  | 2.0-3.5 | 3.5-9.0 | 0.95  | 51’   | 76’   | 126’  |
| 52  | 2.0-4.0 | 4.0-10.0| 0.85  | 56’   | 85’   | 141’  |
| 54  | 2.0-4.5 | 4.5-11.5| 0.75  | 64’   | 96’   | 160’  |
| 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               |

* Atria proportions are for roughly square atria, determined by Cartwright rule-of-thumb. H = height of atria.
** Bold figures are used to size atria plans in Figures 1 & 2. H = 12’ (3.7 m) per story.

3.2 Comparative Plans and Analysis

Three matrices were developed, one each for plan variations of building thicknesses of 3H, 6H, and 7H. Building plans are 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 that can be daylit (RAD)

The matrices for T = 6H and T = 7H are shown in Figures 1 and 2. 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 as service space. The dimensions shown above each plan indicate the length of the atria in plan.

Volumetric implications for T = 7H are illustrated graphically in Figure 3.

Atria length can be determined using the building height - in this case, multiples of the 12’ (3.7 m) floor to floor height - along with the predetermined H/L ratio from TABLE 1.

FAR 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. FAR is established by the following relationship:

\[
\text{Total Floor Area} = \text{Footprint Area} \times \text{FAR}
\]

Actual site FAR will usually be lower since most buildings do not occupy their entire site.

The percentage of rentable area daylit (%RAD) is determined assuming a gross to net ratio (G/N) of 1.35. Typical gross to net ratios for office and apartment buildings are in the range of 1.25 - 1.35. 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 2.5H maximum penetration of daylight. Expressed another way, %RAD is found in this way:

\[
\%\text{RAD} = \left( \frac{A_d}{A_g} \right) \left( \frac{G}{N} \right) \times 100
\]

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 atria should not be counted in the above calculation. The entire floor of the atria, however, is assumed to be sufficiently daylit.

4 RESULTS

4.1 Analysis Results

Required daylight factors, to provide the same 20 fc of illumination for 85% of working hours year round, range from 1.5 at 28°-30° latitude to 11.5 at 60° latitude, indicating that the target is probably not practical at 60°. H/L for the four latitude group ranges from from 1.6 : 1 at 28°-30° latitude to 0.4 : 1 at 56°.

10 story atria have serious structural consequences above 38° lat., where spans exceed 100’ (30 m). Spans for 4 and 6 story atria are less than 100’ at all latitudes.

Atria area as a percentage of a typical floor area or building

![Atria Building Plan Forms for T = 6H Under Overcast Sky (% Rentable Area Daylit @ G/N = 1.35)](image-url)
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 ten 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 = 7H, 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.

The results clearly show that for a typical office or apartment building gross to net ratio (G/N) of 1.35, 80 - 100 %RAD can be achieved with a building thickness of 6 -7H. Below 6H, 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 7H, the %RAD falls below 80%. At 8H, 80 %RAD can not be achieved. These findings hold true for all latitudes and building heights tested.

4.2 Building Thickness R/T

The results suggest a rule-of-thumb for building thickness, using a G/N of 1.35, as follows:

<table>
<thead>
<tr>
<th>28°-38° lat.</th>
<th>40°-48° lat.</th>
<th>50°-52° lat.</th>
<th>54° lat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>36°</td>
<td>44°</td>
<td>56°</td>
<td>64°</td>
</tr>
</tbody>
</table>

4 Story

- FAR 3.8
- 36° 6%
- 44° 86% RAD
- 56° 89% RAD
- 64° 89% RAD

6 Story

- FAR 5.6
- 36° 86% RAD
- 44° 88% RAD
- 56° 89% RAD
- 64° 89% RAD

10 Story

- FAR 8.5
- 36° 89% RAD
- 44° 89% RAD
- 56° 89% RAD
- 64° 89% RAD

For roughly square atria buildings, use a thickness dimension between outside wall and atria of 6 H 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 \( t = 7H \), \( 80 < \%RAD < 90 \).

Because the R/T relationship holds true for all building height/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 building thickness (T) and of the gross to net ratio (G/N). This becomes apparent when examining Figures 2 and 3: there is only a small degree of variation in %RAD for a given value of T.

4.3 Gross Floor Area Targets

A simple method that can be used in a generative way is to use the 2.5H rule and the following table to assure adequate %RAD in a proposed schematic design:

![Atria Building Plan Forms for t = 7H Under Overcast Sky](% Rentable Area Daylit @ G/N = 1.35)
TABLE 2. REQUIRED PERCENTAGE OF GROSS FLOOR AREA DAYLIT

<table>
<thead>
<tr>
<th>%RAD</th>
<th>1.25</th>
<th>1.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>80</td>
<td>74</td>
</tr>
<tr>
<td>90</td>
<td>72</td>
<td>67</td>
</tr>
<tr>
<td>80</td>
<td>64</td>
<td>60</td>
</tr>
</tbody>
</table>

For instance, for a building G/N of 1.35, daylighting 67% of the gross floor area would yield a 90% RAD. Since in the earliest stages of design when the most basic massing decisions are made, sufficient detail will not have been developed to determine the precise %RAD by analyzing the plans, TABLE 1 offers a quick approximate target for the designer. If the target is met or exceeded, then a sufficient area of the tenant space will likely be able to be daylit as the design develops. The formula given above for the calculation of %RAD daylit can be also be used to find a more detailed estimate.

5. CONCLUSIONS

The findings of this study suggest a simple, approximate relationship between building thickness from light court to outside wall and the fraction of tenant space daylit. This R/T can be used in conjunction with an atrium sizing R/T to establish building massing during schematic design. Other tools for the daylight design of individual spaces may be employed after major building form decisions are made. Since a daylight consultant is not usually retained by the designer at the beginning of the project, the designer may proceed with schematic and preliminary design with the confidence that basic decisions about the building’s form will not have to be revised later in the design process. The atria building thickness R/T can be stated simply and can be easily remembered by the designer.

The results further show that the design of atria as lighting fixtures have serious implications on 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° lat., a ten story building requires 6.1 times the light court area per floor as does a four story building providing the same daylight factor. The 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 ten story building increases its area per floor only 1.6 times that of the four story building, while incurring 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.

In sizing atria, it is important to first determine the appropriate required daylight factor. Generalizations about matching DF recommendations to tasks or occupancies can be misleading.

Fig. 3. Volumetric Implications of Atria Sizing Under Overcast Sky
(T = 7H)
given wide variations in daylight availability under different sky conditions and at different latitudes. These generalizations can result in undersized atria, and thus underlighted spaces, or can result in oversized atria, leading to excessive thermal transfer and capital investment.

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. One basic measure of both market and aesthetic potential is the %RAD. For any daylit building, the %RAD can be estimated from TABLE 2 before any details are known about the building's design. For atria buildings, the building thickness R/T can be used to assure an adequate fraction of the tenant space will be daylit.

Atria buildings can cover significant site area. If expensive urban land is to be used efficiently, the urban pattern could be planned based on daylight building forms. Streets could be laid out to serve buildings, rather than building limits being determined by streets. The plan form implications of generic atria buildings for a given building height, illumination requirement, and location’s daylight availability, can be used as building blocks for determining street/block patterns. From an urban planning perspective, block sizes for new development could be set with dimensions appropriate to the generic atria building module that corresponds to the city's latitude (or specific daylight resources) and the desired height limit in the neighborhood. This would insure that land is used efficiently, while still providing for daylighting of interior spaces. It would also contribute to the regional identity of a city.

The next phase of this research will be to combine the generic atria modules from this study with a R/T for street width to building height in order to generate both ideal urban street block patterns for daylighting and to determine the land use planning parameters, such as density limits, appropriate for ensuring daylight access.

6. REFERENCES


