NISTIR 88-4014

Illumination Conditions and Task Visibility in Daylit Spaces

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U.S. DEPARTMENT OF COMMERCE
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Issued March 1989

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ABSTRACT

Illumination conditions are evaluated in typical building spaces based on detailed computer simulations, in order to characterize and quantify the effects of daylighting on task visibility. Examined are the effects of fenestration location and type on task contrast under daylit, electric-lit and combined conditions. The implications of the illumination conditions with daylighting on lighting and daylighting system design are discussed.

Keywords: contrast, daylighting, fenestration, illuminance, luminance, visibility

FOREWORD

This report is part of a continuing research program related to daylighting and lighting performance in buildings. The purpose of this research is to develop improved procedures for building design and evaluation. This research project has been sponsored by the National Institute of Standards and Technology.

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1. Introduction

While daylighting, the use of natural light in interior spaces, has been used extensively throughout history, in recent years a great deal of attention has been focused on building design issues related to daylighting. Much of this interest is linked to the potential energy and cost savings associated with the substitution of free natural light for artificial light which must be purchased in the form of electricity[1,2]. Additional interest in daylighting can be attributed to the psychological, esthetic and commercial aspects of building fenestration systems[3].

Along with the revived interest in daylighting, the need for effective methods for daylighting analysis and design has arisen. Complications occur in this regard due to the very nature of daylight itself (i.e. dynamic solar and sky conditions) and due to the necessity of analyzing the integrated performance of the daylighting and lighting systems[4,5,6].

This paper evaluates the effect of daylighting on task visibility, specifically task luminance contrast. The effects of fenestration type and location are examined using analytical and computer modeling techniques. The impact on task contrast of substituting daylight for electric light is evaluated, as are the influences of task type and viewer orientation relative to the luminous sources, and source size and location.

2. Background

Before proceeding with the detailed analysis of task visibility and illumination conditions in daylit spaces, it is necessary to summarize the parameters used to characterize the performance of interior illumination systems. In general, three of the most important aspects of interior illumination conditions are task illuminance, task luminances and disibility glare potential. These factors are related for a particular design, but are under the control of the designer.[7].

When the lighting designer chooses a particular lighting system, he is essentially specifying a luminance pattern within the room. The luminaires are the primary light sources, but all of the room surfaces serve as secondary sources of reflected light. The light from the luminaires and room surfaces can be described as the luminous surround. Task illuminance is determined by the total amount of light reaching the task from the luminous surround. Task illuminance is the primary design criterion for lighting systems, based upon the assumption that the task will be visible if sufficient task illuminance is provided [8,9].

However, task visibility is strongly related to task luminance contrast (C), which is a measure of the distinctness of the visual task according to:

$$C = \frac{L_B - L_D}{L_B} = 1 - \frac{L_D}{L_B} \qquad (1)$$

where: L_B - task background luminance
L_D - task detail luminance

Thus, task contrast is determined by task luminances. Task contrast is not dependent on the total amount of light falling on the task, but does vary with the direction of the light sources relative to the task and observer. Of course, the most basic factors determining task contrast are the optical reflection characteristics of the task and background, including the presence or absence of pigments or dyes in both fields. This will be referred to later on as "intrinsic" contrast. The important point is that identical task illuminances can result in widely different task contrasts, depending on the nature and location of the light sources[10,11]. The dependence of task contrast on source location stems from the reflectance characteristics of typical tasks which are semi-specular in nature. This means that tasks tend to reflect light to a greater extent at the specular reflectance angle (i.e. mirror-like reflection).

The third aspect of interior illumination conditions, disability glare potential, is related to bright light sources, such as luminaires, being located in the observer's field-of-view [12]. This performance aspect is beyond the scope of this report.

While it does not include all of the factors which influence task visibility, task contrast is a good indicator of illumination system performance [12,14,15]. For typical office tasks at typical light levels, higher contrast levels mean better task visibility [16], at least up to contrasts up to 90 percent, as defined by eq.(1). This effect can be seen in figure 1, which schematically represents the combinations of task contrast and background luminance that yield equal subjective task visibility. The visibility reference function (VL1) was determined for threshold visibility, while the visual performance criterion function (VL8) is intended to represent more normal viewing conditions. Threshold visibility (VL1) is defined as representing a constant level of subjective visibility. VL8, however, is simply a constant multiple of VL1, and its use to represent constant subjective contrast is controversial.

For typical light levels and tasks, the slope of the VL8 curve is nearly zero. This means that task visibility is nearly equal for constant task contrast. Thus, task visibility increases with task contrast. It should be noted that controversy still surrounds the shape of the iso-visibility curves at high background luminance levels, with evidence to suggest both negative and positive slopes [17,18,19]. However, task contrast remains a reliable indicator of task visibility, for a given level of luminance.

Since task contrast is a function of light source location, it follows that task contrast may well differ for electric light sources and fenestration elements, due to their location relative to the task and observer. Most luminaires are oriented horizontally, and located overhead, while many fenestration elements are oriented vertically and located on wall surfaces.

While task contrast is a good ordinal measure of the visibility of a task for constant luminance, it is not the most useful parameter for characterizing illumination system performance because the intrinsic contrast of various task types varies considerably. Contrast rendition factor, CRF, was developed to get around this limitation [20]. CRF allows comparison of the relative performance of illumination systems by indicating the ratio of task contrast under a particular system (C) to task contrast under a fixed reference condition, namely uniform diffuse (spherical) illumination (C_s) according to:

$$CRF = \frac{C}{C_s} \qquad (2)$$

Calculation or measurement of C_s gives equal weight to all possible source locations. A CRF value of one does not mean the best possible contrast has been achieved, but rather that contrast equals that for spherical illumination. CRF values greater than one are entirely possible.

A useful measure of the effectiveness of a luminous environment towards utilizing the full contrast-producing potential of a particular task can be defined as:

$$CUF = \frac{C}{C_m} \tag{3}$$

where: CUF = contrast utilization factor

C_m = maximum possible contrast for the given task

Values of CUF are bounded by zero and one. CUF may be a better indicator of the performance of an illumination system than CRF, since CUF is referenced to the best possible contrast, while CRF is referenced to an arbitrary contrast.

3. Methodology

The impact of daylighting on task visibility was evaluated in three steps. First, the effect of source location on task contrast was evaluated for a series of ten tasks. These tasks consisted of various types of details, such as pencil or pen lines, viewed at different angles. Using literature values of the bi-directional reflectance properties of each task [21], task contrast was computed for point light sources at different locations relative to the task and observer. Such an analysis emphasizes the effect of source location on task contrast, and highlights the differences between task types. Particular attention was given to the extremes of task contrast which can be obtained through manipulation of light source location.

The second stage of the evaluation consisted of evaluating the effect of fenestration size and location on task contrast. This analysis was performed using the CEL-1 computer program [21,22]. Task contrasts were computed and compared for various fenestration alternative.

The third step in the analysis consisted of evaluating the effect of mixing daylight and electric light on task contrast. The CEL-1 computer program was used to model and calculate task contrasts as the electric lighting was dimmed in response to daylight, while maintaining constant task illuminance.

4. Results

4.1 The Influence of Source Location on the Contrast of Typical Office Tasks

The dependence of task contrast on source location was evaluated through analysis of the bi-directional reflectance characteristics of various typical office tasks. Since the determination of task contrast requires the specification of a particular task, it is of interest to assess the potential variations in task contrast for different task types to see if task type influences the optimal selection of source location.

The tasks evaluated included pencil tasks for various viewing angles, ballpoint pen, felt-tip pen, printed and xerographic tasks. Luminance contrast was calculated for 666 source locations for each task type, assuming an otherwise black surround. While in most interior spaces the walls and ceiling function as secondary, reflective light sources, their total contributions to task illuminance will usually be less than those of the directly emitting luminous sources. As a result, they are excluded from the present analysis. Also, the intent is to evaluate the effect of source location, and reflecting surfaces can be analyzed using the same techniques as emitting surfaces, since they are just less intense sources. The orientation of the observer, task and source locations, and the definitions of the azimuth and declination angles for the source are presented in figure 2.

Figure 3 displays the variation in task contrast for a pencil task viewed from an angle of 10 degrees from normal, as a function of source location. The source location ranges from a declination angle of zero to 90 degrees relative to the task normal, and from zero to 180 degrees azimuth relative to viewing direction. The vertical direction on the figure corresponds to contrast, with higher contrasts denoted by peaks in the surface. As would be expected, minimum task contrast is obtained for azimuths near zero and declinations near 10 degrees (i.e. near the specular reflectance angle). Task contrast is greater for source locations at greater declinations and azimuths, with the effect of declination being much stronger.

The source locations corresponding to minimum task contrasts shift as the viewing angle varies. As shown in figures 4 through 7, which correspond to pencil tasks viewed from angles of 25, 32.5, 40 and 50 degrees, minimum task contrast occurs for source locations of zero azimuth and declinations near the viewing angle. If the tasks are oriented horizontally, the source locations corresponding to these angles can be determined quite easily with reference to the angular coordinate system of figure 2. The source location of zero azimuth, zero declination would be directly overhead. Azimuth of zero would mean sources directly in front of the viewer, while azimuths of 180 would be behind the viewer. If the task surface was tilted, the source locations must be evaluated relative to the task normal.

Figure 8 displays the variations in task contrast for a ball point pen task viewed at 25 degrees. Due to the nature of ink on paper, contrast variations are much less than for the pencil tasks, but minimum contrast still occurs near the specular reflectance angle as would be expected. Figure 9 shows the same information for a drafting pen task at 25 degrees. A much sharper contrast drop is apparent here near the specular reflectance angle. Contrast variations for a felt tip pen task are minimal, as shown in figure 10, due to the reflectance characteristics of felt tip pen ink, which is nearly a diffuse reflector. Figures 11 and 12 exhibit the expected contrast minima near the specular reflectance angle for an offset printing task and a xerographic task, respectively.

The region of minimum contrast is small but very important. This is the region in which the source inhibits the ability to see the task. It is of interest to observe how the region of minimum contrast changes as viewing angle varies.

The variations in contrast for all of the tasks are summarized in table 1, which displays contrast under spherical illumination, and the maximum and minimum potential contrasts for point source illumination. Two different contrast minima are shown, one being the minimum absolute value of the contrast, the configuration for which the task detail would be least visible against the background, and the other being the algebraic minimum, for which a negative value indicates that task detail luminance exceeds the background luminance (i.e. light detail, dark background). The latter case corresponds to maximum reverse contrast.Also listed are the source angles which correspond to each of the contrast extremes.

This table clearly indicates the relationship between minimum task contrast and source location, with contrast minima occurring near the specular reflectance angle as would be expected. Source location for maximum task contrast, however, varies somewhat with task type. The source declination angles which produce the greatest task contrasts tend to be large, usually 70 or 85 degrees. The exception is the offset printing task, which exhibits a maximum contrast for a declination of 35 degrees. The azimuth angles associated with maximum task contrast vary considerably, but examination of the individual contrast values indicates that in the region where contrast was maximum, variations in azimuth had very little effect on contrast. Thus, the global maximum contrast for each task was nearly equaled throughout the full range of azimuth angles for the optimum declination angle.

The sphere contrast values in table 1 give an indication of the inherent contrast of each of the tasks. The felt tip pen, for example, has a sphere contrast of over 0.5, while the pencil task is nearer to 0.17. The felt tip pen task always has a greater contrast than the pencil task. The drafting task, however, has a high sphere contrast, 0.43, but is very sensitive to source location, showing a negative contrast for sources at the specular reflectance angle.

Examination of the range of task contrasts and their relationship to source location indicates that the somewhat arbitrary choice of task type does not strongly influence the effect of source location on task contrast. While it is clear that task type does affect task contrast ranges, the relative impact of source location on task contrast is very similar throughout the gamut of tasks which were evaluated. Since, in most office environments, a variety of task types can be expected, the selection of a task which is sensitive to source location, such as a pencil task, can be argued to be appropriate for design purposes.

Table 1. Task Contrast Ranges

Task	Viewing Angle	Sphere Contrast	Maximum Contrast			Minimum Absolute Contrast			Minimum Algebraic Contrast		
			Value	Az	Decl.	Value	Az	Decl.	Value	Az	Decl.
Pencil	10	0.1567	0.2594	0	85	0.0703	5	10	0.0703	5	10
Pencil	25	0.1668	0.2448	60	85	0.0633	0	25	0.0633	0	25
Pencil	32.5	0.1716	0.2482	65	85	0.0527	0	30	0.0527	0	30
Pencil	40	0.1753	0.2567	55	85	0.0373	0	40	0.0373	0	40
Pencil	55	0.1742	0.2642	75	85	0.0049	0	45	-0.0745	0	65
Ballpoint Pen	25	0.2559	0.2887	0	85	0.1952	0	20	0.1952	0	20
Drafting	25	0.4249	0.5033	115	70	0.0048	10	30	-0.2892	0	25
Felt-Tip Pen	25	0.5161	0.5548	180	65	0.4249	0	25	0.4249	0	25
Offset Printing	25	0.3083	0.3488	180	35	0.0016	0	25	-0.0640	0	20
Xerographic	25	0.1384	0.1790	10	85	0.0401	0	25	0.0401	0	25

Note: All ranges are in degrees

Other tasks, such as three dimensional objects or self-luminous displays (CRT's, etc.) will have different contrast characteristics than the flat tasks included in the present analysis. However, the contrast of a flat task in the same general orientation as the three dimensional task may serve as a useful starting point for evaluating the contrast of the three dimensional task. Since curved surfaces can usually be approximated as a series of connected flat surfaces, the flat task analysis can be applied repeatedly to evaluate a three dimensional task.

Another consideration is the effect of task orientation relative to a horizontal plane. While many office tasks are performed in a horizontal orientation, the viewer is frequently free to tip the task to improve task contrast. Tipping a task has the effect of increasing the angle between an overhead luminous source and the task normal, thereby moving the overhead luminous source away from the specular reflectance angle for the viewer [23]. However, task illuminance will decrease due to tipping unless other luminous sources are located in the tipped direction, in which case low task visibilities may still occur. It has been shown that the viewer will alter the orientation of task and light source to obtain good contrast when such adjustment is possible [24].

Since sphere contrast is frequently used as a reference base for evaluating task contrast (i.e. the normalizing factor in the calculation of CRF), sphere contrast was compared to maximum contrast to provide an indication of the effectiveness of spherical illumination towards utilizing the full contrast potential of each task. Table 2 presents the ratio of sphere contrast to maximum contrast, and maximum CRF, for each task.

Sphere contrast is seen to range from 60 to 70 percent of maximum contrast for the pencil tasks, to 77 percent for the xerographic task, and from 84 to 93 percent for the other tasks. This indicates that substantial improvements in task contrasts are possible using optimally located luminous sources versus spherical illumination, particularly for sensitive tasks such as pencil tasks.

One other issue which should be mentioned is the effect of source location on task illuminance. As source declination increases, the amount of light striking the surface, or task illuminance, decreases with the cosine of the declination angle. The azimuth angle has no effect on task illuminance. The effect of source location on task illuminance is approximated graphically in figure 13. It is clear that choosing source location involves a trade-off of task illuminance with task contrast, whereby greater declination angles increase contrast while decreasing illuminance. However, source azimuth angle can be selected to maximize contrast without an illuminance penalty.

4.2 The Effect of Fenestration Location on Task Contrast

Since task contrast is strongly dependent on the relative orientation of the viewer and luminous source, fenestration type and location can be expected to exert a strong influence on task visibility. This effect was evaluated using the CEL-1 (Conservation of Electric Lighting) computer program. The program computes detailed luminance distributions on room surfaces, and the resulting task contrasts [21,22].

A large, open interior space was simulated with no fenestration, and with windows, skylights or sawtooth structures. All glazings were modeled as diffusely transmitting. A standard pencil task was chosen to be performed at nine locations throughout the space, with viewing direction parallel to the window wall. Six rows of fluorescent luminaires were modeled, also oriented parallel to the window wall. The room layout is displayed in figure 14, and the locations of the luminaires and tasks are shown in figure 15.

Task contrasts were calculated first with electric light only, and then with each fenestration type (without electric lighting) for overcast skies.

Average task CRF, and standard deviation, were computed for each configuration, as shown in table 3.

Table 2. Ratio of Sphere Contrast to Maximum Contrast, and Maximum CRF

	Sphere Contrast / Maximum Contrast	Maximum CRF
Pencil; 10 degrees	0.604	1.66
Pencil; 25 degrees	0.681	1.47
Pencil; 32.5 degrees	0.691	1.45
Pencil; 40 degrees	0.683	1.46
Pencil; 55 degrees	0.659	1.52
Ballpoint Pen; 25 degrees	0.886	1.13
Drafting; 25 degrees	0.844	1.18
Felt-Tip Pen; 25 degrees	0.931	1.07
Offset Printing; 25 degrees	0.884	1.13
Xerographic; 25 degrees	0.773	1.29

Table 3. Task CRF Versus Fenestration Type, Nine Task Locations

Fenestration	Average Task CRF	Std. Deviation
None	0.8837	0.0289
Skylights	0.9076	0.0189
Sawtooth	0.9184	0.0111
Window	1.0353	0.0587

Average CRF, and thus task contrast, is seen to be greater for each of the fenestration options than for the no fenestration option with electric lighting. This is due to the advantageous orientation of the fenestration elements relative to the task viewing direction, particularly for the window option, which provides an average contrast which exceeds that which would be obtained from spherical illumination. The standard deviation values are an indication of the variability of task contrast throughout the space. This variability is also displayed in figures 16, 17, 18 and 19 for the no fenestration, skylights, sawtooth and window configuration, respectively. The centers of the contrast contours correspond to task locations. The greatest variation in task contrast is observed for the window case, with contrasts being highest towards the rear of the room, and lowest near the window. This effect is due to the fact that reflected light from the walls and ceiling is less near the back of the room relative to light coming directly from the window. The light from the window strikes the task at a low angle and generally normal to the viewing direction. For task locations near the window, reflected light from the walls and ceiling causes lower contrasts, because more light is reflected towards the task at the specular reflectance angle.

Contrast with the sawtooth and skylights falls between that for the window and no fenestration cases, with the sawtooth performing slightly better than the skylights. This is because the majority of the light comes from above the tasks, but is distributed more evenly across the ceiling than the electric lighting only case.

The variations of task contrast throughout the interior spaces with no fenestration, skylights and sawtooth are similar, being minimum for task locations where the viewer has most of the room in front of him, and maximum when he is near to, and facing towards, a wall. Some variation also occurs depending on the proximity of the viewer to an overhead luminaire or fenestration aperture. This pattern is opposite the pattern observed for the window case, as was described above.

In an earlier section of this report, task contrasts versus source location were displayed graphically in three dimensional plots. In order to compare the source locations occupied by windows to ceiling source locations, similar three dimensional plots were generated showing the range of incident angles subtended by a window and the ceiling, for three room sizes. The rooms were square, either 10, 20, or 50 feet on a side, with eight foot ceilings. The task location was the room center at a desk height of 2.5 feet, and the window occupied one entire wall.

Since a window and a ceiling are extended sources, light from either will strike the task from a range of directions. If the task is near a large window, for example, a large range of incident angles will be occupied by the window. As room floor size increases, the percentage of incident angles occupied by the window decreases, for a centrally located task. The converse is true for the ceiling, which occupies more incident angles as room floor size increases. In figures 20 through 25, the vertical dimension is a discretized existence indicator, either zero or one. If the window or ceiling is located at a particular angle, a value of one is plotted. The slightly slanted fall-off at the plateau edges is an artifact.

Figure 20 shows the declination and azimuth angle ranges occupied by the ceiling of a ten foot wide square room, for a centrally located task. The horizontal plateau indicates the ranges where the ceiling is located. It is clear, as would be expected, that the light from the ceiling strikes the target at the lower declination angles (near normal), throughout a full range of azimuth angles. In comparison, as shown in figure 21, the window occupies a limited azimuthal range at high declination angles. This means that light from the window will strike the task only from directions that produce high relative contrast, while some light from the ceiling will strike the target from the poor contrast specular reflectance angle.

The ceiling of a 20 foot wide square room occupies a larger range of incident angles, as shown in figure 22, while a window in the same room constitutes a narrower range of azimuth angles at high declination (figure 23). In this configuration, the contrast produced by light from the window would be near the maximum possible, although illuminance levels on the task would be low due to the large incident angle.

The low task illuminance could be counteracted by tipping the task toward the window without seriously compromising the task contrast, since the specular reflectance angle would be 90 degrees from viewing direction.

For the 50 foot wide square room, the ceiling monopolizes almost all incident angles compared to the window, as shown in figures 24 and 25. The window would not provide a great deal of illumination on a horizontal task, but the light from the window which did strike the target would produce very high relative contrast. Again, tipping of the task would help to compensate for the low-illuminance condition. In comparison, it would be very difficult to orient the task to escape light from the ceiling.

4.3 Mixing Daylight and Electric Light

In the previously described simulations, daylight and electric light were not mixed to enable their separate effects to be examined. However, in many daylighting applications, the electric light is dimmed in response to daylight gains. The effect of substituting daylight for electric light on task contrast, while maintaining constant illumination levels, was evaluated by simulating an office space with a single window and a fluorescent lighting system. The layout of the simulated room is shown in figure 26. Overcast skies were simulated, since contrast from daylight is independent of solar location for overcast conditions. Figure 27 shows how task CRF varies with exterior daylight level at a location in the center of the room. When exterior daylight illuminance is zero, the electric lighting system is fully on and task CRF is 0.902. As exterior daylight illuminance increases, increasing amounts of daylight fall on the task causing contrast to increase, very rapidly at first, until task contrast approaches that which would occur with daylight only, a CRF value of 1.119. Task CRF never reaches the level for daylight only, however, because the lighting system was constrained to a minimum of 30 percent of full output, as is typical of many control systems.

Since task contrast can be expected to vary with task location, the difference between task CRF with daylight only, and task CRF with electric light only was computed for various locations and displayed in figure 28 as a contour plot and figure 29 as a three dimensional plot, which has been rotated 180^{o} for clarity. Task CRF with daylight is seen to be greater than for electric light by 0.14 to 0.38. The greatest improvement in task CRF occurs for task locations directly under the fluorescent luminaires, but substantial improvement is apparent throughout the room. The lack of symmetry in the CRF plots is due to the fact the viewing direction is parallel to the window. Thus, a task location with the observers back to the wall produces a different CRF than a location near to, and facing, the opposite wall.

5. Discussion of Results

The analyses in this report have demonstrated the effectiveness of building fenestration components towards providing high task visibility in interior spaces. The source of the effectiveness of fenestration systems lies in their favorable location relative to typical task orientations, leading to high task contrasts. Windows are particularly effective at providing high task contrasts.

While beyond the scope of this report, the glare potential of fenestration elements should also be considered. The best conditions for seeing occur when the entire field of view of the observer is an uniform as possible. In the case of windows, if the observer maintains a line of sight at as angle parallel to or away from the window, glare problems can be avoided. If the window is wide enough, the line of sight should be nearly away from the window, leading to high task contrast and little glare potential. This assumes that there are opaque walls enclosing the room.

In the case of overhead fenestration, such as skylights or clerestories, diffusely transmitting glazings are frequently employed to prevent excessive direct beam solar radiation from striking the task areas. The use of wells reduces the glare potential from ceiling fenestration, and aids in the distribution of light. Task contrasts are not as favorable with overhead fenestration as with windows, however, due to the high angle orientation of the fenestration. It is more difficult to orient the task so that the majority of the light comes from a low angle slightly behind the observer. Tasks must be tilted to nearly vertical to achieve maximum contrasts. However, the superior daylight collection and distribution capability of ceiling fenestration systems favors their use from energy considerations.

6. Conclusions

The effect of luminous source location on task contrast was evaluated for ten typical tasks. It was shown that the choice of task type did not strongly influence the optimum source locations. A comparison of maximum task contrast to contrast under spherical illumination showed that task contrasts could be much greater for directional illumination than for spherical illumination.

Fenestration elements which admit light at low incident angles relative to the work plane help to utilize the full contrast potential of the task. Computer simulations demonstrated that task contrast increased when daylighting was substituted for electric light in a windowed office. Task contrast for overhead fenestration fell between the electric light only case and the window configuration.

The results indicate that overhead and side daylighting can provide improved task visibility compared to overhead lighting. This result, combined with the known energy benefits of daylighting provides additional motivation for the use of building fenestration systems.

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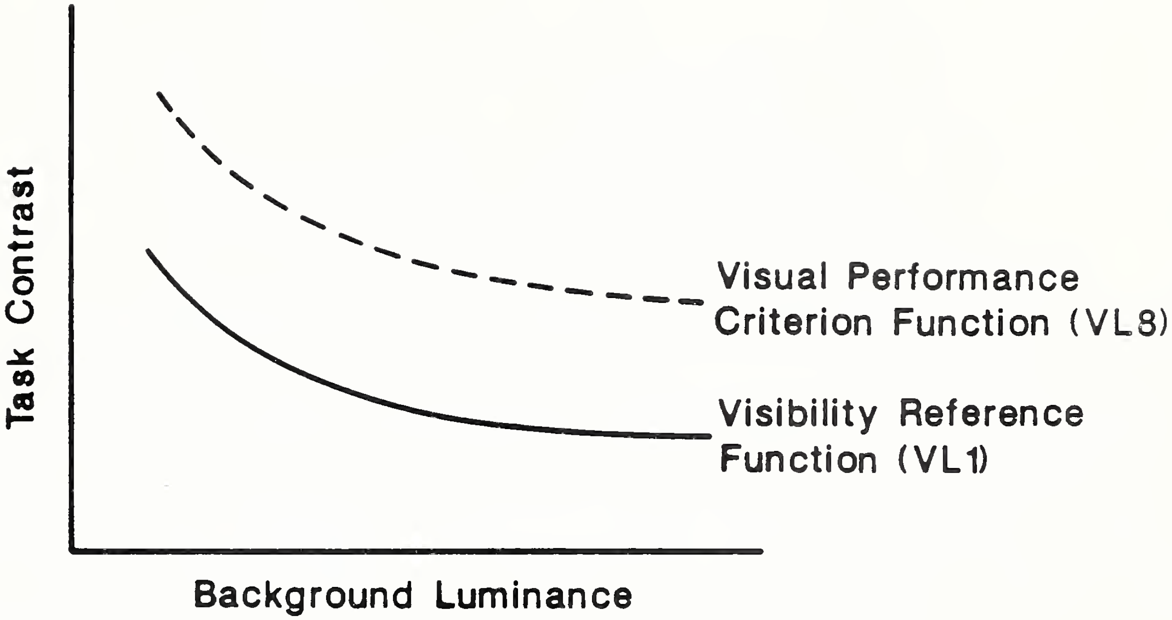


Figure 1. Luminance Contrast versus Background Luminance for Equal Visibility

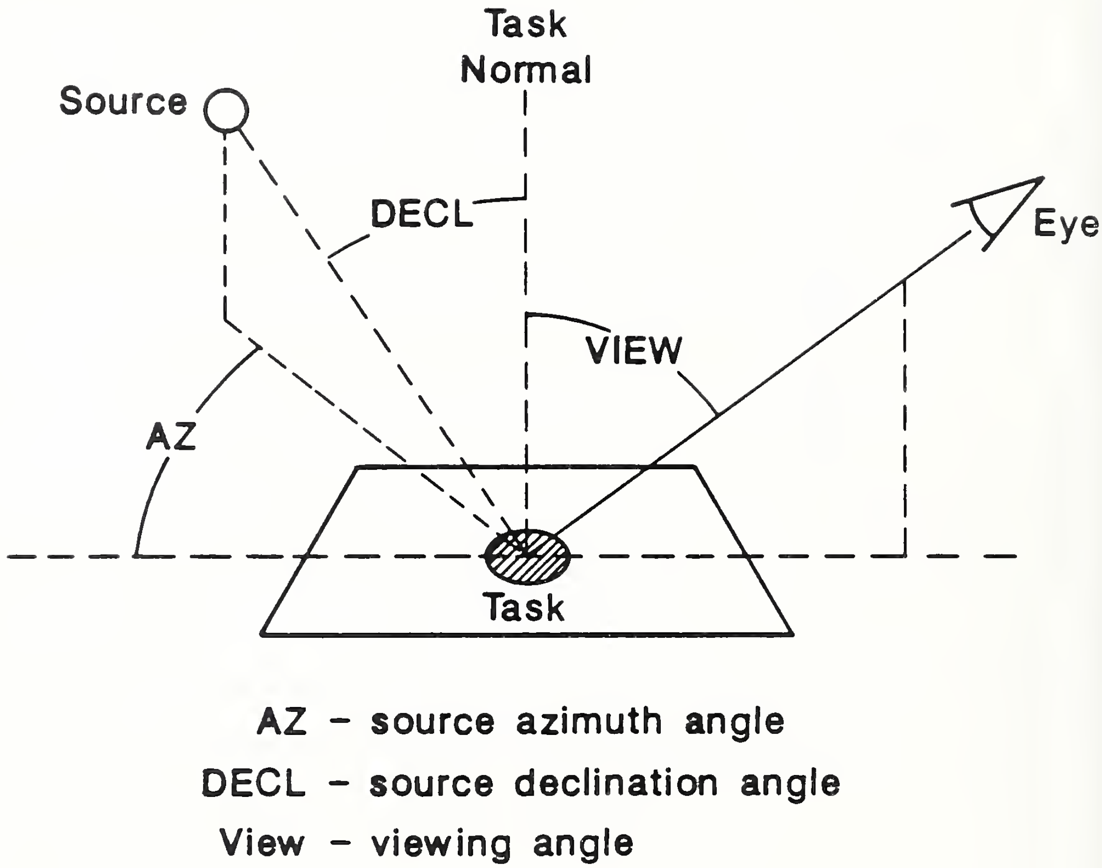


Figure 2. Definitions of the Azimuth and Declination Angles Relative to the Observer, Task and Source

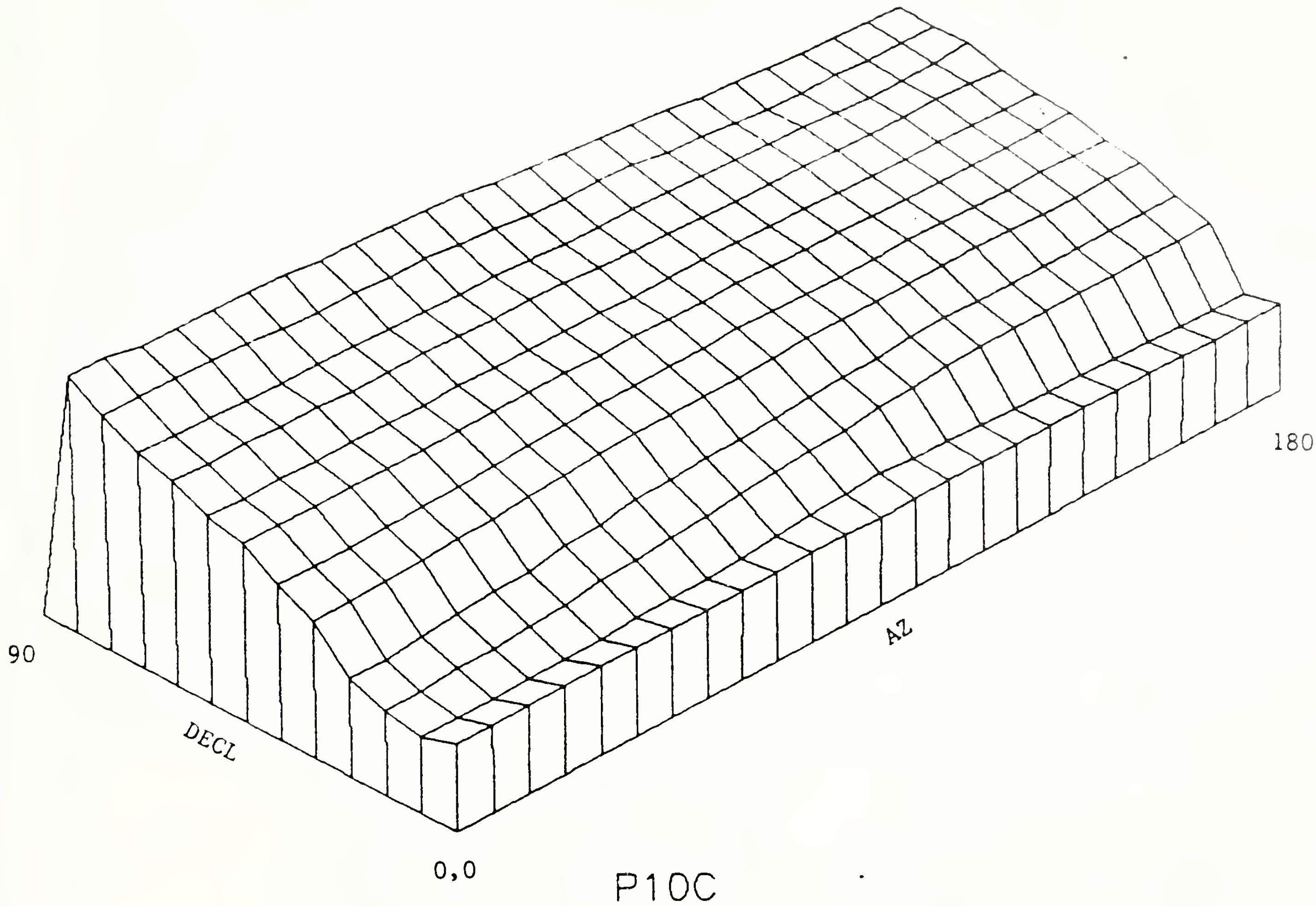


Figure 3. Task Contrast Versus Source Location, Pencil Task, Viewing Angle 10° from Normal

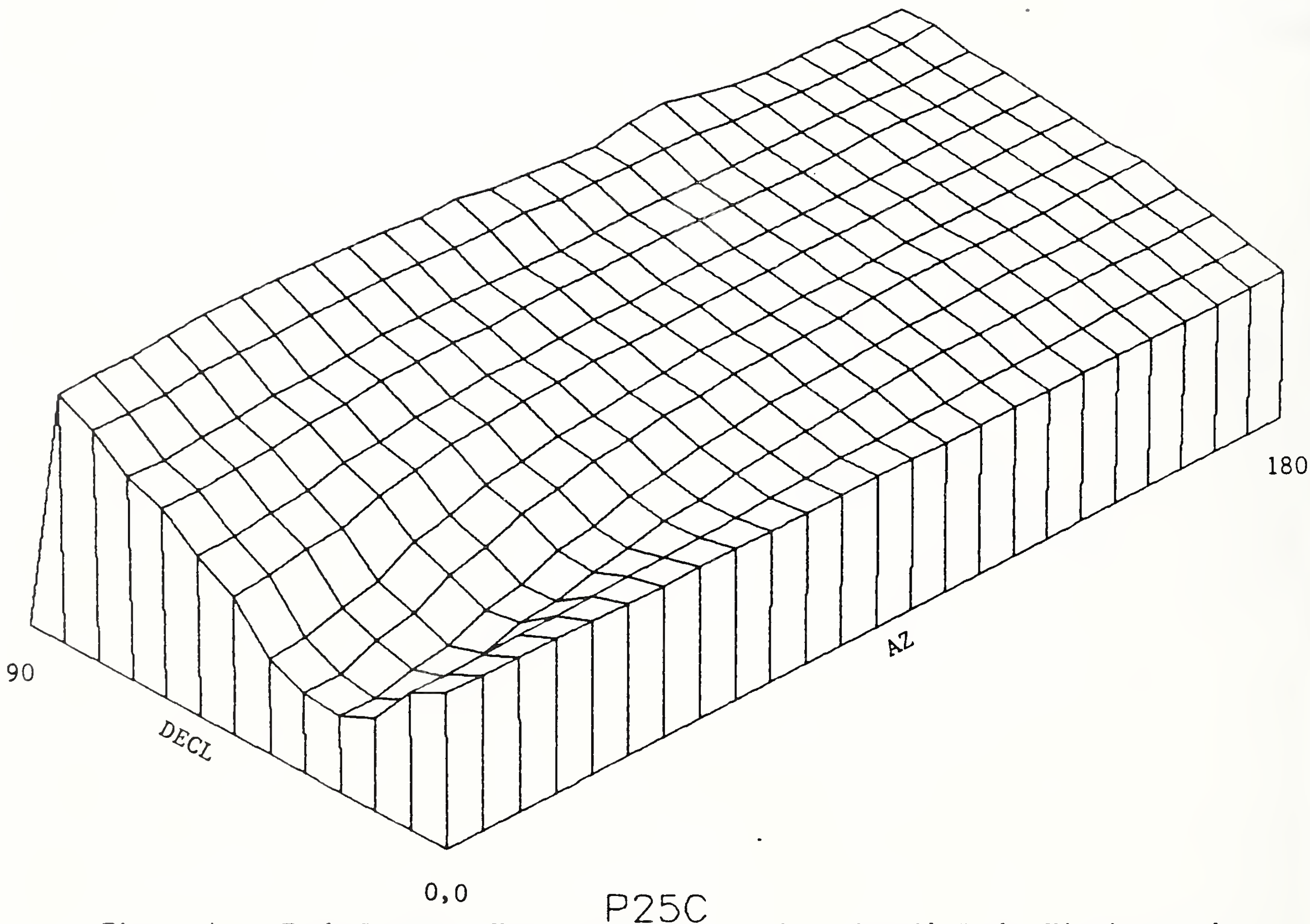


Figure 4. Task Contrast Versus Source Location, Pencil Task, Viewing Angle 25° from Normal

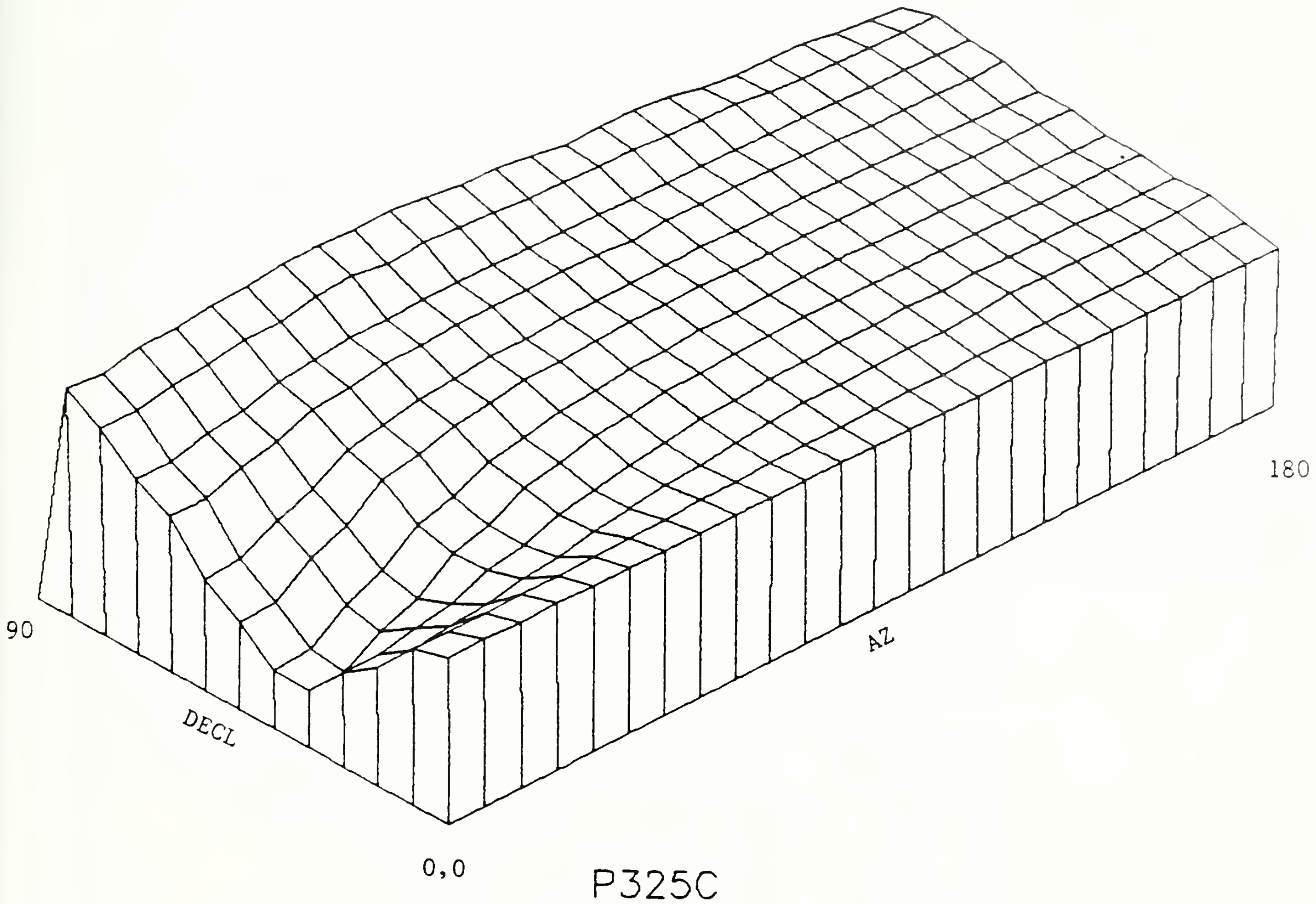


Figure 5. Task Contrast Versus Source Location, Pencil Task, Viewing Angle 32.5° from Normal

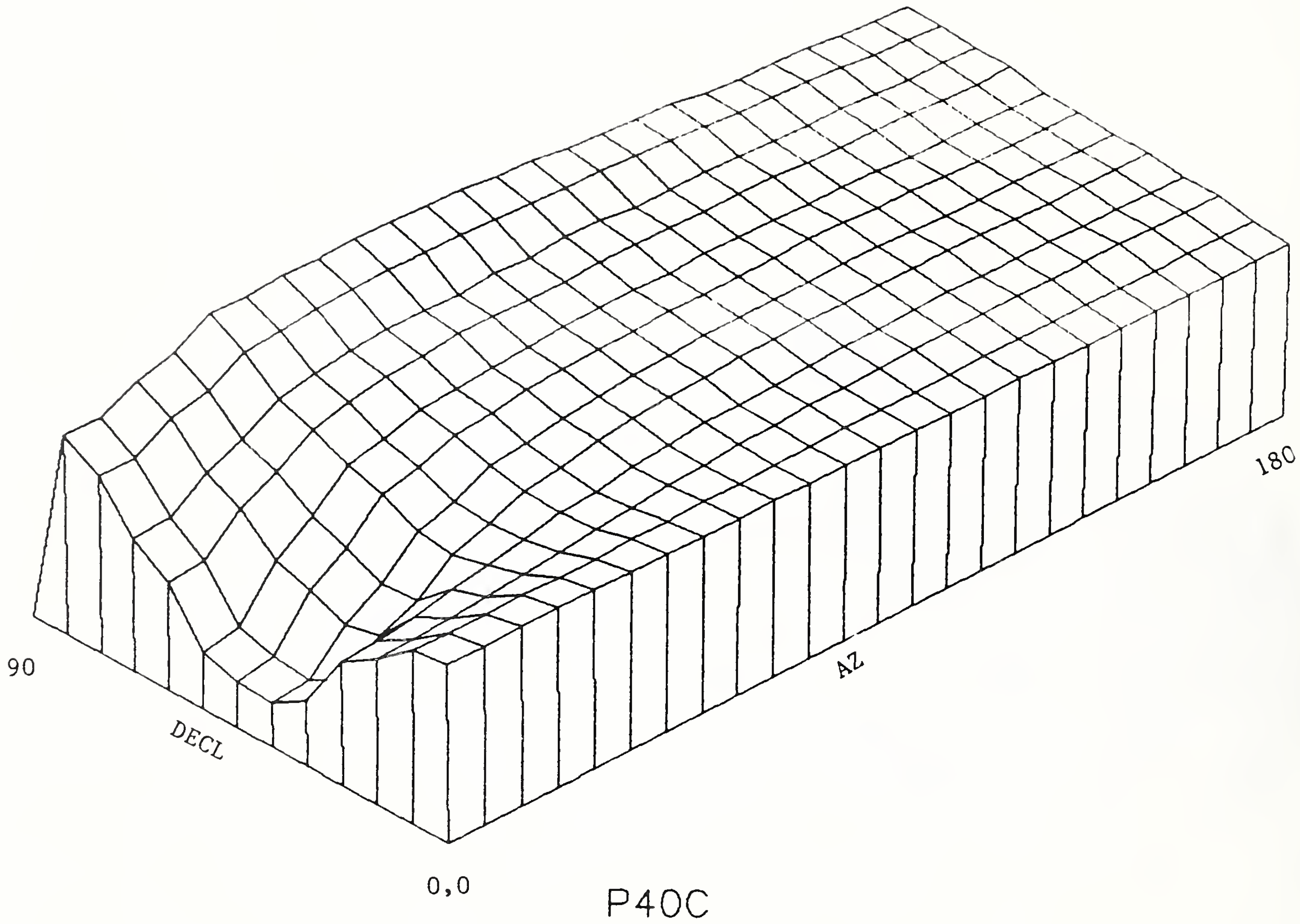


Figure 6. Task Contrast Versus Source Location, Pencil Task, Viewing Angle 40° from Normal

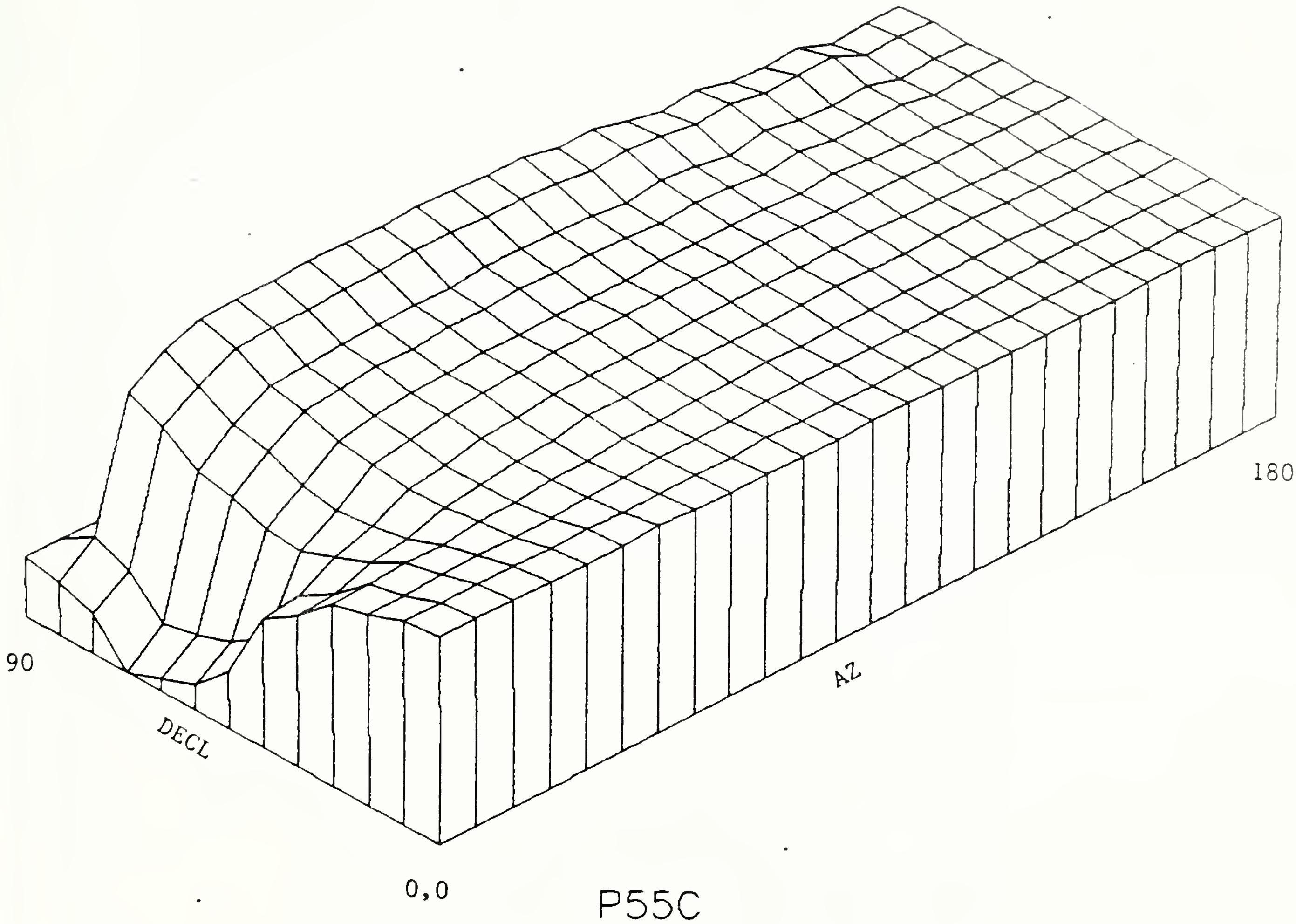


Figure 7. Task Contrast Versus Source Location, Pencil Task, Viewing Angle 55° from Normal

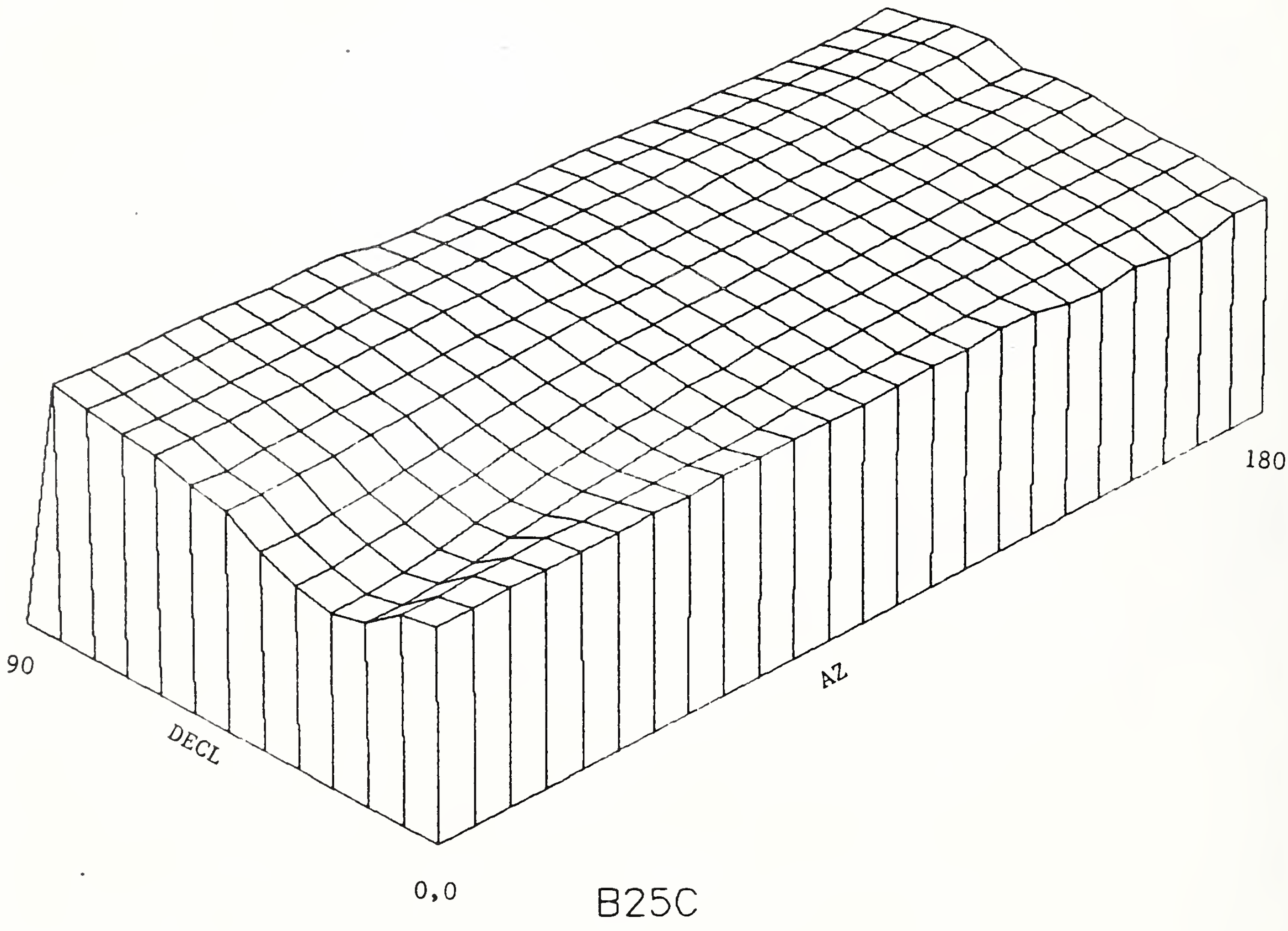


Figure 8. Task Contrast Versus Source Location, Ballpoint Pen Task, Viewing Angle 25° from Normal

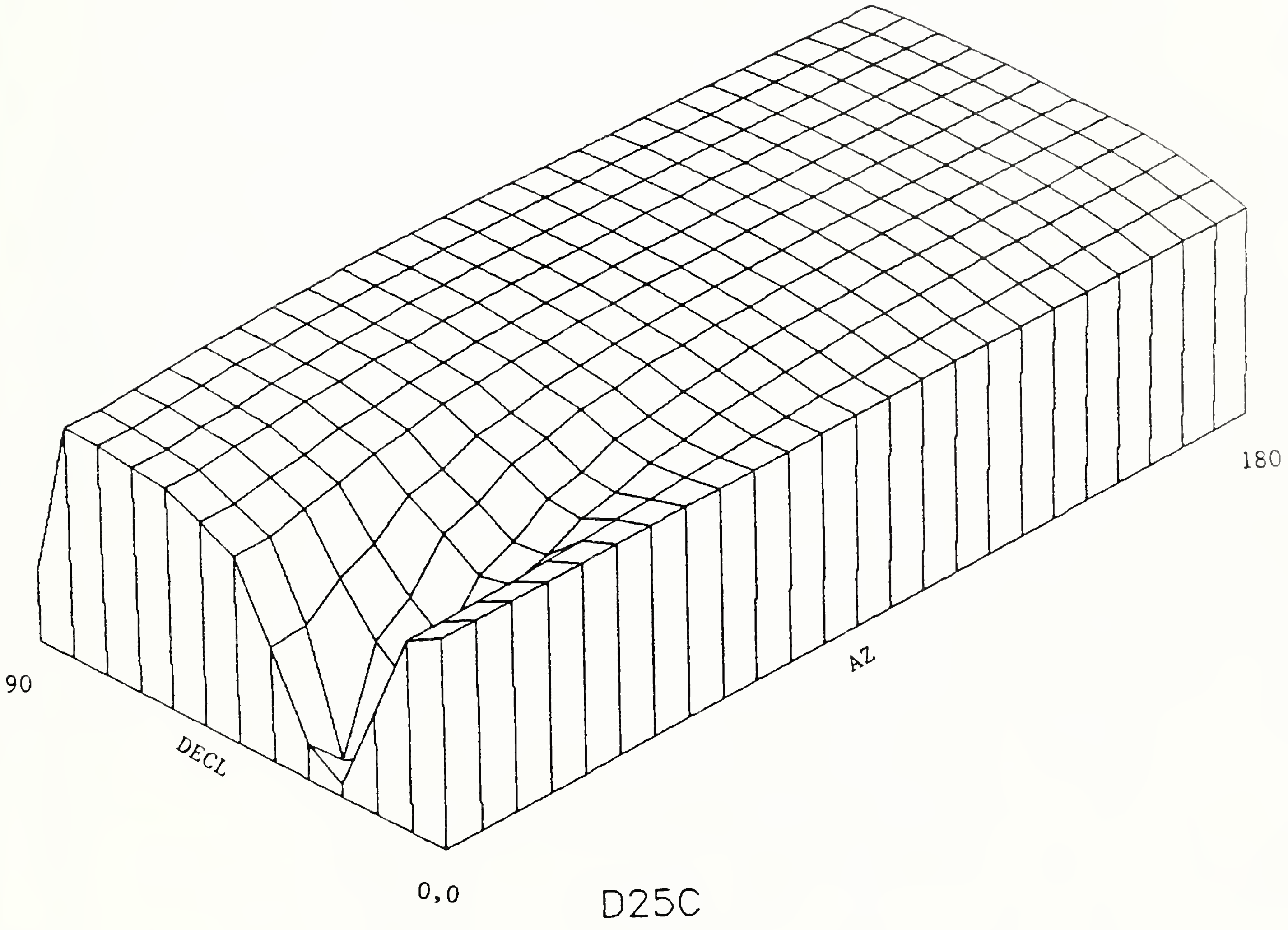


Figure 9. Task Contrast Versus Source Location, Drafting Pen Task, Viewing Angle 25° from Normal

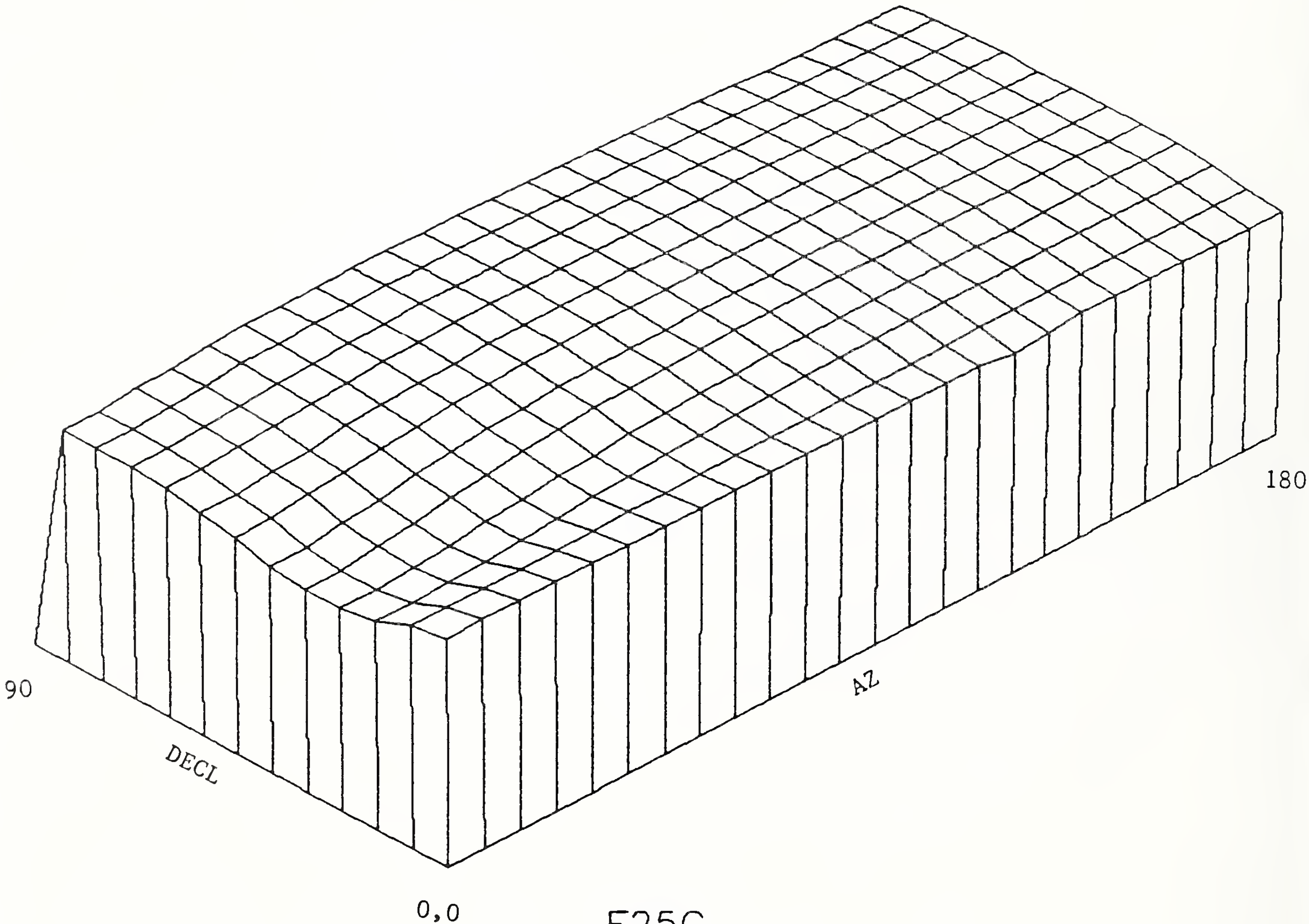


Figure 10. Task Contrast Versus Source Location, Felttip Pen Task, Viewing Angle 25° from Normal

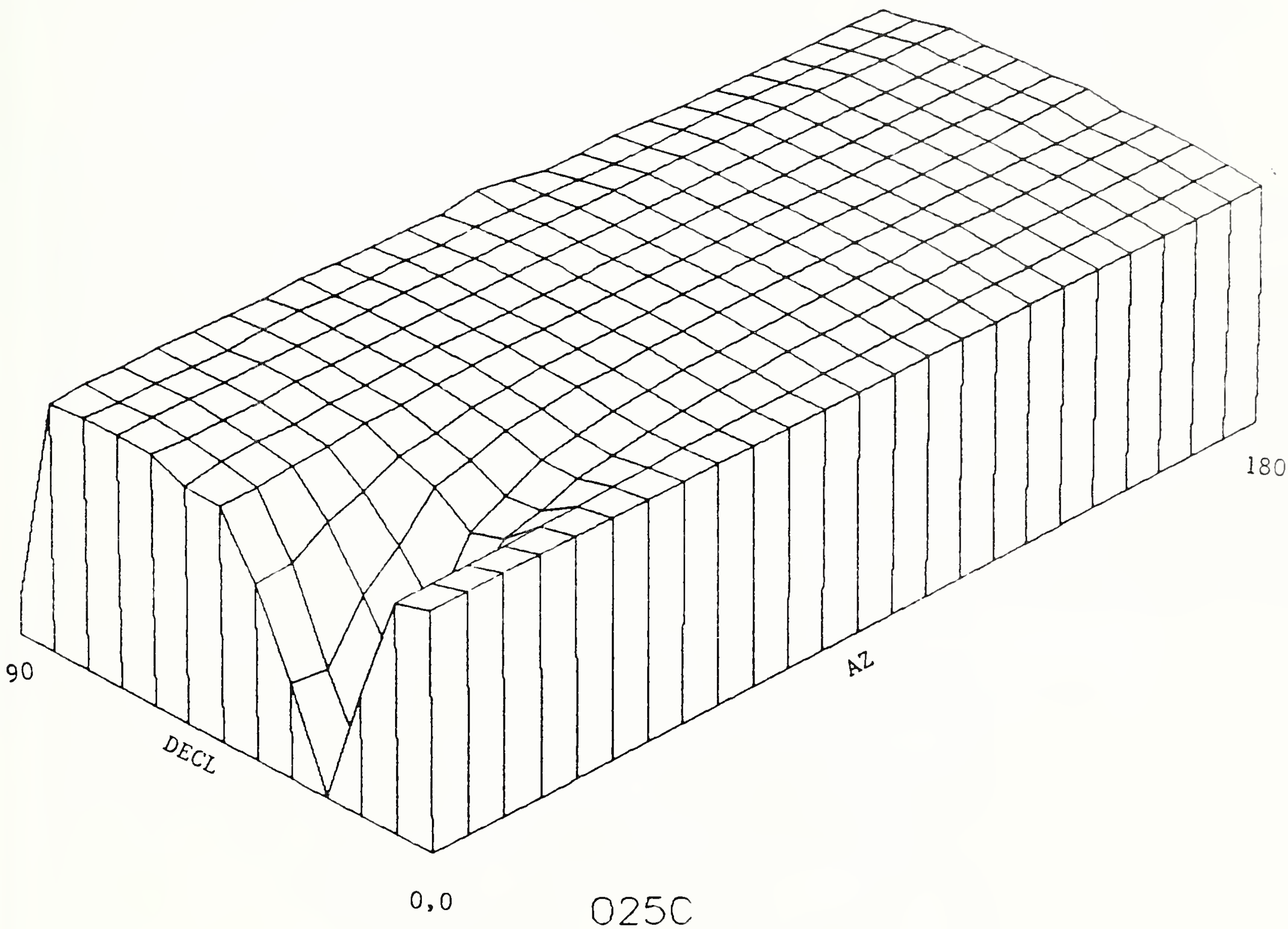


Figure 11. Task Contrast Versus Source Location, Offset Task, Viewing Angle 25° from Normal

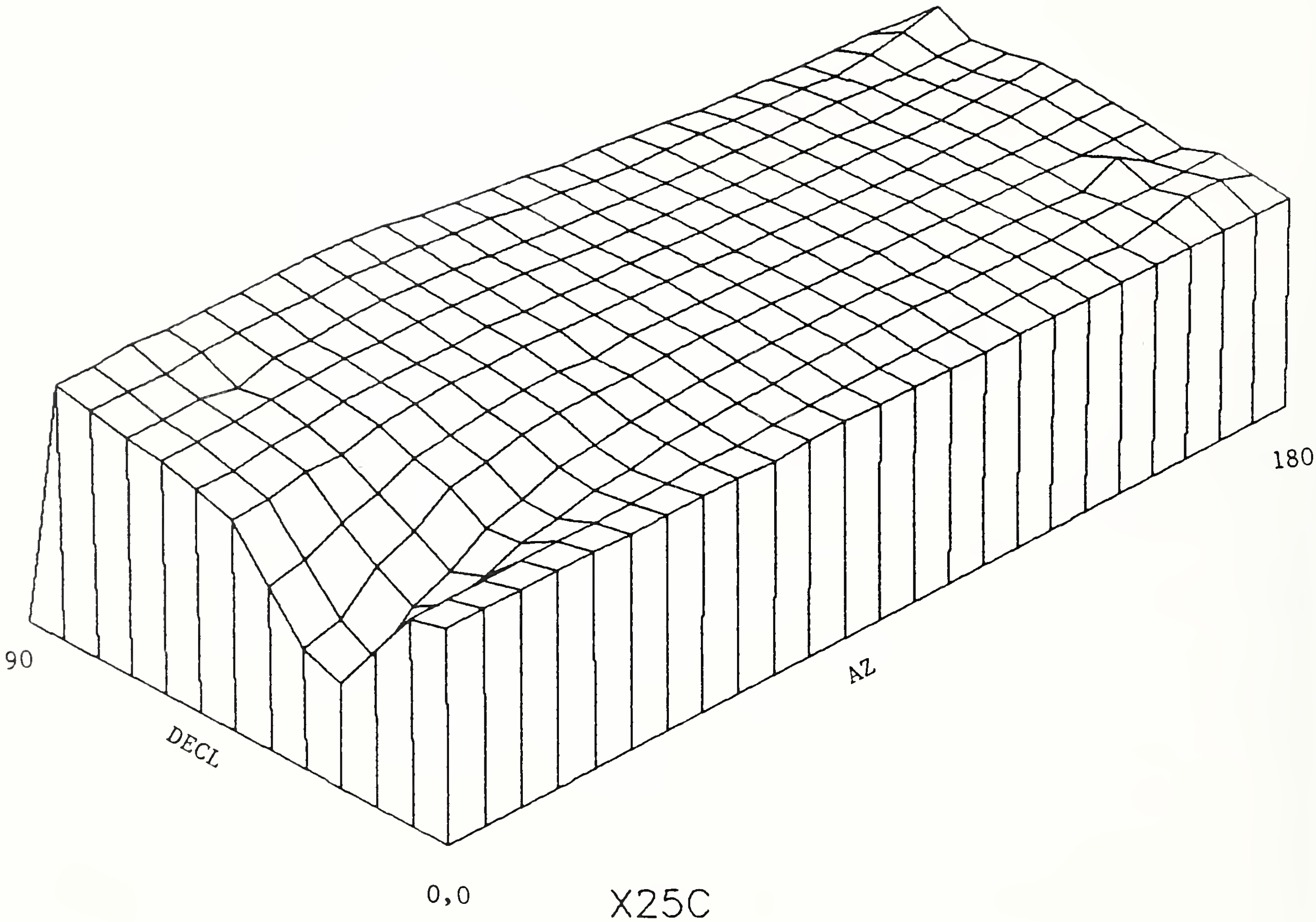


Figure 12. Task Contrast Versus Source Location, Xerographic Task, Viewing Angle 25° from Normal

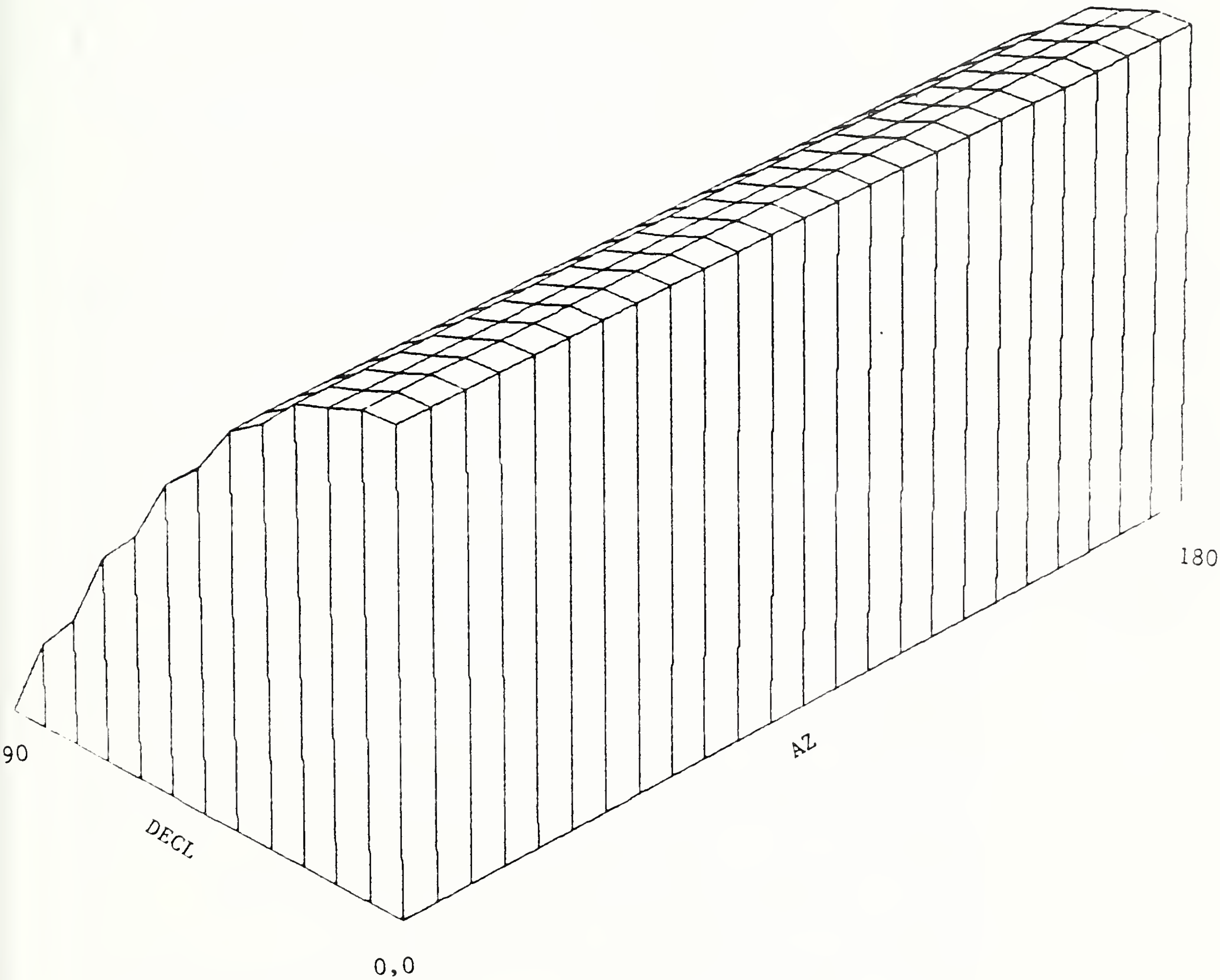


Figure 13. Task Illuminance Versus Source Location

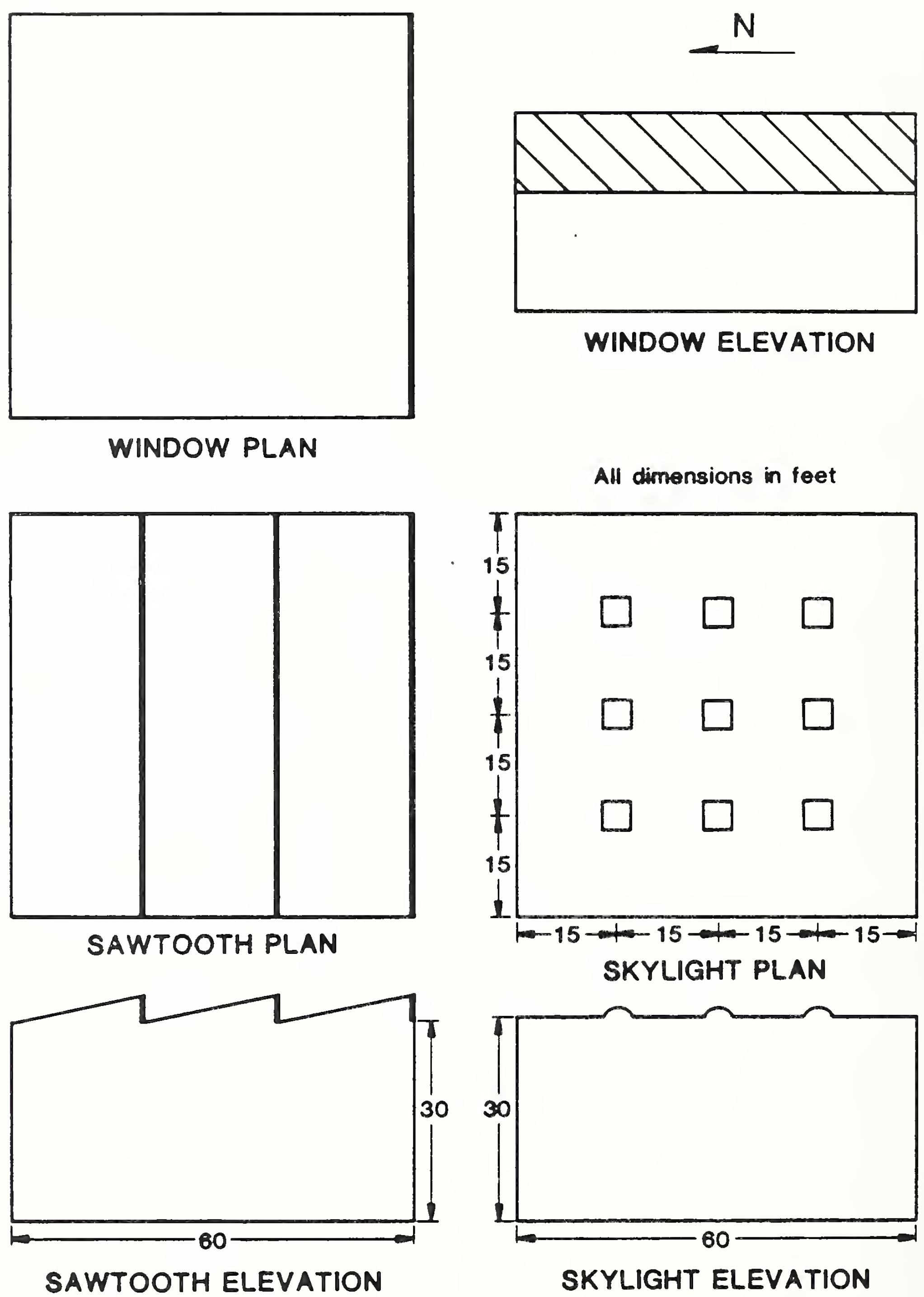


Figure 14. Layout of Simulated Room with Fenestration Locations

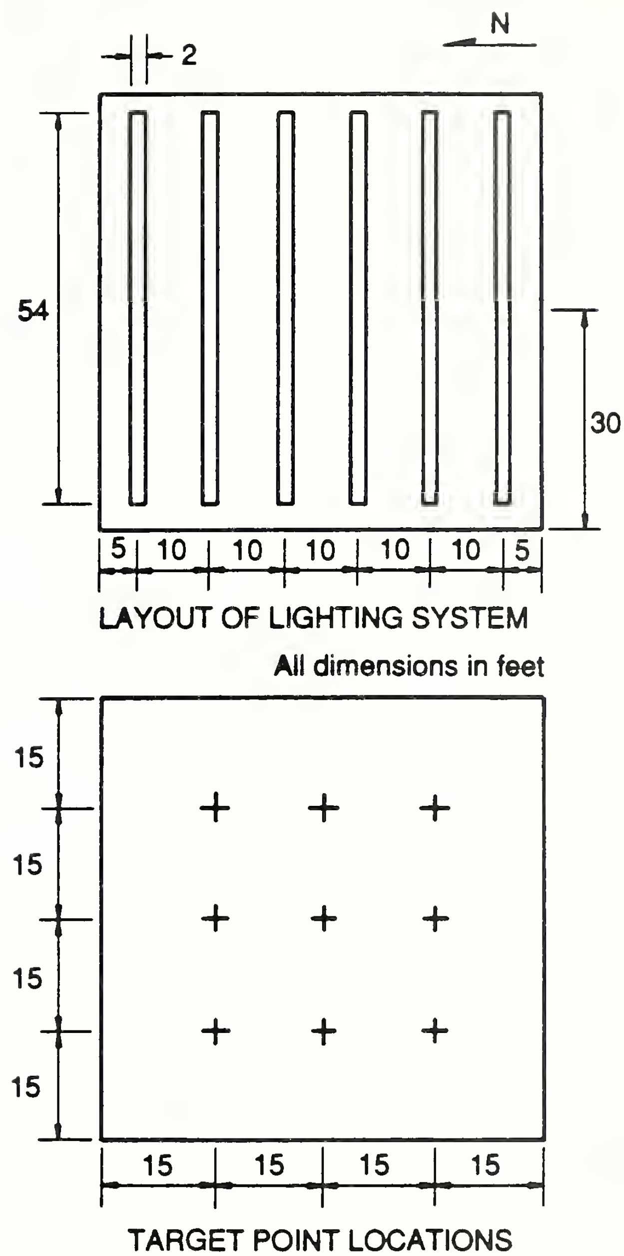
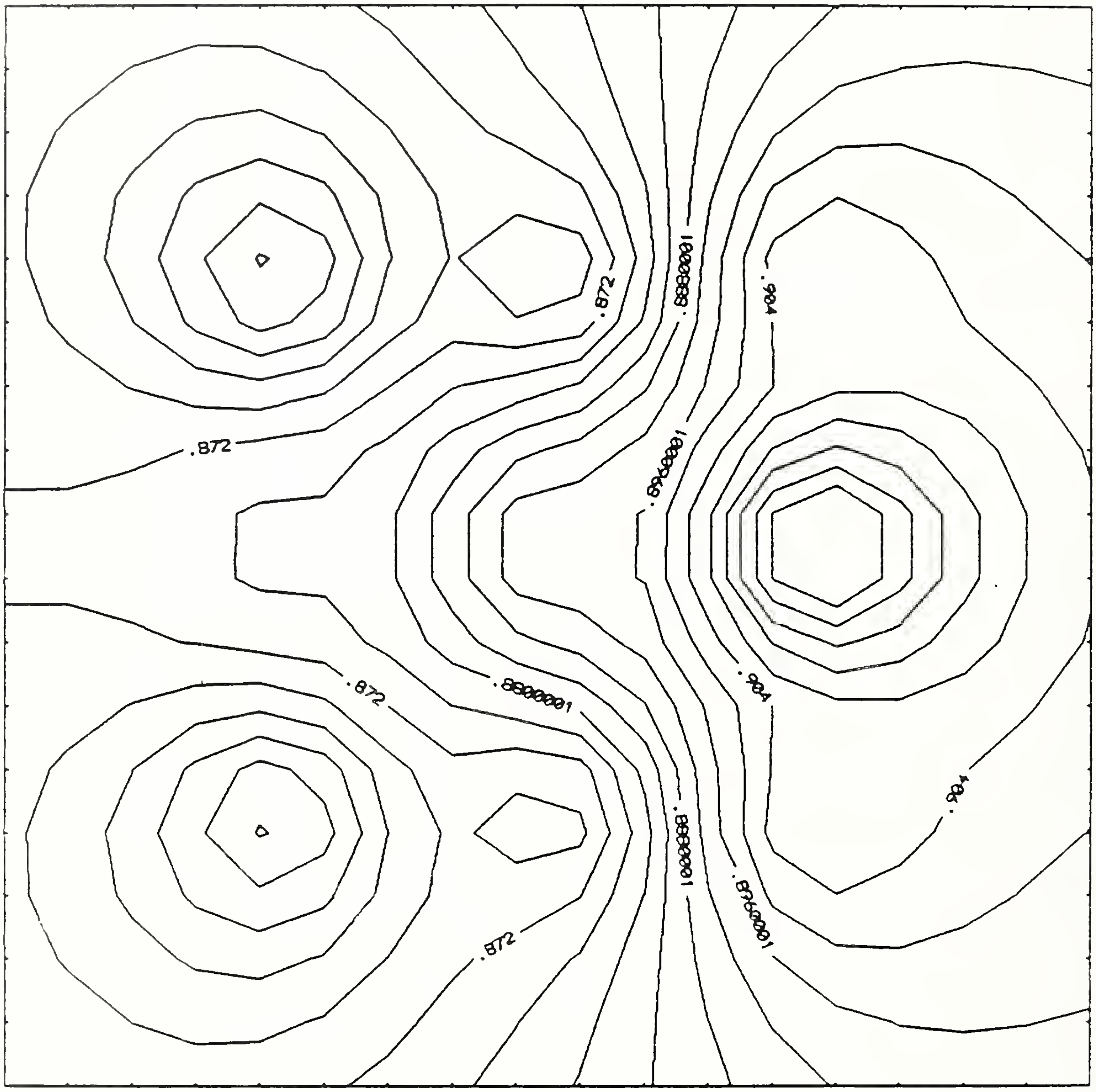


Figure 15. Layout of Simulated Room Showing Task and Luminaire Locations



CRF, BASE BUILDING, NO FENESTRATION

Figure 16. CRF Profiles with No Fenestration

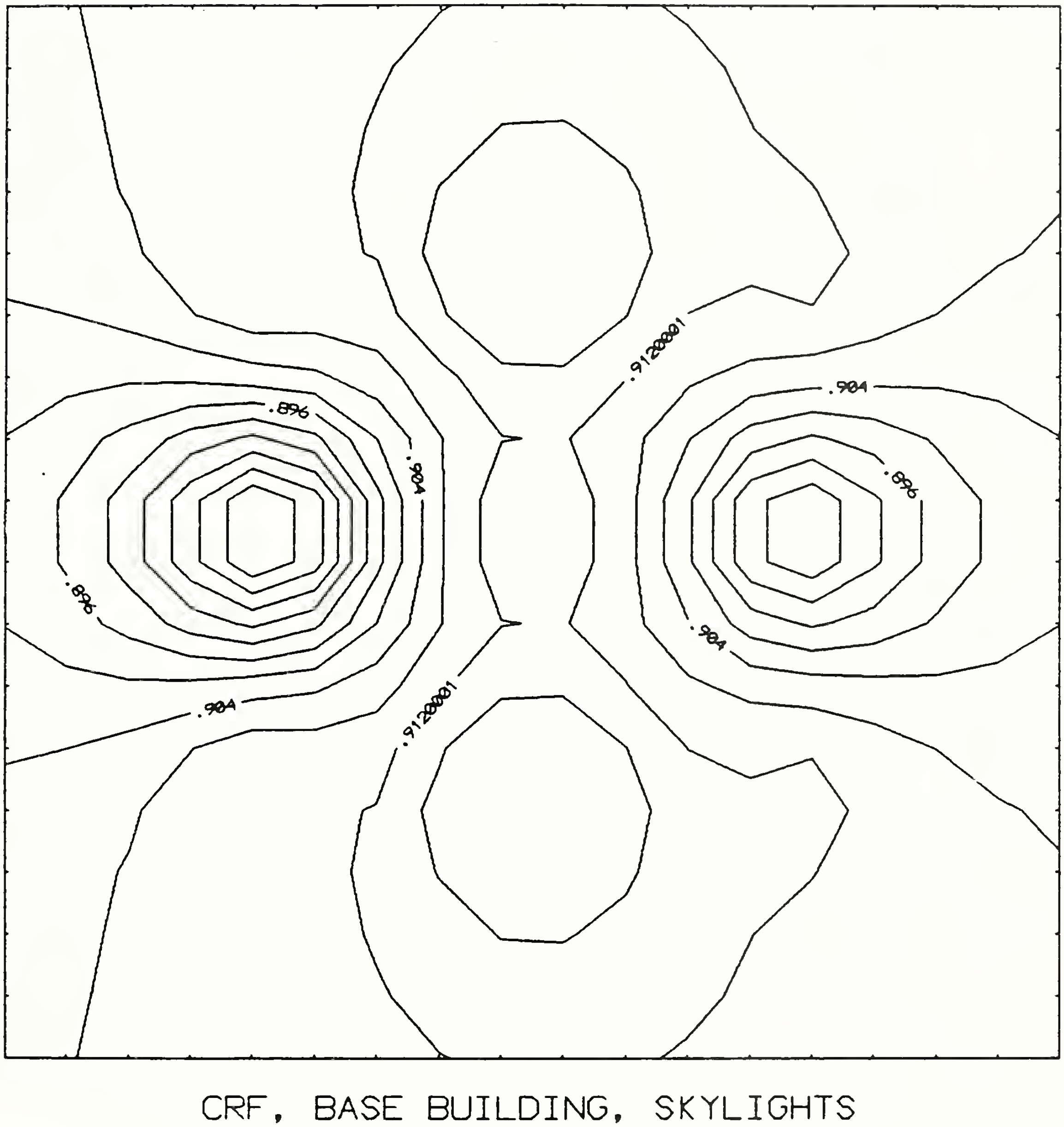
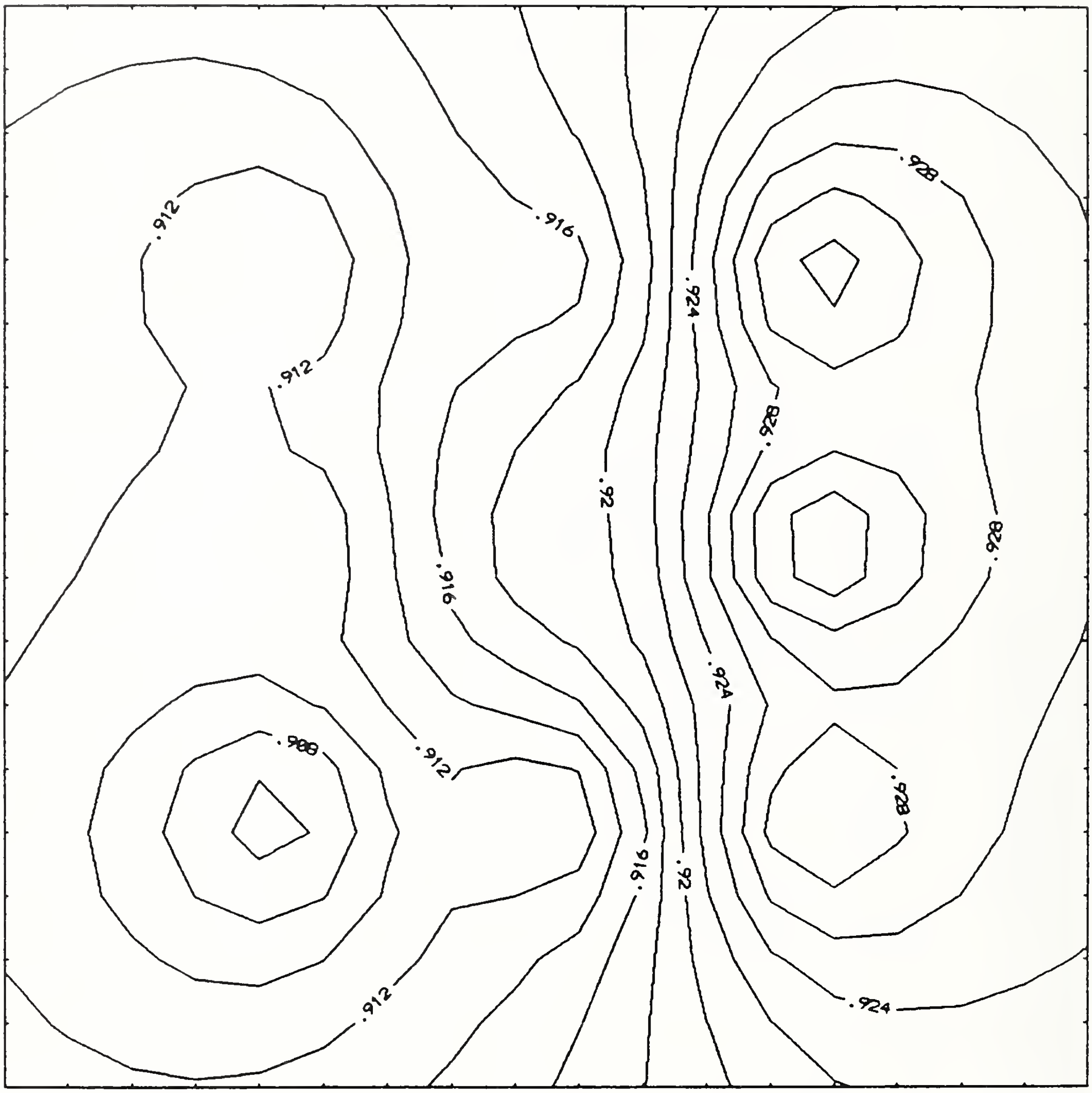
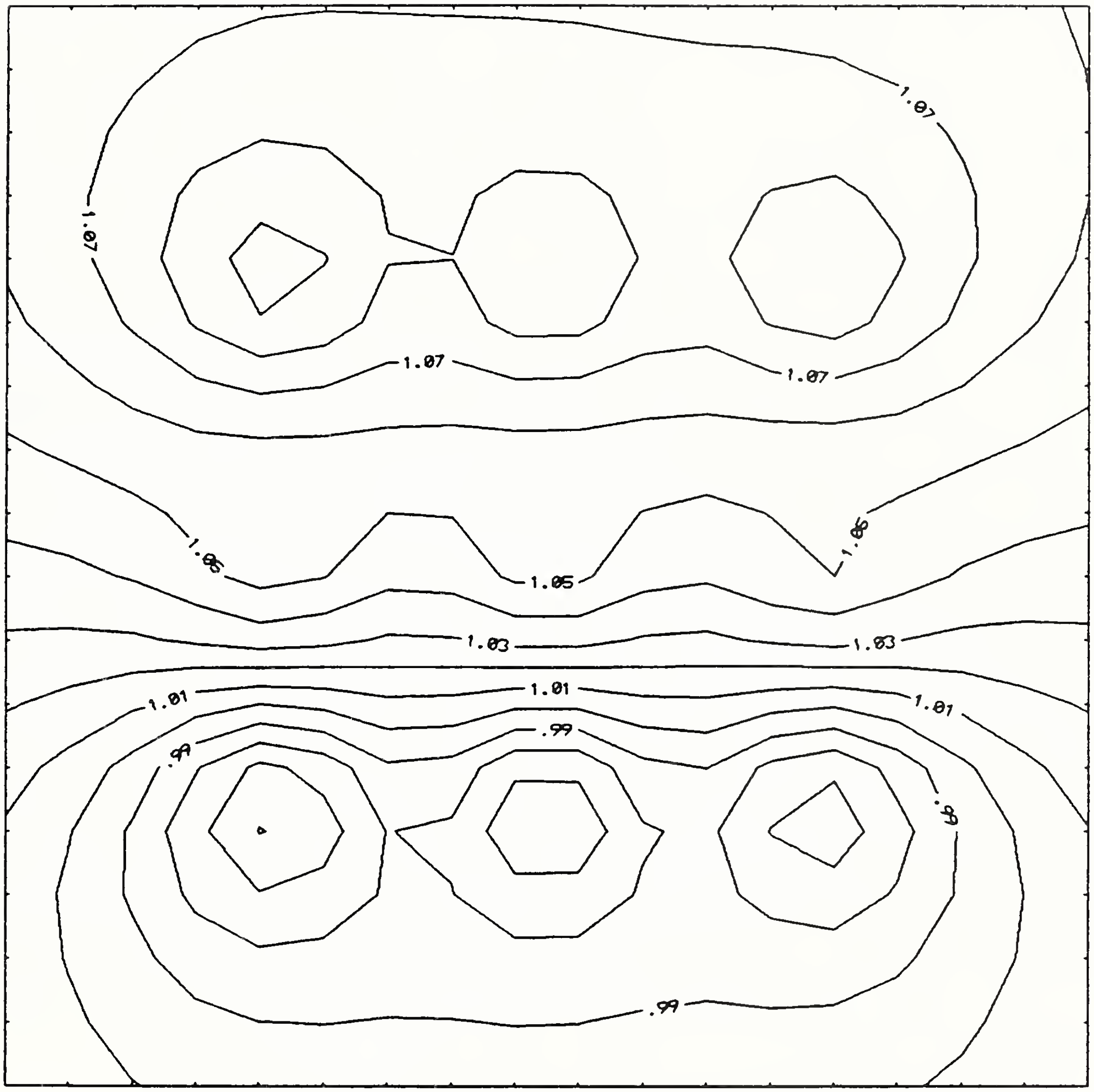


Figure 17. CRF Profiles With Skylights



CRF, BASE BUILDING, SO. SAWTOOTH

Figure 18. CRF Profiles With South-Facing Sawtooth



CRF, BASE BUILDING, SO. WINDOW

Figure 19. CRF Profiles with South Window

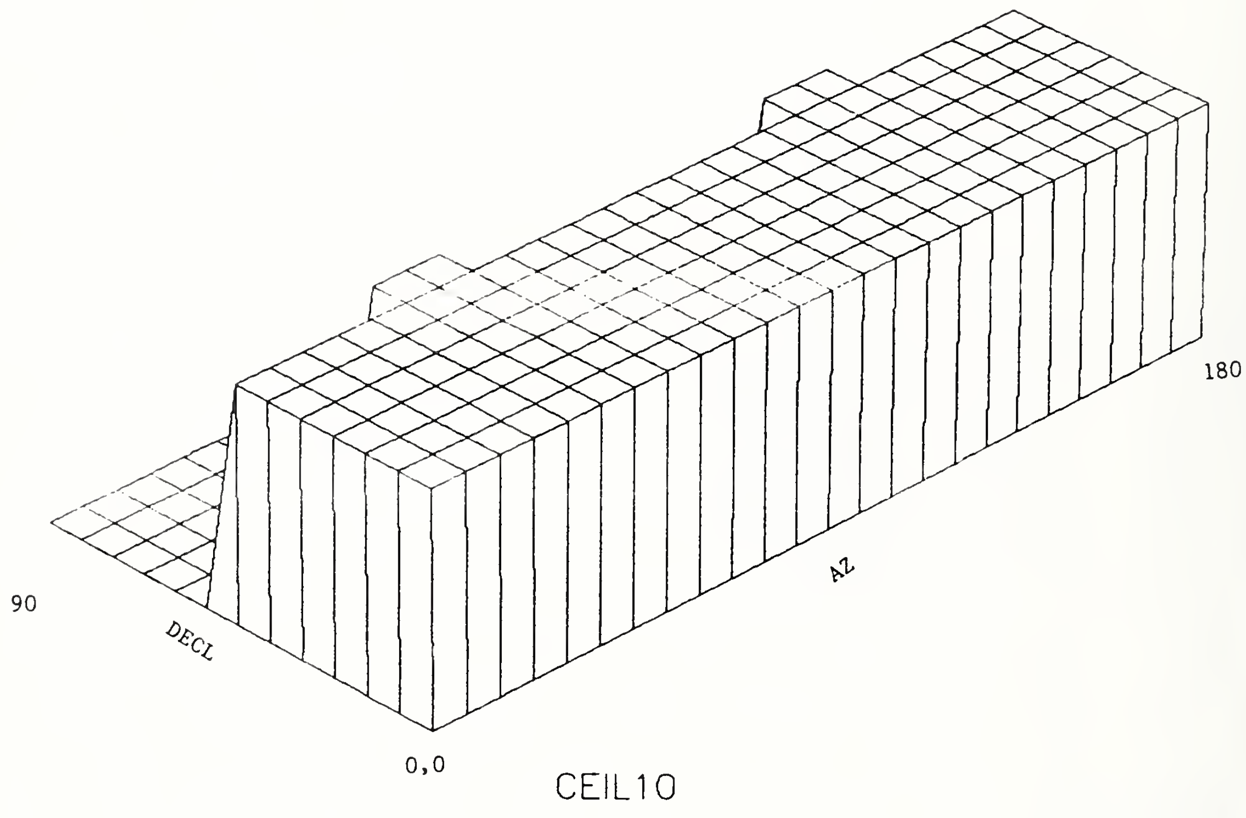


Figure 20. Incident Angles for Ceiling from Center of 10 Foot Wide Square Room

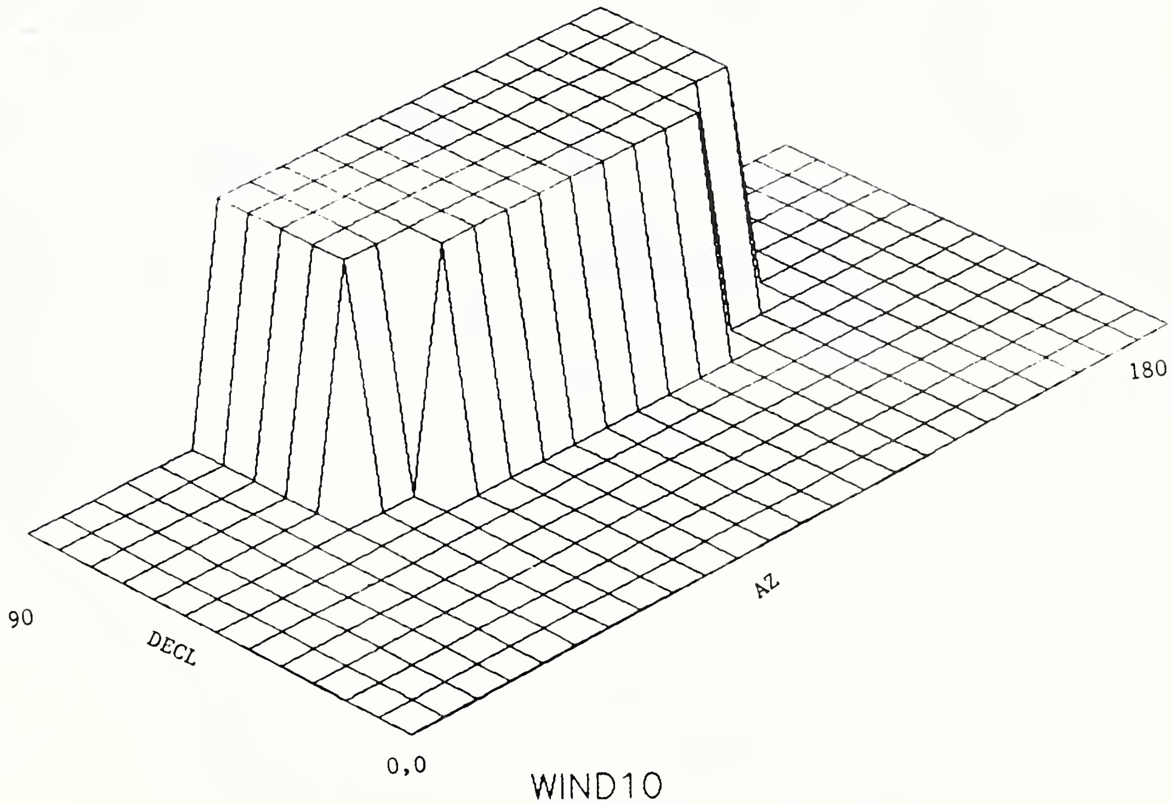


Figure 21. Incident Angles for Window from Center fo 10 Foot Wide Square Room

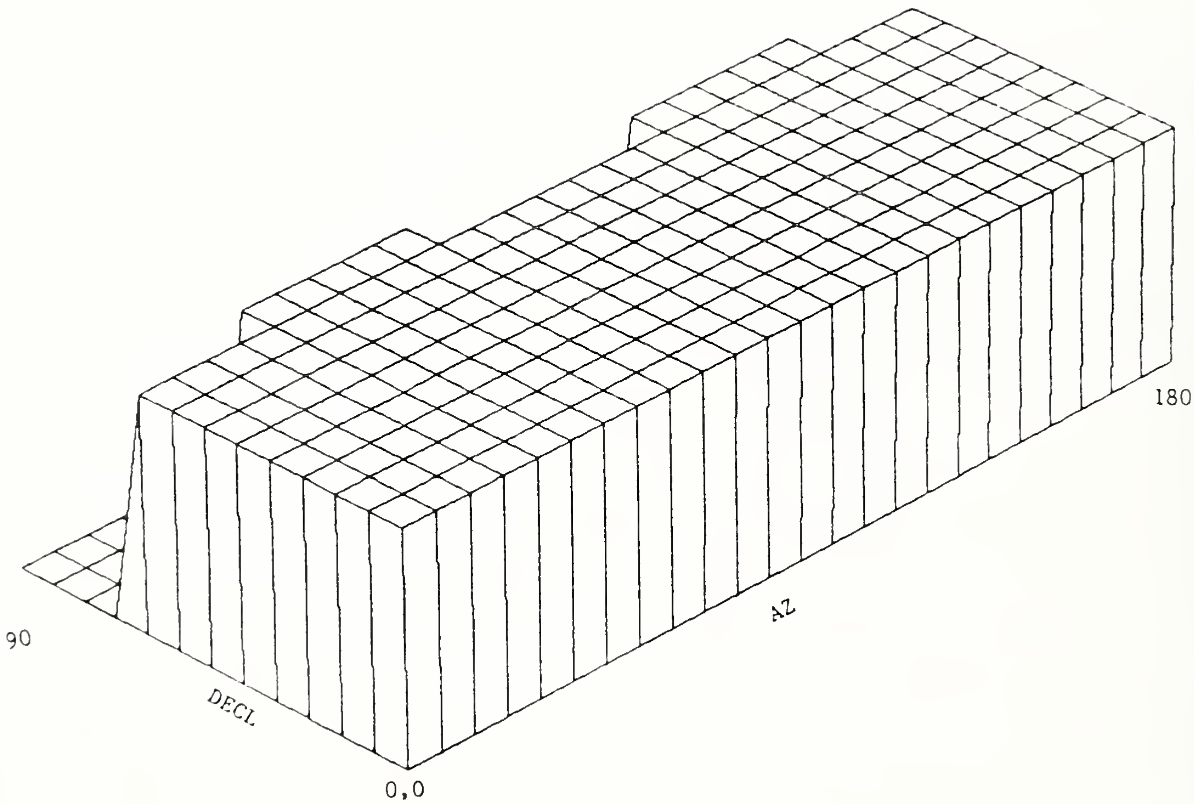


Figure 22. Incident Angles for Ceiling from Center fo 20 Foot Wide Square Room

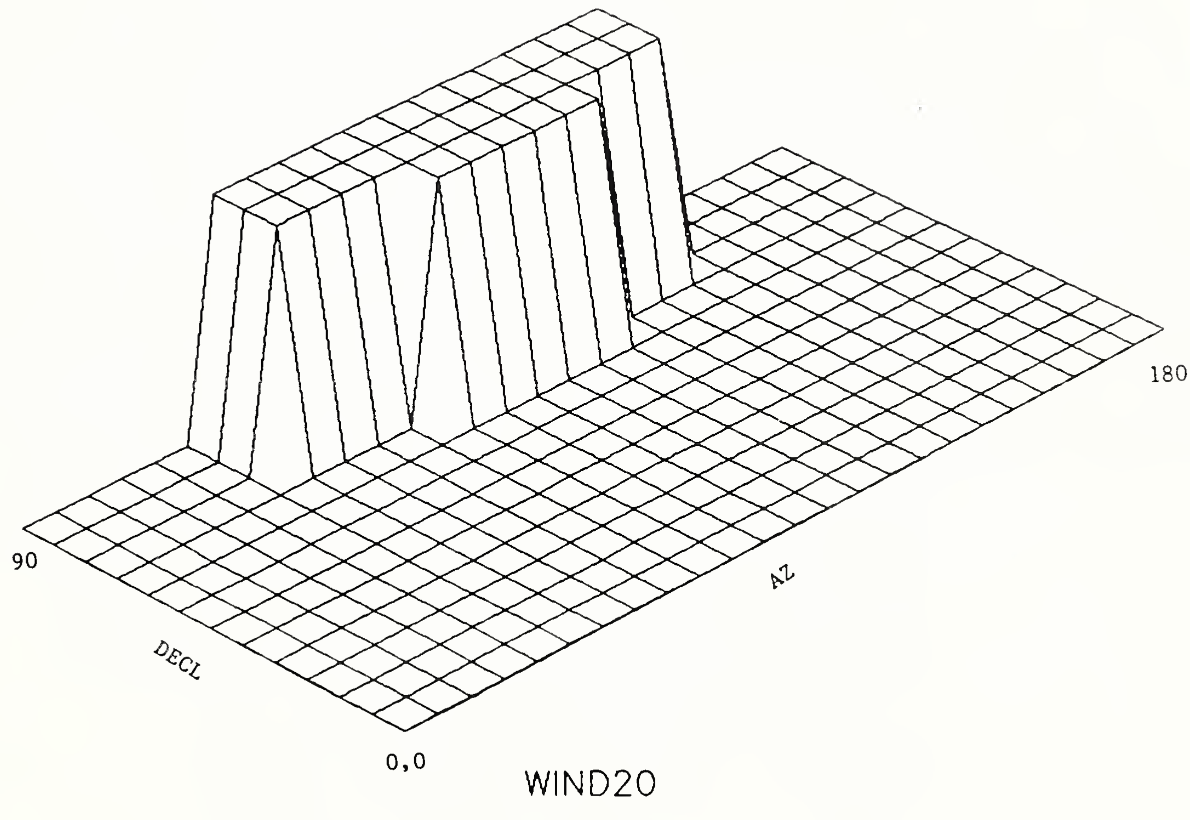


Figure 23. Incident Angles for Window From Center of 20 Foot Wide Square Room

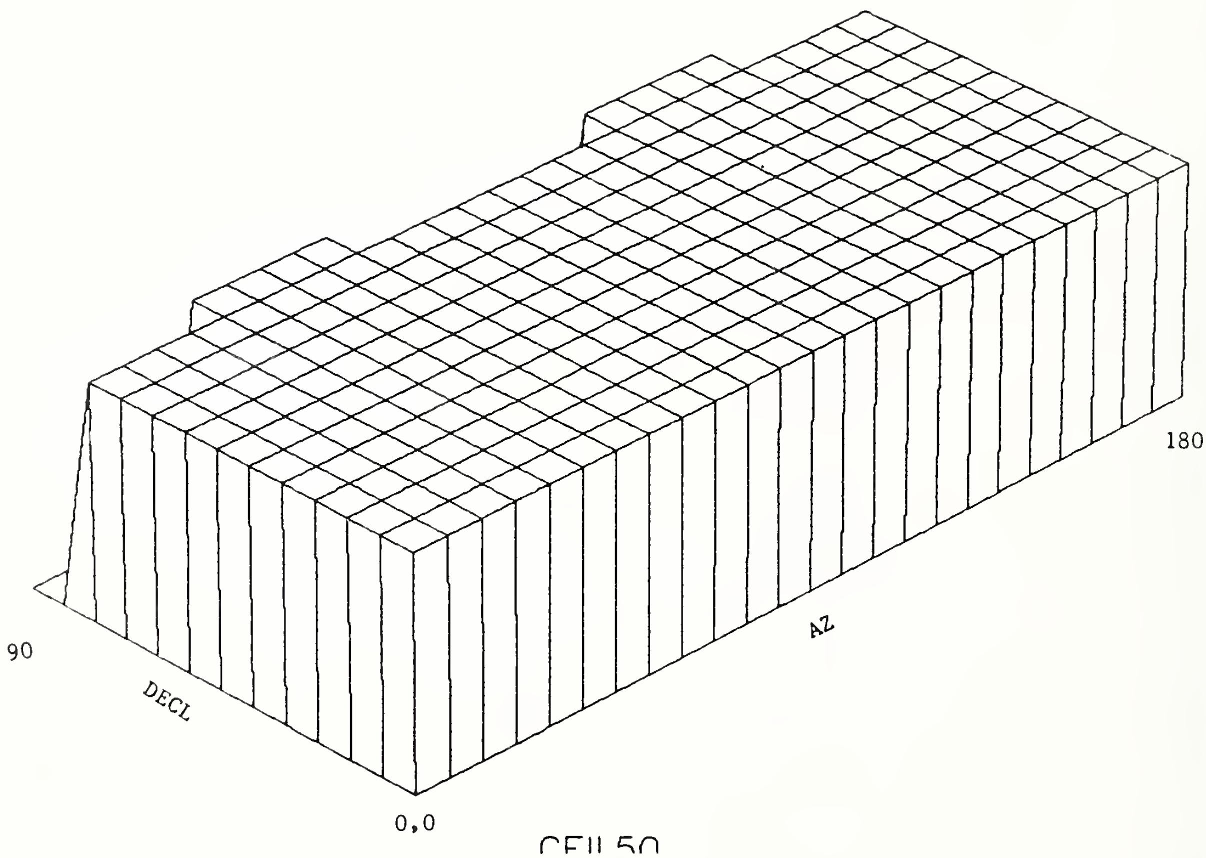


Figure 24. Incident Angles for Ceiling from Center of 50 Foot Wide Square Room

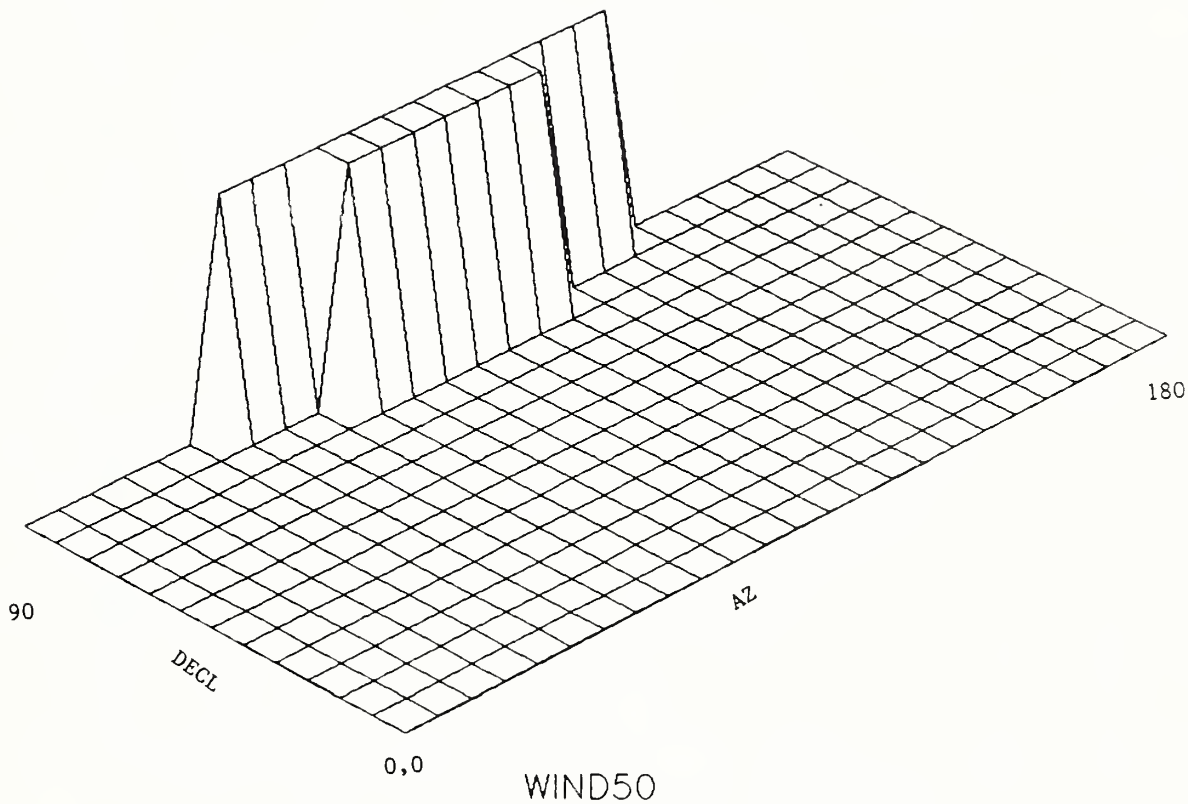


Figure 25. Incident Angles for Window from Center of 50 Foot Wide Square Room

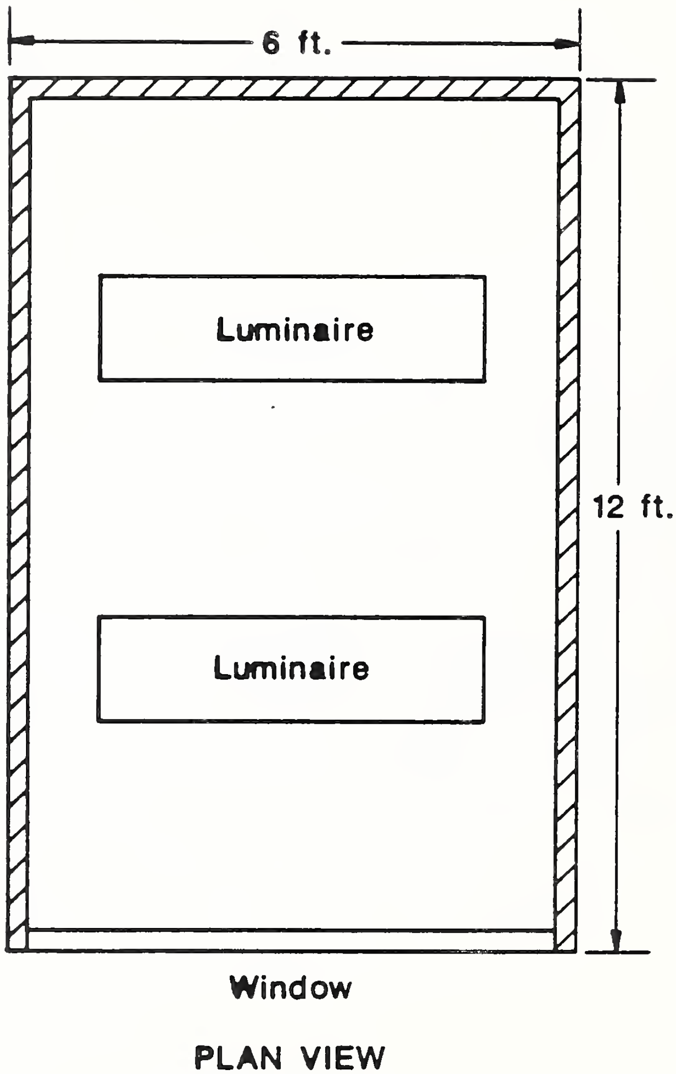


Figure 26. Layout of Simulated Room

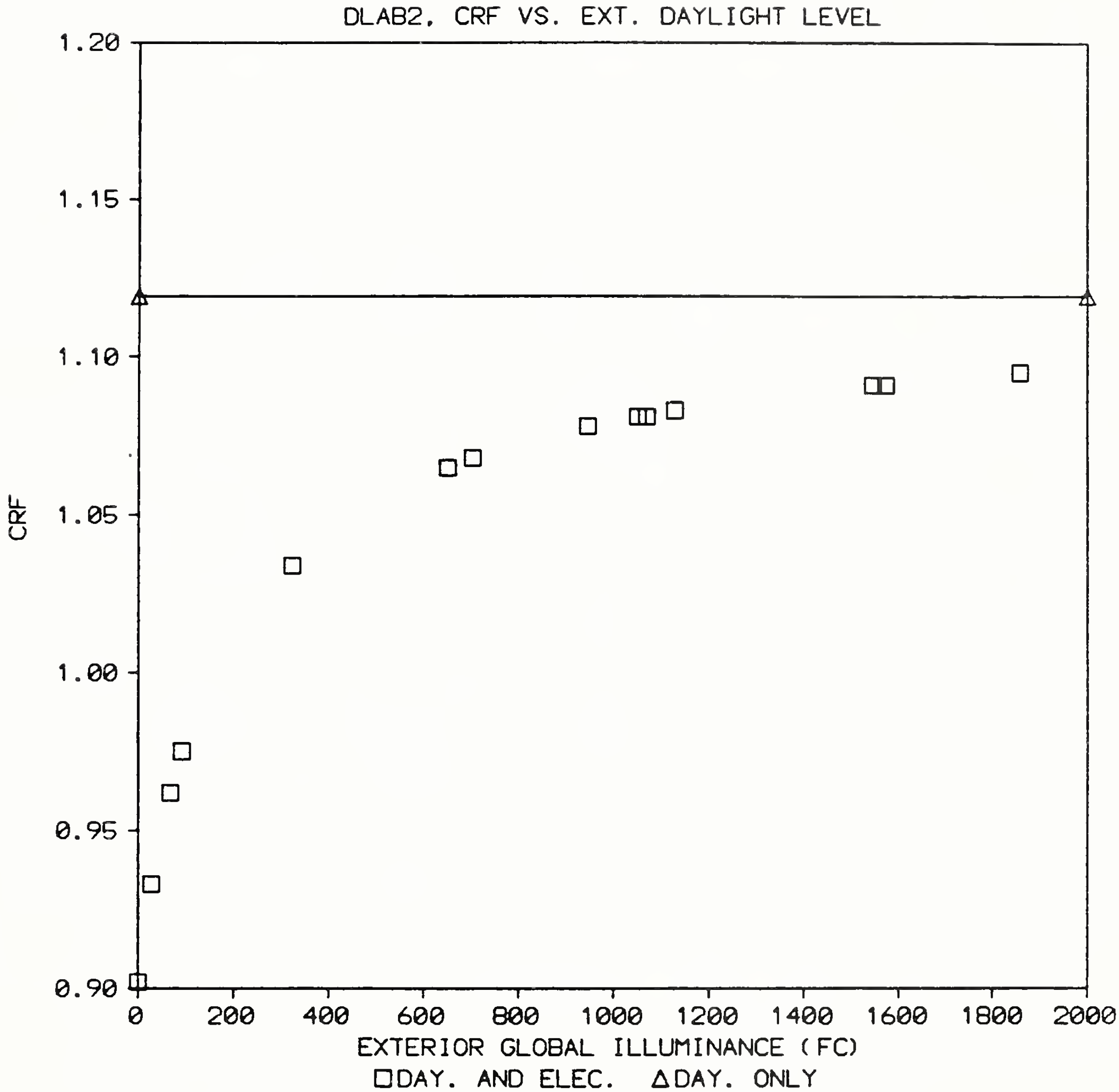


Figure 27. CRF Versus Exterior Daylight Level with Dimming

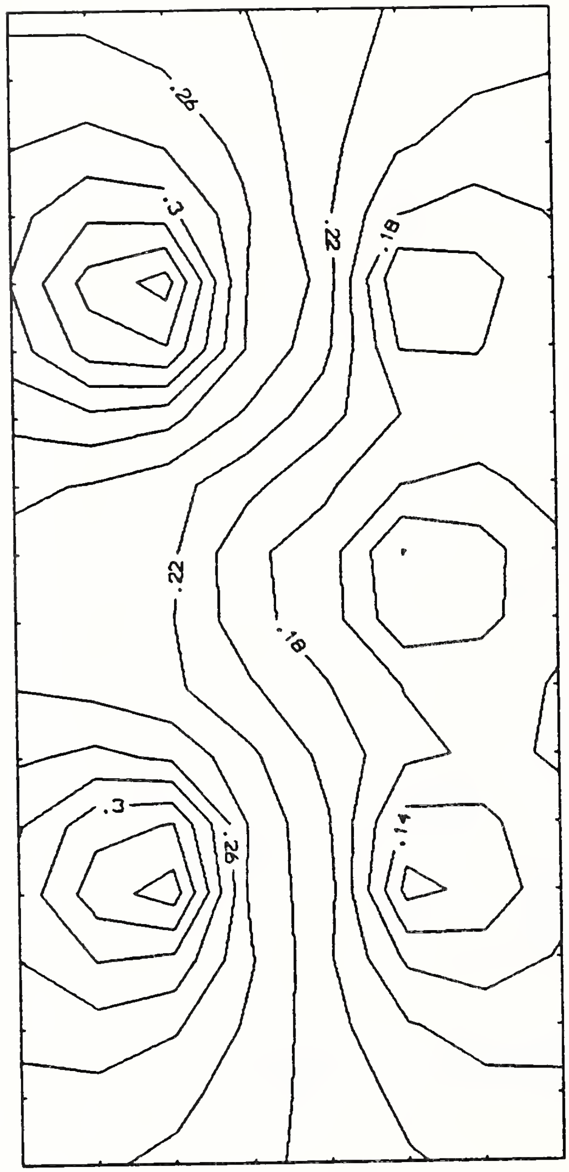


Figure 28. Change in Task CRF Substituting Daylight for Electric Light - Contour Plot

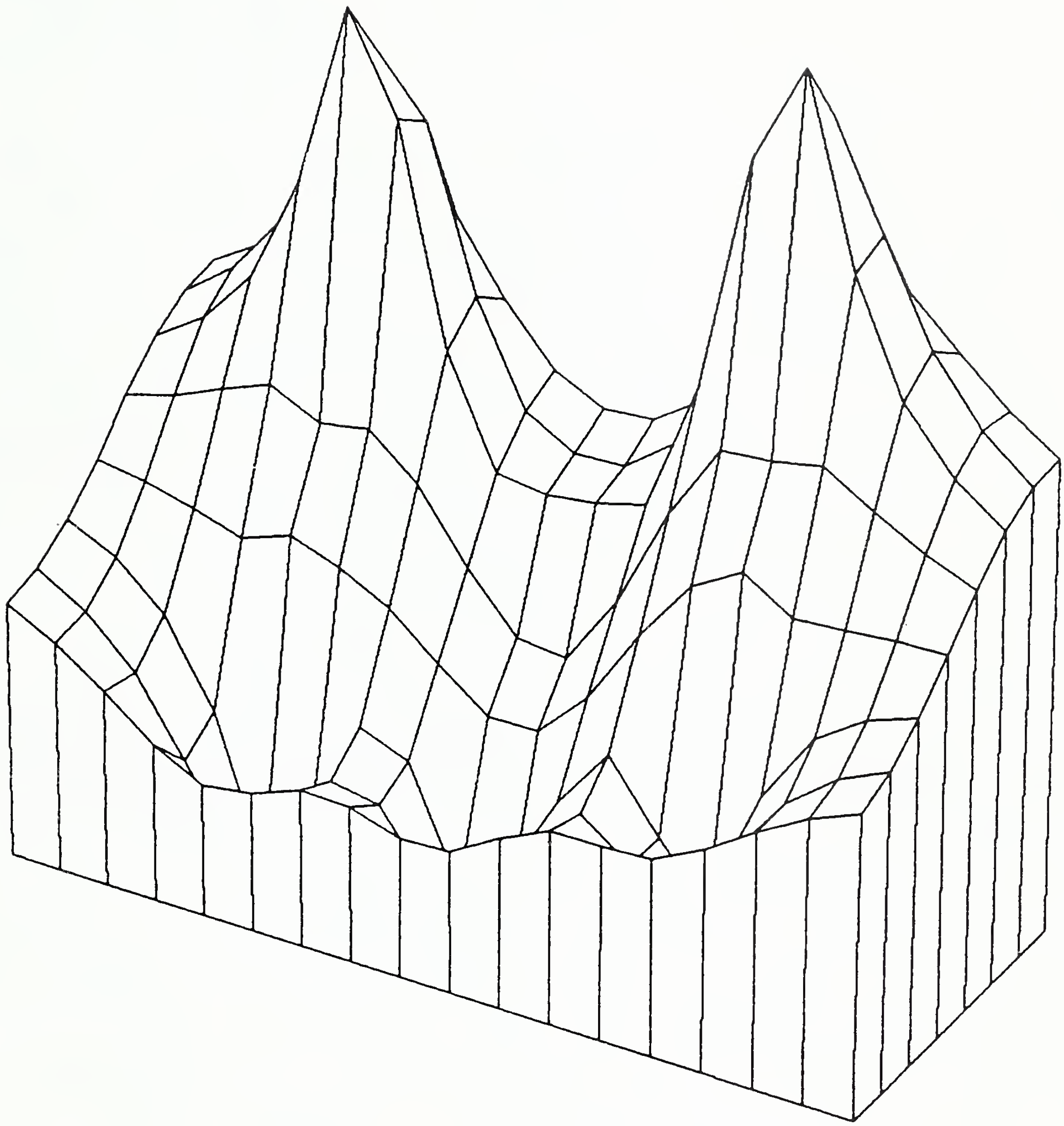


Figure 29. Change in Task CRF Substituting Daylight for Electric Light - 3D Plot

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NISTIR 88-4014	2. Performing Organ. Report No.	3. Publication Date MARCH 1989

4. TITLE AND SUBTITLE

Illumination Conditions and Task Visibility in Daylit Spaces

5. AUTHOR(S)

Stephen J. Treado

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

10. SUPPLEMENTARY NOTES

__ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

Illumination conditions are evaluated in typical building spaces based on detailed computer simulations, in order to characterize and quantify the effects of daylighting on task visibility. Examined are the effects of fenestration location and type on task contrast under daylit, electric-lit and combined conditions. The implications of the illumination conditions with daylighting on lighting and daylighting systems design are discussed.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

buildings, contrast, daylighting, fenestration, illuminance, lighting, luminance, visibility

13. AVAILABILITY

X Unlimited

__ For Official Distribution. Do Not Release to NTIS

__ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

X Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

54

15. Price

$14.95

USCOMM-DC 6043-P80