THE ENERGY POTENTIAL OF DAYLIGHTING IN A CLASSROOM

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An analysis is presented where a classroom of prescribed size and occupancy has various fenestration designs applied to it and the resulting thermal and daylighting energy performance calculated. An attempt is made to relate the heating/cooling requirements of a window opening with its potential as a source of natural light. The parameters glass area, glass type (double-pane, reflective, etc.), and ceiling height are evaluated for a classroom in Ann Arbor, Michigan operated over the course of a 9-month school year. Comparisons are made between the performance of a design based on ASHRAE Standard 90-75 and alternate fenestration designs. Although the computerized thermal analysis and the daylight analysis had to be done separately, actual weather data and corresponding daylight readings for Ann Arbor, Michigan are used for both. Results show a potential energy savings when daylighting is carefully integrated into the building's envelope design, especially for southern exposures, but such savings will be realized only if applied with the other energy variables in mind.

INTRODUCTION

The oil embargo of 1973 brought attention to the need to reduce energy wastefulness in buildings and has stimulated a renewed interest in daylighting. Many architects and engineers feel natural illumination has a potential as an energy-saving tool. It has been estimated that roughly 33 percent of the nation's total energy is consumed in heating, cooling, and lighting buildings [1], yet at a time when much research is being directed to the development of renewable energy systems, such as solar heating and cooling, little effort is being spent on natural lighting (daylighting). Since up to five percent of the nation's energy use is attributed to electric illumination [2,3], a study of daylighting as a source of both natural light and beneficial solar heat gain seems particularly appropriate.

The purpose here is to explore daylighting as one possible technique for energy conservation in buildings. The goal is to answer the question: at a time when energy conservation is a major concern, can daylighting be used as an energy-conservation tool in current building design? To answer this question, three areas of concern were evaluated -- glazing area, glazing type, and ceiling height. All three have important daylighting as well as thermal energy implications.

Several energy-related factors affecting daylighting can be identified as follows:

- conduction losses through both glazing and window frame;
- convection losses due to infiltration and/or ventilation;
- solar heat gain;
- heat gain due to the supplemental electric lighting; and
- supplemental electric energy for the lighting systems.

These factors respond to external weather conditions; therefore they are continually changing. To retain these dynamic responses, a daylighting/energy analysis must be evaluated on a dynamic basis and be performed over a complete weather cycle. The close interrelationship between these energy-related factors and the external climate conditions requires that detailed weather data and daylight-availability data be used. The relationship between incident solar insolation and daylight should also be retained as much as possible.

The task was undertaken at The Pennsylvania State University to perform a daylight/energy analysis that would incorporate all factors mentioned above. The intent was to evaluate more precisely the daylighting performance and to answer the question previously stated.

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METHODOLOGY

A classroom was selected as the study model. The advantages of a classroom lie in its consistent size and occupancy -- many of the classrooms constructed in the past 20 years follow a similar design. The study model's base conditions were modeled after existing classrooms in the State College Senior High School. In this way direct comparisons were possible between study conditions and those found in the full-scale classroom. The classroom dimensions were 9.14m x 6.71m (30' x 22') and had an initial 3.05m (11') ceiling height before alterations were made (Fig. 1). The occupancy comprised of a teacher and 24 students who used the room from 8:00 a.m. - 12:00 noon and from 1:00 p.m. - 4:00 p.m., Monday through Friday. The classroom was occupied during a 9-month school year (September - May), except legal holidays. Table 1 lists other pertinent information regarding building operating conditions.

Weather conditions were taken for Ann Arbor (Willow Run Airport), Michigan, since it was the only location with sufficient daylight availability data. These data were from Boyd's measurements taken between 1953 and 1954[4]. He recorded and classified illuminance using a bin method where four bins were established based on the maximum to minimum ratio between the vertical readings recorded (north, south, east, west). The bins, or classes as he labeled them, can be envisioned as follows:

Bin	Max/Min Ratio	Sky Condition
Class A	1.0 - 1.5	Perfectly Overcast
Class B	1.5 - 2.5	Mostly Cloudy
Class C	2.5 - 3.5	Partly Cloudy
Class D	3.5	Clear Sky

Boyd took readings every 15 minutes and classified these values into one of the four classes for each month, repeating this process for an entire year. Monthly totals were averaged for each class and listed as shown in Table 2. By grouping the data in this way, a programmable calculator made it possible to calculate the interior daylight conditions, as described below.

Thermal weather data were obtained from the U.S. Weather Bureau[5]. Since the information was supplied in the form of monthly averages, maxima, minima, and standard deviations, the Monte Carlo computer program developed by Degelman[6] was used to obtain hourly weather data. The program has a probabilistic and a deterministic nature and is based on statistical simulation methods. A validation procedure revealed good correlation with actual hourly weather.

The hourly thermal computations were done through an interactive process between Degelman's WEATHER program and a companion energy analysis program BEAP-4.[7,8] This second program, developed by the Department of Architectural Engineering at the Pennsylvania State University, supplied peak design loads and year energy consumption in accordance with ASHRAE recommended procedures.[9] Although mean temperatures were prescribed (Table 1), an hourly indoor temperature swing allowed temperatures to vary $\pm$ 1.7°C (3°F) during school hours and + 8.3°C/-5.5°C (+15°F/-10°F) during periods of no occupancy. The program also adjusts the thermal U-value hourly in response to the varying wind speed. Both computer programs have been designed to provide loads on the equipment and are usually augumented with an equipment simulation package to determine the entire system requirements, but for the purpose here, the analysis stopped at the loads phase. In this way, questions regarding equipment performance were avoided.

The lighting loads were computed on a programmable calculator. It took as input exterior vertical and horizontal illumination (E_v and E_n), the ground reflectance (Rg), and the time duration at this value, and the, and yielded electric energy and thermal gain as output (Fig. 2). The Lumen Method[10] predicted interior daylight illumination from these exterior daylight data. This method is recommended by the Illuminating Engineering Society of North America[11] and has the ability of calculating interior daylight for clear and overcast skies. Being based on empirical measurements on full-scale classrooms,[12] this predictive method, as apposed to other daylighting methods, seemed particularly appropriate. Such parameters as interreflections, ground reflections, and directionality of reflected light were considered, but of special importance was its ability to incorporate Boyd's data as input.

The Lumen Method was used to obtain two coefficients, A and B, such that,

$A = A_{ft} \times MF \times T_g \times C_{sky} \times K_{sky}$; and

$B = A_{eff} \times MF \times T_g \times C_{ground} \times K_{ground} \times 0.5$

where,

A = effective glass area

MF = maintenance factor

T_g = glass transmission factor

C & K = tabulated emperical values found in the Lumen Method tables[10].

Since only E_v and E_h changed over time, a general equation,

$E_{interior} = E_{sky} + E_{ground} = (A)E_v + (B)E_hR_g$

was developed for each sky condition and for each of three points in the room. The three points--a maximum, a mid-point, and a minimum--corresponded to locations 1.6 m (5 feet) from the fenestration, the middle of the room, and 1.6 m (5 feet) from the interior wall, respectively (Fig. 1), were used to establish zones with the illumination of each point respresenting the average for that zone.

The electric lighting system comprised of three rows (corresponding to the three zones) of four surface - mounted luminaires each. Fluorecent luminaires (I.E.S. - #30)[13] with two lampes and prismatic wrap around lens were used. The system provided 50 footcandles of maintained illumination on a horizontal work plane in accordance with current recommendations of the I.E.S. (RQQ committee report).[15] The electric lighting system was designed to match the power budget allowed by Section 9 of ASHRAE Standard 90-75[14] when operated at full power output. In this way, any lighting system that meets the ASHRAE requirements should perform at least as well as the above design.

The fluorescent dimming strategy was also separated into three sensor/luminaire systems one for each row of luminaires, and was designed to respond to its own daylighting level. The dimming performance followed a simple typical dimming equation,

% input power = 0.7 (% light output) + 0.3.

This linear equation assumed that the power load would approach 30% of the full load as the light output approached zero, but that once this point was reached, the power was temporrarily shut-off. Such an equation represents a conservative yet realistic estimate of dimmer performance [16,17,18].

The interfacing between the computerized thermal analysis and the daylighting analysis can be best understood by reviewing Figure 3. Monthly weather information was divided into two parts: monthly daylight data recorded in bins and the other weather data recorded as monthly summaries of averages, maximums, minimums, and standard deviations. These latter values were translated into hourly values via computer weather modeling using the WEATHR program, discussed above, and interactively fed into the building loads program. The computed electric loads were added as a block load month by month. The heat from the luminaires was either added to the monthly cooling load or subtracted from the monthly heating load, depending on whether or not it was a month requiring cooling. This approach works well as long as each month can be defined as either a cooling or a heating month. Fortunately, the two months (October and April) which required both, had low lighting loads, and therefore the uncertainty in knowing whether to add or subtract affected the results very little.

It was hoped a coincident daylight/solar heat gain analysis was possible, but because of an insufficient data base, a less satisfactory approach had to be taken. Although the methodology described used monthly weather simulations, all data were based on real climatic conditions as much as possible. Of particular importance was the application of detailed daylight information, of which Boyd's data are the most complete data presently available. The results, as will be shown, compare well with similar studies where instead of modeling the hourly weather conditions, the sky conditions were modeled.[19,20]

DISCUSSION

The analytic procedure was to establish an initial set of conditions, making alterations in the design as each daylighting variable was studied. For each alteration, thermal and lighting analyses were performed separately, adding the results for the total energy consumption. Alterations in the variable, glass area, were made first. Four glass areas were evaluated: no glass; the maximum allowed under ASHRAE Standard 90-75 (25%); an alternate fenestration design (46%); and the existing conditions as found in the State College High School (73%). Since it was impractical to try meeting the Standard with single glazing, double glazing was substituted. The results are shown in Figures 4 and 5. The dotted lines represent a region of uncertainty where the apex of the curves is cut out by simply connecting the two end-points. Recognizing that the apex represents the optimum energy point, this region should not be overlooked, but it must be understood that for daylighting purposes, glass areas under 20% of the wall area are not useful since severe glare problems quickly develop.

It is clear the southern exposure requires the least energy, the northern exposure the most, the east and west exposures somewhere in between. For the non air-conditioned classroom, daylighting causes energy efficiency at approximately 25% glass area for east/west exposures and more than 60% for south exposures. In the air-conditioned classroom, the difference between exposures is less. Also, the slope of the curves is steeper, especially for the south exposure where the slope changes drastically. But only when these curves are put in contrast with those without daylight utilization can the daylighting impact really be shown. Such a comparison is made in Figure 6 for the north and south exposures where daylighting is seen to reduce the annual load by up to one third. Clearly the daylighting role becomes a critical factor in the energy efficiency of the window.

These curves can also be used to evaluate the relative impact of the Section 4 requirements of ASHRAE 90-75. Judging by Figure 4, it appears that by satisfying only the overall U-value (U_o) to meet the non-air-conditioned requirement saves all but the north exposure from excessive energy waste. The east and west orientations begin to consume slightly more energy than the no-glass condition, yet still within a $\pm$ 10% range. When both the overall U-value and the Overall Thermal Transfer Value (OTTV) are met, Figures 4 and 5 imply an energy savings for South, East and West exposures, even though only the air-conditioned classroom requires this. Not until Figure 6 is shown does the problem surface. In meeting both requirements, it is only when daylighting is included that the full potential of the Standard is reached, yet within this standard no direct credit is given for daylighting.

If from the standpoint of glass area, daylighting is said to be energy efficient, the next step would be to determine the role of glass type on performance. Here only the south exposure was evaluated (Fig. 7). This bar chart displays the double-glazed window as the most conserving. It is noted that tinted and reflective glazing provide no energy savings, even for an air-conditioned made, but this is due to the lack of summer-time use and would change drastically if the summer months were included. The low shading coefficients and low daylight transmittance prevent the tinted and reflective glazings from being of any value here.

Another variable of concern in daylighting is the ceiling height. A ratio of between 2 and 2-1/2 to 1 of room depth to ceiling height will usually provide acceptable visual daylight uniformity on the work plane, but also requires a larger air volume and proportionately more glass (assuming the fenestration extends to the ceiling). When these proportions are exceeded, uneven daylight distribution usually triggers a psychological response causing the user to turn on the electric lights, even though adequate task illumination may exist. It should also be pointed out that glazing should normally extend to the ceiling, not only for light penetration, but also in order to minimize glare. ALthough it is possible to separate the fenestration into a vision strip (low glass) and glass along the ceiling (high glass), the daylighting predictive method employed could not evaluate such a configuration.

Figure 7 shows the classrooms energy performance as a function of ceiling height. As expected, increasing the ceiling height increases the energy demand. Thus, to meet the need for illumination deep within the classroom, the added energy for electric illumination is not as great as when providing this light from the windows.

CONCLUSIONS

The conclusions should begin with a special note. The intent of this paper was to answer a specific question assuming a well defined set of conditions; to project these results by saying they apply to other conditions equally well is dangerous. In some respects this classroom is unique. Such parameters as occupancy, operating schedule, location, and electric lighting system, all held constant throughout this analysis, may significantly affect the results if changed. Nonetheless, useful information can still be obtained.

The following conclusions are drawn:

1. The energy efficiency of a building designed for daylighting is strongly affected by the other energy variables. It is not realistic to separate the daylight energy apart from its related solar heat gain or conduction losses.

2. The daylighting/energy relationship is highly dependent on exterior weather conditions, the installed wattage of the lighting system, and on the dimming strategy.

3. For a classroom following conventional daylighting design, a 2.44m (8-foot) ceiling is the most efficient. Thus, adjusting ceiling height for light penetration alone is not energy conserving.

4. Double glazing is extremely important when daylighting is employed as an energy tool. Multiple glazing reduces conductive losses while still allowing a high glass transmittance and shading coefficient.

5. For the 9-month school year, reflective films and heat absorbing glass do not save energy. Even for the "air-conditioned" classroom, the losses in daylight and beneficial solar heat gain do not outweigh the cooling advantages.

6. When daylighting is fully utilized, glazing up to the maximum percentage allowed under section 9 is almost always beneficial. The only exception is the northern exposure, and east/west exposures over the O.T.T.V. limit.

7. As seen in Figure 4, daylighting holds a dominant role in the energy usefulness of fenestration.

8. Finally, the answer to the initial question can be answered: Yes, at a time when energy conservation is a major concern, daylighting can be used as a tool for energy conservation in buildings.

But with the answer to one question comes the asking of many others. What kind of psychological implications does daylighting have in the environment? Are teachers willing to let the lights be turned down, or off, if enough daylight is available? What is the daylight potential in other buildings? These and similar questions need to be addressed if daylighting is to be reinstated as an aid in meeting the energy needs of the future.

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Table 1

Classroom Operting Conditions

Ventilation Load		472 m^3/sec/person (10cfm/person)
Free Cooling Cut-Off Temperature		11°C (52°F)
Occupancy Load:	Sensible	73.28 w/person (250 Btuh/person)
	Latent	58.62 w/person (200 Btuh/person)
Heating Dry-Bulb Temperature		22°C (72°F)
Relative Humidity		40%
Cooling Dry-Bulb Temperature		24°C (75°F)
Relative Humidity		50%
Room Surface Reflectances:		
	Wall	0.59
	Ceiling	0.80
	Floor	0.30
Window Factors:		
	Glass Transmittances (Visible)	0.89 (single glazing)
		0.79 (double glazing)
		0.19 (tinted glazing)
		0.15 (reflective glazing)
	Shading Coefficients	1.00 (single glazing)
		0.90 (double glazing)
		0.53 (tinted glazing)
		0.37 (reflective glazing)
	Mullion Factor	0.89
	Maintenance Factor	0.90
Lighting Systems:		
	Maintained Illuminance	50 Fc
	Luminaire Type	IES#30
	Coefficient of Utilization	0.58
	Lumens per Lamp	3150
	Lamps	2 - F 40/CW/RS
	Luminaire Dirt Decpreciation (LDD)	0.90
	Lamp Lumen Decpreciation (LLD)	0.84
	Lamp/Fixture/Ballast Wattage	108 W
	Power Budge	1.97 w/S.F.

Table 2. Daylight Availability (from Boyd, 1958)

Month Year	Class	% Of The Time At This Class	Number of 15 Minute Intervals	Horizontal Illumination (Footcandles)	North Vertical Illumination (Footcandles)	South Vertical Illumination (Footcandles)	East Vertical Illumination (Footcandles)	West Vertical Illumination (Footcandles)
January 1954	A	68	326	720	340	380	350	370
	B	7	34	1560	570	1190	720	900
	C	4	19	2750	730	1960	1190	940
	D	21	101	2740	430	4810	2000	1400
February 1954	A	50	252	1140	550	610	550	590
	B	8	40	2600	860	1970	1330	1170
	C	2	11	2340	790	2230	1510	1160
	D	40	201	3370	580	5260	2340	1490
March 1954	A	50	264	2200	890	1000	930	940
	B	3	16	3020	1040	1700	1320	1420
	C	12	63	4080	1110	3250	1940	1850
	D	35	185	5720	840	5330	3730	2010
April 1953	A	33	174	2590	990	1110	1030	1100
	B	16	85	4110	1230	2220	1670	1720
	C	5	26	5330	1240	3070	2220	2020
	D	46	243	6790	910	4520	3060	2830
May 1953	A	41	197	2740	1050	1170	1130	1150
	B	15	72	4270	1500	2160	1730	1740
	C	7	34	5500	1510	3060	2070	2430
	D	37	177	7870	1190	4220	2590	3350
September 1953	A	10	46	2480	970	1280	1140	1050
	B	11	50	2670	920	1620	1050	1400
	C	6	27	3810	990	2409	1390	1890
	D	73	333	6650	790	5680	3530	2540
October 1953	A	17	86	1200	510	570	560	570
	B	5	25	2000	720	1360	970	1220
	C	2	10	2930	870	2500	1250	1730
	D	76	383	5210	650	6350	2980	2810
November 1953	A	37	187	1130	510	640	550	600
	B	9	45	2040	740	1630	1140	1000
	C	5	25	2470	720	2410	1460	920
	D	49	247	3080	560	5190	2360	1570
December 1953	A	39	206	820	370	470	420	440
	B	10	53	1590	600	1300	800	940
	C	7	37	1980	660	1900	1030	1140
	D	44	232	2350	510	4290	1660	1350

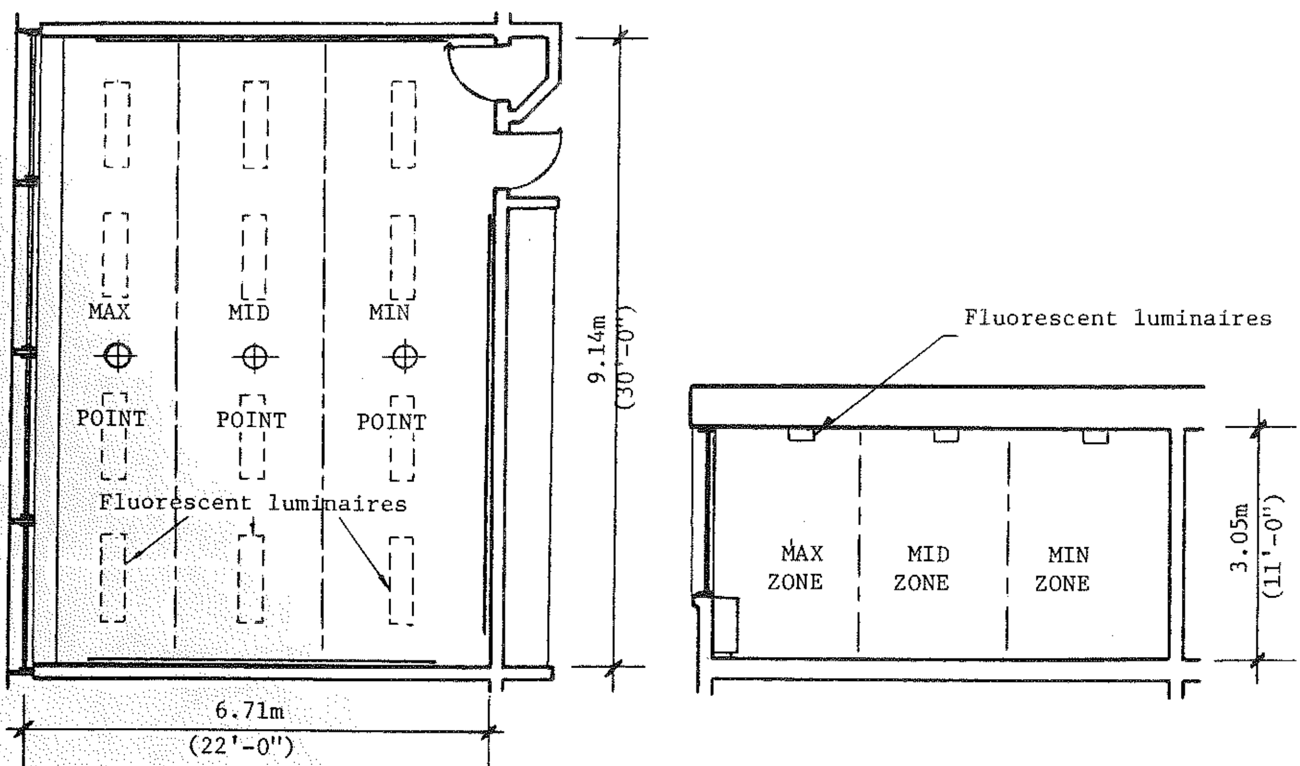

Figure 1. The classroom as zoned for lighting purposes.

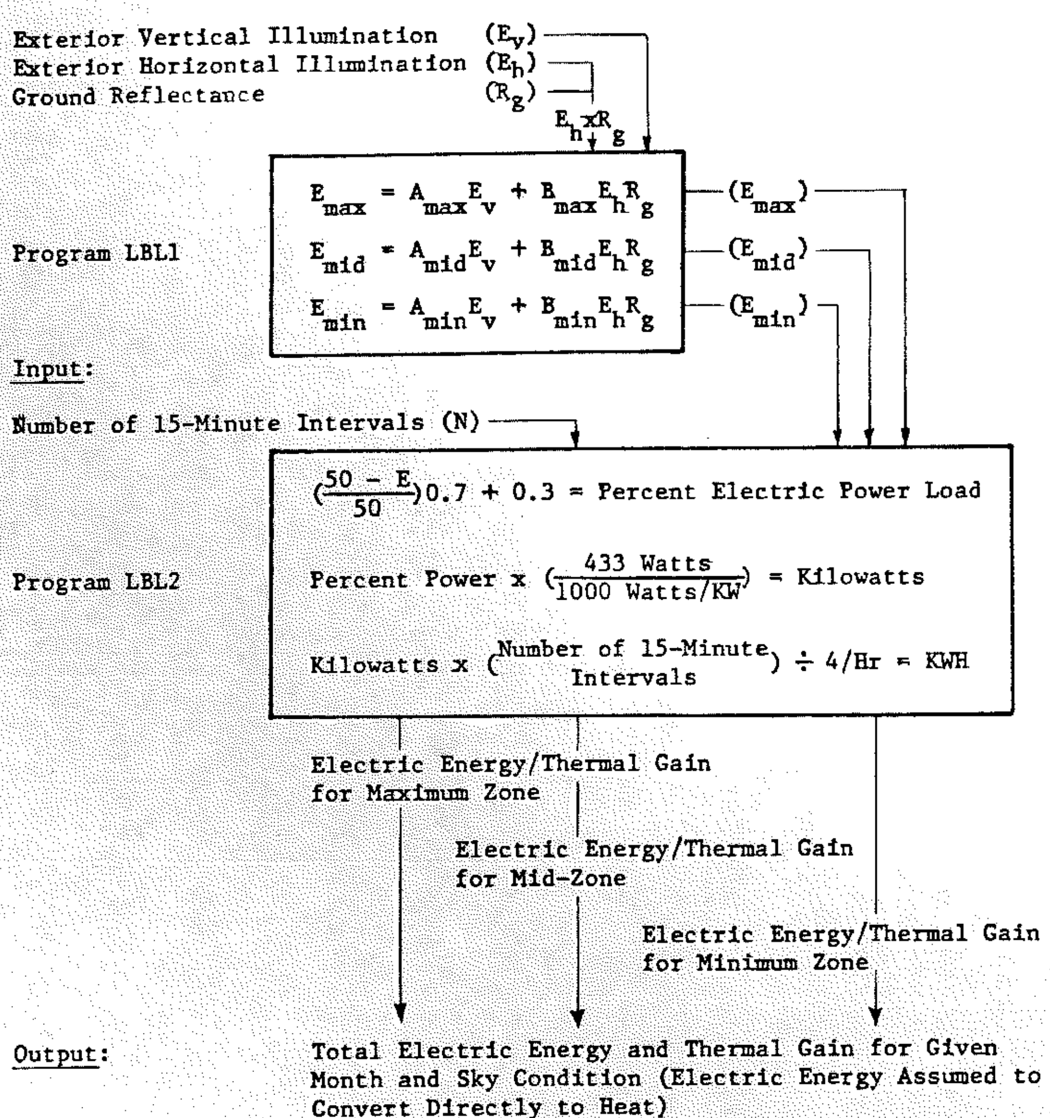

Figure 2. Flow chart for using the programmable calculator to predict energy consumption due to the electric lighting.

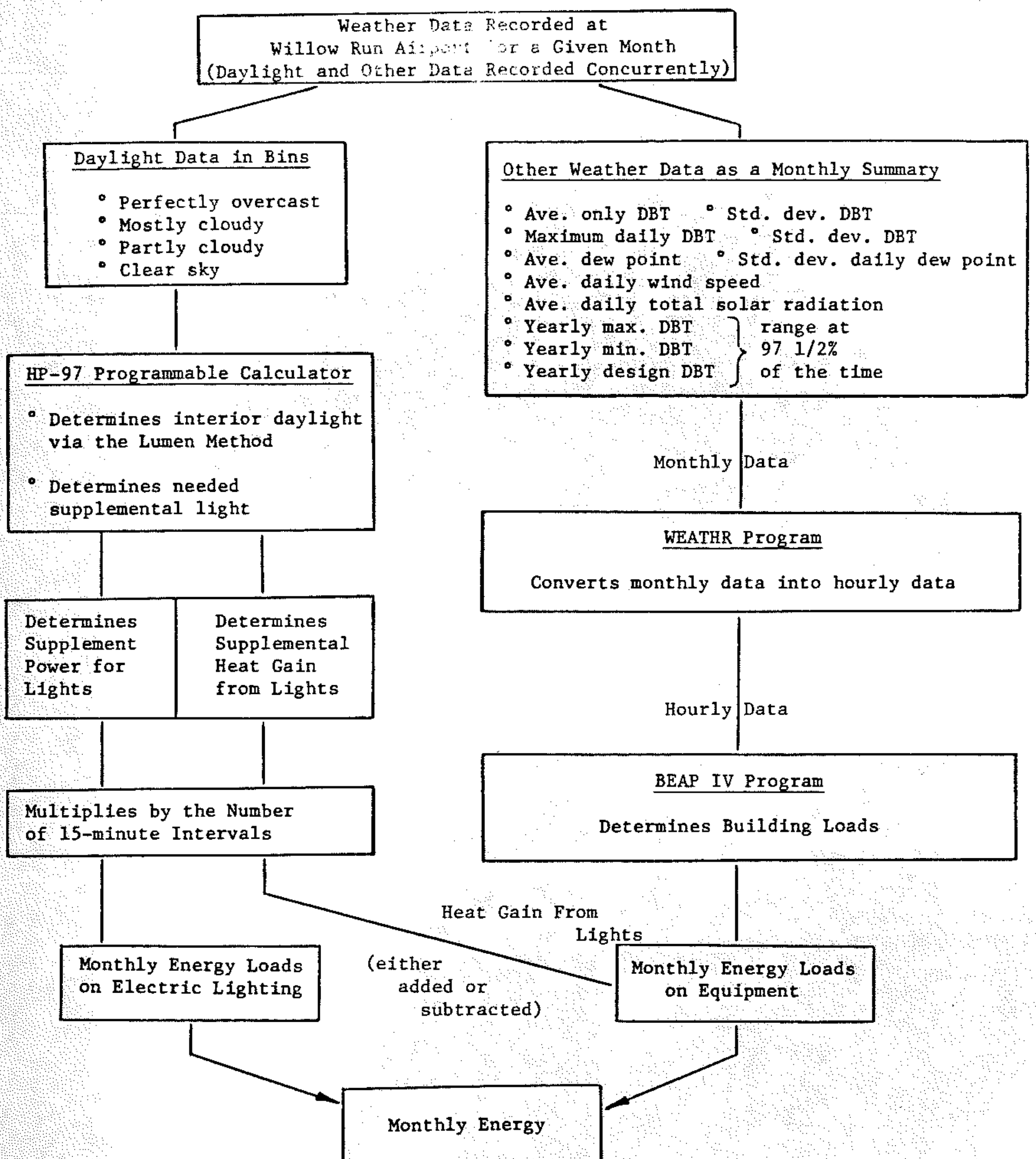

Figure 3. Flow chart for calculating the monthly energy consumption.

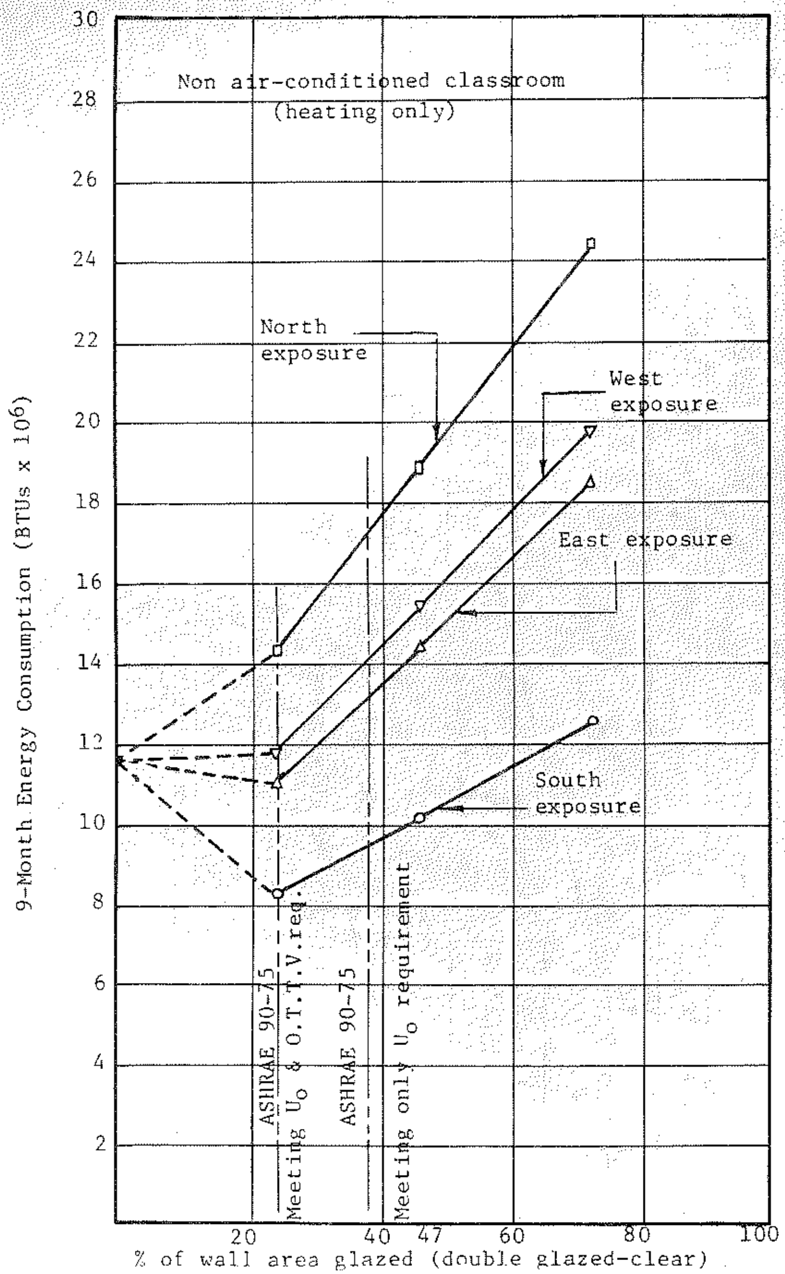

Figure 4. Energy performance as a function of glass area for a "non-air-conditioned" classroom (heating only).

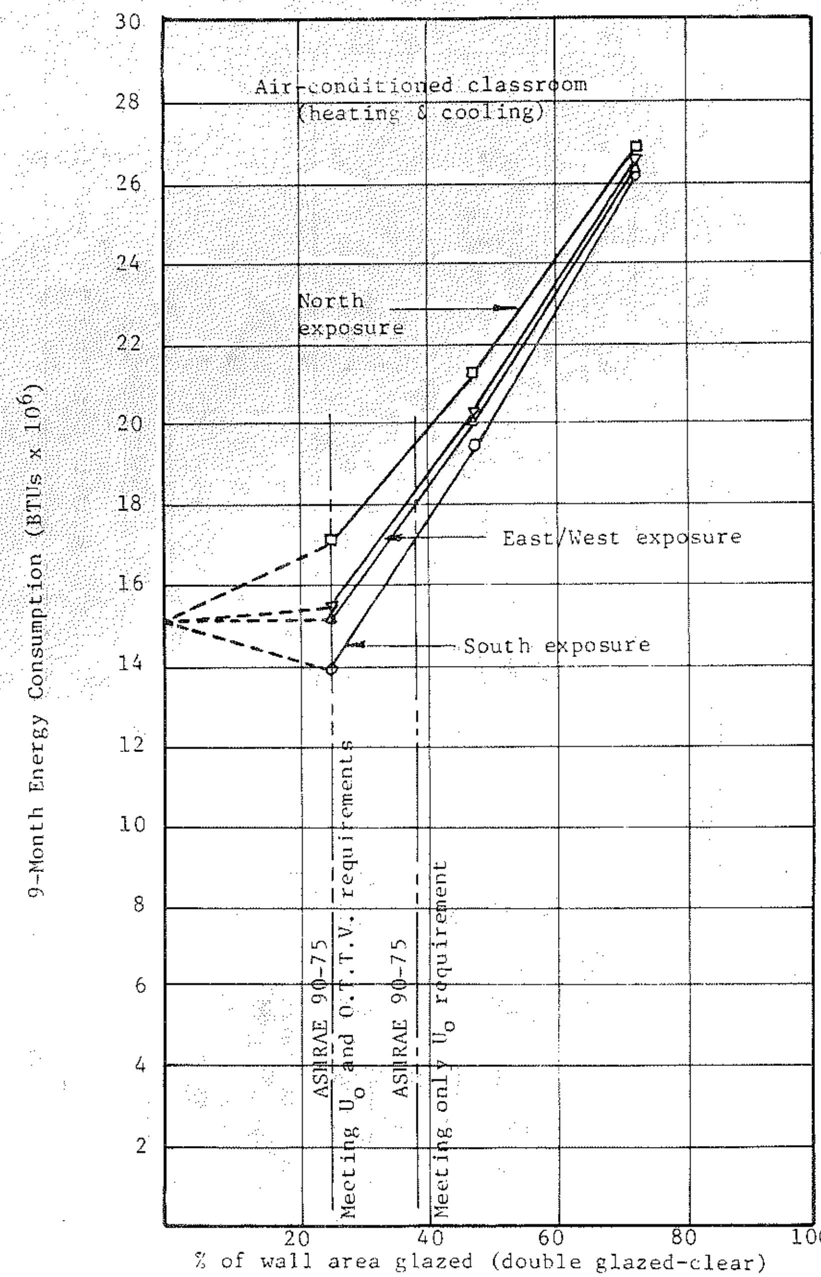

Figure 5. Energy performance as a function of glass area for an "air-conditioned" classroom.

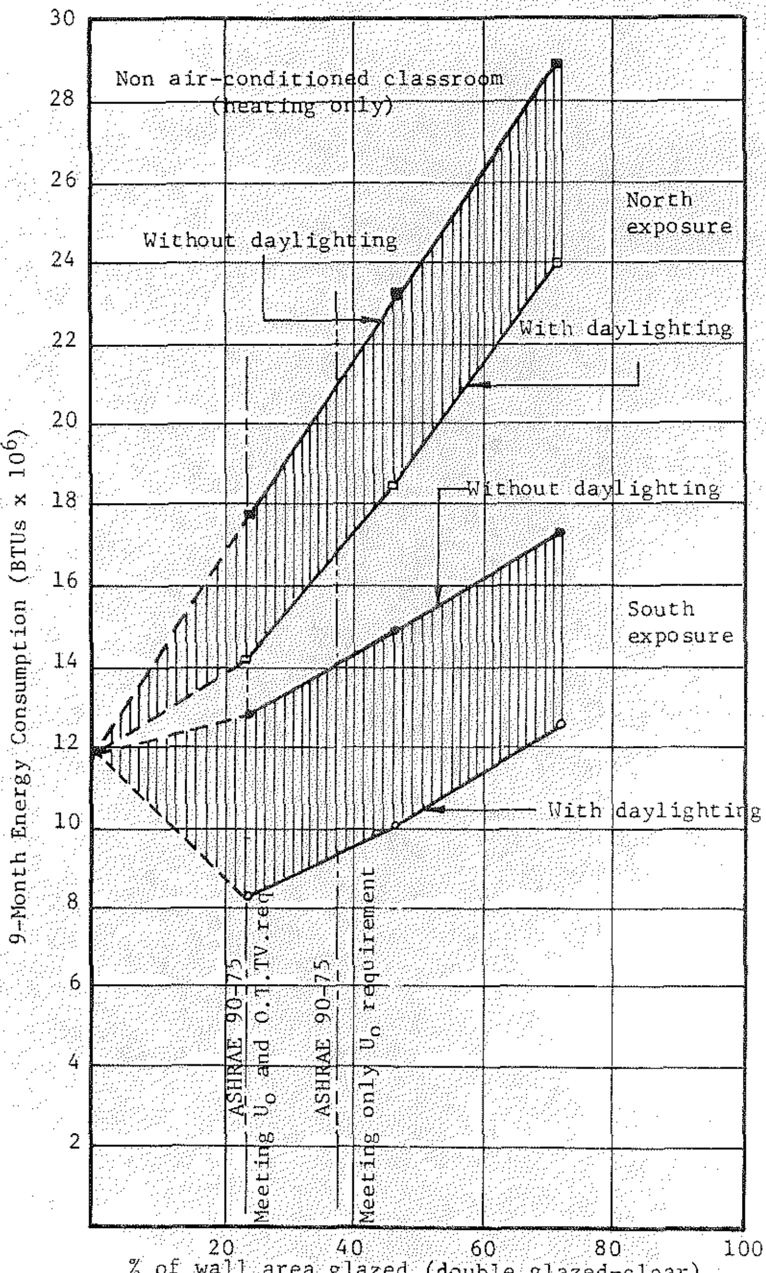

Figure 6. Energy performance as a function of glass area for a "non-air-conditioned" classroom with and without daylighting (heating only).

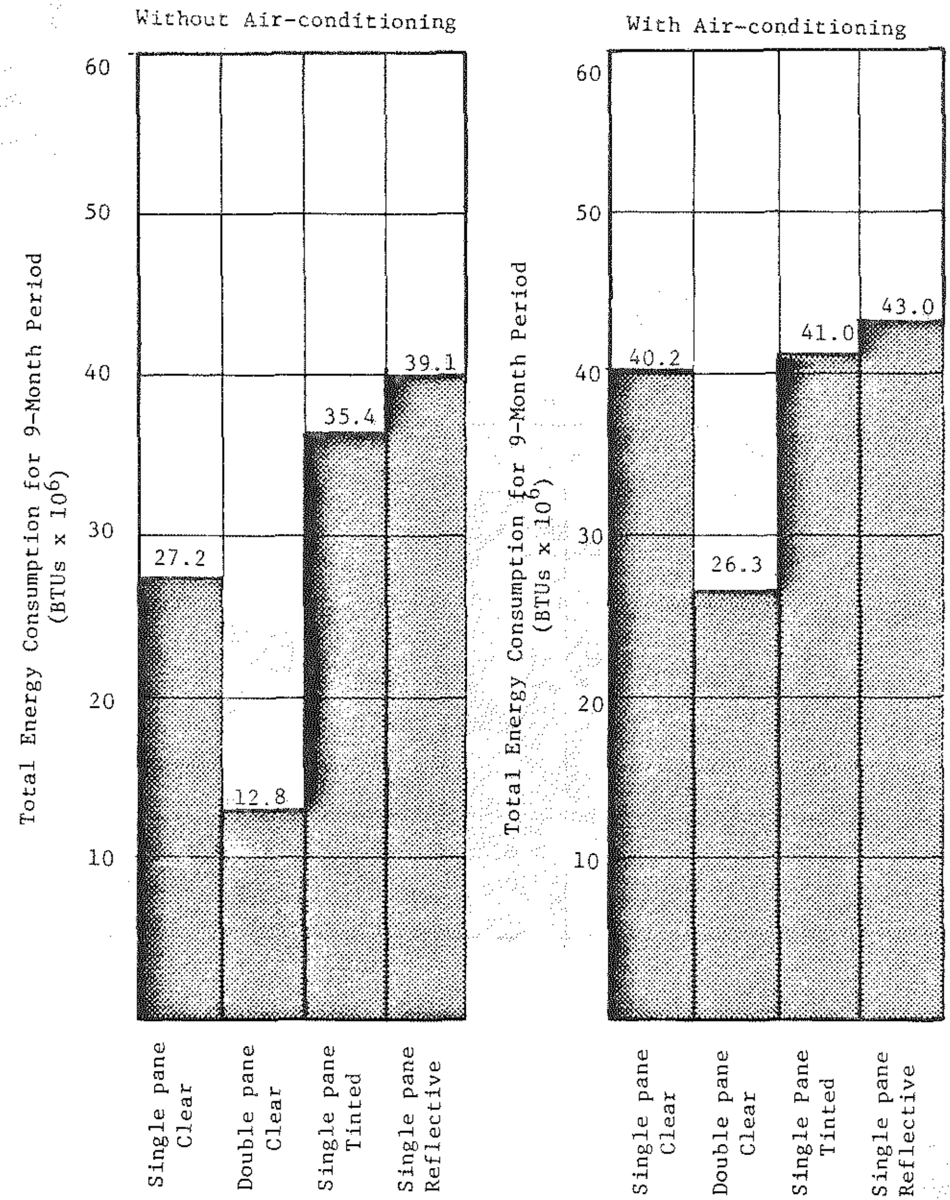

Figure 7. Effect of glass type on energy performance for a south exposure.

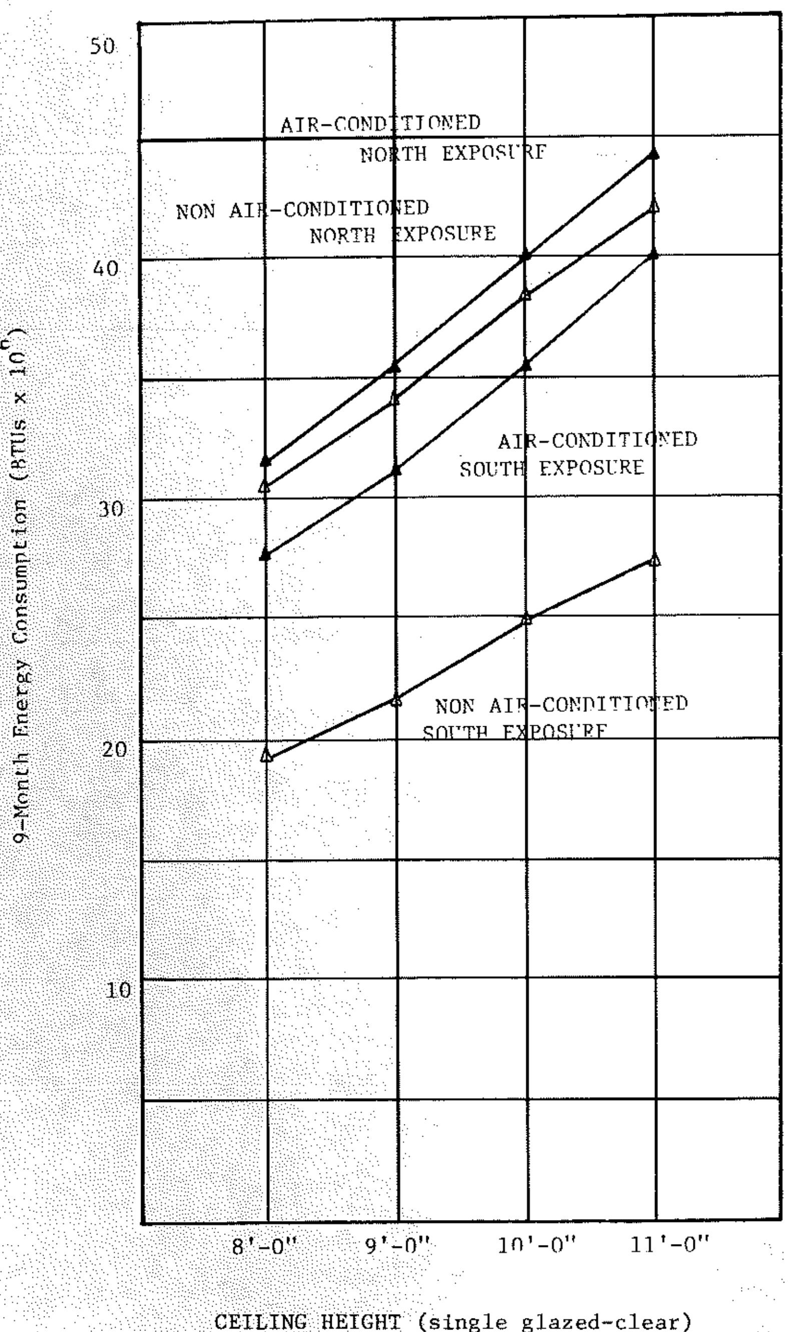

Figure 8. Energy performance as a function of ceiling height.